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Doctoral Thesis

Spatial analysis at multiple scales of ecosystem services supply of forest and agricultural landscapes in NW Iberian Peninsula

Tesis doctoral

Análisis espacial a múltiples escalas del suministro de servicios ecosistémicos en paisajes forestales y agrícolas en el NO de la Península Ibérica

Author: José Valentín Roces Díaz

Directors:

Dr. Pedro Álvarez Álvarez

Dr. Emilio Rafael Díaz Varela

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2.- Autor	
Nombre: JOSÉ VALENTÍN ROCES DÍAZ	
Programa de Doctorado: RECURSOS BIOLÓGICOS Y BIODIVERSIDAD	
Órgano responsable: DPTO. BIOLOGÍA DE ORGANISMOS Y SISTEMAS. UNIVERSIDAD DE OVIEDO	

RESUMEN (en español)

En los últimos años los Servicios Ecosistémicos (ES), definidos como los bienes y servicios que los ecosistemas aportan al bienestar de la sociedad, han sido reconocidos como de una gran importancia en campos relacionados con las ciencias ambientales, la ecología y la planificación territorial. La importancia de la dimensión espacial en información relativa a los ecosistemas ha propiciado la integración de perspectivas de análisis espacial en las evaluaciones de ES. El empleo para dichas evaluaciones de mapas de usos y coberturas del suelo o cartografías temáticas suele implicar errores asociados a la sobre-simplificación o generalización de la zona de estudio. Dada la dependencia entre los ES y los procesos de funcionamiento ecológico que no son constantes a medida que varía la escala, y de su heterogeneidad espacial y temporal, la definición de métodos de análisis del patrón espacial de los ES empleando datos adecuados, minimizando errores y obteniendo modelos espaciales más precisos resulta actualmente esencial. Así, el objetivo general de esta tesis es analizar la distribución espacial a múltiples escalas del suministro de ES y de algunos de los ecosistemas que los proporcionan. Para ello se emplean datos de diferentes fuentes en paisajes agrícolas y forestales del noroeste de la Península Ibérica. En esta zona los ecosistemas forestales son un elemento fundamental del paisaje y proporcionan un amplio rango de ES. Por ello se ha comenzado con su caracterización ecológica, definiendo de una forma precisa las zonas de hábitat potencial más adecuadas para las principales especies forestales. Así, las áreas potenciales para bosques de *Quercus robur* L. y *Castanea sativa* Mill. se han localizado por debajo de 500 m sin temperaturas bajas. Mientras que para los bosques de *Quercus petraea* (Matt.) Liebl. y *Fagus sylvatica* L. se corresponden con zonas con menores temperaturas y a mayores altitudes. A continuación, sobre mapas digitales categóricos de coberturas del suelo, se ha analizado la distribución de la provisión de ES mediante estadística espacial. El análisis se ha centrado en una selección de seis ES (alimentos, materiales, energía, regulación de erosión, climática, y culturales), empleándose la métrica multi-escalar *lacunarity* para analizar la regularidad de los las zonas de no suministro. Los resultados muestran divergencia en los niveles de agrupamiento espacial de los ES, siendo mayores en provisión de alimentos y materiales. A su vez, se pudieron identificar las escalas (extensiones) espaciales que maximizan la probabilidad del suministro de cada ES. Por otro lado se adoptó una perspectiva funcional para el análisis de la provisión de ES. Para ello, se desarrollaron modelos espaciales de provisión de ES sobre la base de la Productividad Primaria Neta, calculada para un año fisiológico empleando el índice ∑NDVI a partir de datos Landsat 5-TM, y luego combinando el índice con variables socio-ambientales. El patrón espacial resultante se ha analizado con dos métricas multi-escalares (lacunarity y *four term local quadrat variance*). Los resultados revelan un patrón más agrupado para los servicios de provisión y más disperso y extendido para los de regulación, con escalas espaciales características para cada tipología. Por último, empleando una cartografía temática forestal de alta precisión, se evaluó el suministro potencial de varios ES forestales. Se exploraron las relaciones espaciales entre dichos ES, encontrando que varían de forma significativa entre aquellos asociados a bosques autóctonos frente a los de plantaciones de especies alóctonas. A su vez, se determinó la presencia de zonas de concentración del suministro de ES (*hotspots*) a diferentes escalas espaciales. Los resultados obtenidos en esta tesis muestran la localización nichos ecológicos forestales y la distribución de ES a varias escalas en el noroeste Ibérico, así como el efecto de diferentes fuentes de información en el análisis de los patrones espaciales de ES.

RESUMEN (en Inglés)

Ecosystem services (ES) can be defined as the goods and services that ecosystems provide to the society for its well-being. The importance of ES in different fields of environmental sciences, ecology and land planning has been highlighted in recent years. The relevance of spatial aspects of the data describing ecosystems has driven the use of several spatial analysis techniques and methods for ES assessment. However, the extended use of Land Use/Land Cover maps may lead to uncertainty and bias due to oversimplification and generalization of the study area and associated elements. Ecosystem services and the ecological processes that generate them are strongly related. These processes are not constant at all spatial scales and display high levels of spatial and temporal heterogeneity. Thus, appropriate selection of the data sources and analytical methods used to characterize the ecosystems is essential for development of accurate models and minimization of potential bias in the assessments. The general objective of this research was to carry out a multi-scale analysis of the spatial pattern of ES supply and the distribution of some ecosystems that provide the ES. Different data sources were used to characterize agricultural and forest landscapes in the NW Iberian Peninsula. Forests are major components of the landscape in the area, and several authors have highlighted the wide range of ES that these ecosystems provide. We first characterized the ecosystems in order to identify the areas where the main forest tree species in the area are growing. *Quercus robur* L. and *Castanea sativa* Mill. forests are mainly located in zones below 500 m where low temperatures do not usually occur. By contrast, *Quercus petraea* (Matt.) Liebl. and *Fagus sylvatica* L. forests are associated with lower temperature zones at higher elevations. We then used digital soil cover data to analyze the pattern of supply of six ES (provision of food, materials and energy, regulation of climate and erosion, and cultural services) by spatial statistical methods. We used the lacunarity metric to analyze the regularity of the no supply areas at multiple spatial scales. We found some divergence in the thresholds of spatial clustering of the ES and obtained higher values for food and materials provision. We also identified the spatial scales (extensions) at which the probability of supply of each ES is maximized. In addition, we used a functional approach to analyze the pattern of supply of a similar set of ES. We developed spatial models of these ES on the basis of Net Primary Production, calculated for a phenological year from Landsat 5-TM data and using the ∑NDVI index. The index was then combined with some socio-environmental variables. We used two multi-scale metrics (lacunarity and four term local quadrat variance) to analyze the observed patterns. The analysis revealed clustered patterns for provisioning services and a more extended distribution for regulating services, with different characteristic spatial scales for each type. Finally, we used a high resolution forest thematic map to assess the potential supply of some ES from forest ecosystems. We thus explored the spatial relationships between these ES and found some differences between the ES associated with native forests and those supplied by forest plantations of exotic species. We also determined the zones with a high density of elements involved in ES supply at different spatial scales. This enabled us to identify the locations of the most

important areas for some ecosystems in relation to the supply of different ES in the NW Iberian Peninsula. Finally, we also analyzed the most characteristic spatial scales and the effect of different types of data sources on ES assessment.

SR. DIRECTOR DE DEPARTAMENTO DE BIOLOGÍA DE ORGANISMOS Y SISTEMAS
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Desde que tengo memoria, siempre he tenido una (pequeña) obsesión por dos elementos, que o bien atraviesan (y forman) el paisaje -los caminos y senderos- o bien sirven para representarlo -los mapas- (dijo alguien una vez que no hay un buen libro que no contenga un mapa; también hablaba Borges de un Imperio obsesionado con la cartografía; y él mismo y Eco trataron de describir el patrón y el mapa de unas bibliotecas que se asemejaban a laberínticas colmenas; y Pratt (y también Eco) habla de una Isla Escondida que no aparecía en los mapas, y que al igual que la biblioteca de Eco, está regida por un monje). Como, en definitiva, esta tesis habla de paisajes y de mapas y de cómo estos representan el medio y sus ecosistemas, he estructurado los agradecimientos en base a estos conceptos. Por un lado, personas que han formado (y forman) parte del camino seguido durante esta tesis doctoral -en un sentido estricto-, y por otro personas que han formado (y forman) parte del paisaje en donde dicho camino se integra, y por tanto, aparecen en mapa que lo representa (o en los mapas pasados o en los futuros o en los que quizás sean). A todos ellos, mi más sincera y profunda gratitud.

El camino

> *A smoky mist, resembling that of the Indian summer, enveloped all things, and of course, added to my uncertainty. (…) Everywhere was variety in uniformity. It was a piece of composition, in which the most fastidiously critical taste could scarcely have suggested an emendation. I had turned to the right as I entered this road, and now, arising, I continued in the same direction. The path was so serpentine, that at no moment could I trace its course for more than two or three paces in advance. Its character did not undergo any material change.*
>
> Edgar Allan Poe -Landor´s Cottage-

A quienes desde el ambiente universitario habéis dedicado tiempo y esfuerzo para que este trabajo pudiera llevarse a cabo, para que yo pudiera recorrer por mi cuenta -pero nunca solo y abandonado- el mencionado camino.

> *Well I stumbled in the darkness*
> *I´m lost and alone*
> *Though I said I´d go before us*
> *And show the way back home*
>
> *Tom Waits* -Long Way Home-

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El mapa

I'm a-goin' back out
'fore the rain starts a-fallin',
I'll walk to the depths
of the deepest black forest,
(…)
And reflect it from the mountain
so all souls can see it.

Bob Dylan -A Hard rain´s A-Gonna Fall-

A todas aquellas personas que forman parte del paisaje que veo cada día (y que me reconforta). Por acompañarme por los otros caminos que aparecen (o que aparecían y ya no lo hacen, pero siguen estando) o que quizás aparecerán en un futuro (porque la única norma inmutable es el cambio) en el citado mapa.

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Introduction

General aspects and a brief history of the Ecosystem Services concept

From a general point of view, the concept of Ecosystem Services (ES) has been defined as "*the benefits of nature to households, communities, and economies*" (Boyd and Banzhaf, 2007). This concept became popular in the late 1990s and has since increased in importance in different scientific fields. The works of Ehrlich and Mooney (1983), Braat et al. (1979) or de Groot (1987) have contributed to the initial adoption and extension of the concept, addressing the socio-economic relevance of ecological functions and the goods and services provided by ecosystems. Some years later, the topic was analyzed in depth by Gretchen Daily in her book "Nature´s Services" (Daily, 1997) and diffusion of the ES concept became widespread after publication of the paper by Costanza et al. (1997) in the journal Nature, in which the authors estimate the monetary value of the main types of ecosystem in the world on the basis of the services that they provide to society. One of the factors underlying the growing acceptance of the term is its key idea "*that ecosystems are socially valuable and in ways that may not be immediately intuited*" (Daily, 1997).

The concept was perceived as extremely important by international organizations, who adopted it to assess the condition of the world´s ecosystems and impacts related to global change processes (e.g. loss of biodiversity, land use change and climate change) and how both have the potential to influence human well-being. Thus, when the United Nations (UN) formulated the Millennium Development Goals[1] for the year 2000, the ES approach was considered highly valuable for the seventh goal, i.e. *to ensure environmental sustainability*. Consequently, the Millennium Ecosystem Assessment (MA)[2] was launched in the early 2000s, with the following main objective: *to assess the consequences of ecosystem change for human well-being and the scientific basis for action needed to enhance the conservation and sustainable use of those systems and their contribution to human well-being.*

The MA, which was carried out between 2001 and 2005, involved more than 1,300 experts worldwide. It produced five thematic volumes and six scientific reports that would establish a framework for most subsequent ES-based-analysis. Other initiatives, such as The Economics of Ecosystems and Biodiversity (TEEB)[3], focused

[1]The Millennium Development Goals are eight international goals established at the Millennium Summit of the United Nations in 2000, following adoption of the United Nations Millennium Declaration. These goals are related to some problems in the daily lives of some people that seriously affect their well-being.

[2]http://www.unep.org/maweb/en/Index.aspx
[3]http://www.teebweb.org/

on "*drawing attention to the economic benefits of biodiversity including the cost of biodiversity loss and ecosystem degradation*", also played a relevant role. This initiative involves numerous partners (i.e. the United Nations Environments Programme, the European Commission, National Environmental Agencies, etc.) and has led to research being carried out at different scales to highlight the importance of ES to society and the need to include this concept in land planning and management. Following completion of these international projects, governments of different countries began to perform ES-based-analysis of their ecosystem types. In Spain, the *Evaluación de los Ecosistemas del Milenio* (EME)[4] began in 2009 with contributions from a large number of researchers at different Spanish Universities (e.g. Autónoma de Madrid, Complutense, Alcalá de Henares, Politécnica de Madrid, Oviedo, Zaragoza, Granada, Huelva, Murcia, etc.) and other institutions (e.g. Fundación Biodiversidad, Ministerio de Agricultura, Alimentación y Medio Ambiente, Instituto Pirenaico de Ecología-CSIC, Estación Experimental de Zonas Áridas – CSIC, Instituto Mediterráneo de Estudios Avanzados (IMEDEA)-CSIC).

One of the most important contributions of the early studies concerning ES was the development of an ES classification, which was an essential starting point for further research. Although the classification developed by MA (2005) is widely used, different authors focused on, discussed and defined alternative classes of ecosystem functions and services (De Groot et al. 2002; Wallace, 2007; Costanza, 2007; Fisher and Turner, 2008; Fisher et al., 2009; Haines-Young and Potschin, 2013). Three general categories of ES are accepted (definitions and examples following MA, 2005):

- Provisioning services: "*the products people obtain from ecosystems, such as food, fuel, fibres, fresh water, and genetic resources.*"
- Regulating services: "*the benefits people obtain from the regulation of ecosystem processes, including air quality maintenance, climate regulation, erosion control, regulation of human diseases, and water purification.*"
- Cultural services: "*the nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences.*"

Although the Millennium Ecosystem Assessment mentioned a fourth category, i.e. supporting services *("necessary for the production of all other ecosystem services, such as primary production, production of oxygen, and soil formation*"), this can be considered as complementary to the others. In this study, we have used the initial classification of three ES types. The supporting services can be considered as

[4] http://www.ecomilenio.es/

intermediate services or functions in contrast with the other three categories, which are closer to being recognised as "final services". As the present research focuses on analysis of "final ES", we did not include supporting services in our assessment (following other classifications such as those proposed by Haines-Young and Potschin, 2013). Figure 1, adapted from the MA (2005) classification, includes some examples of the ES in the above-mentioned categories and illustrates how these are related to different aspects of human well-being.

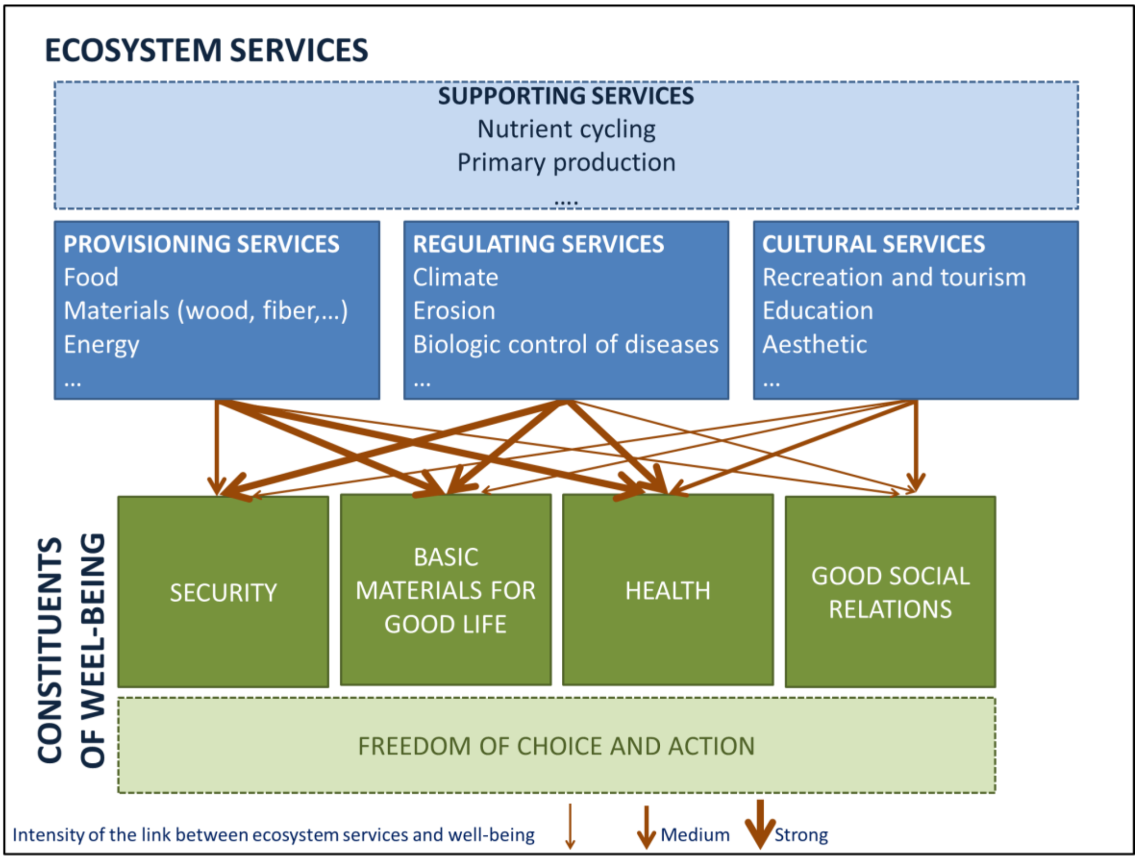

Figure 1. Relationships between ES and different constituents of human well-being. Adapted from MA (2005).

Biodiversity is a major component of ecosystem functioning and thus drives the provisioning of ES that are the basis of human well-being. Gaining detailed knowledge of the ecological process that produce the ES will involve identification of those elements of the ecosystems that control the process that produce these services (Kremen, 2005). Different types of proxies have thus been used to establish links and quantify the relationships between ecological processes and ES (Luck et al., 2009; Harrington et al., 2010; Mace et al., 2012). However, species loss and other threats to biodiversity are directly associated with the capacity of ecosystems to provide services, and some studies (MA, 2005; Sala et al. 2005; Cardinale et al., 2012) have related the loss of biodiversity in the last centuries and decades to the impact of human activities on ecosystems.

The ecological unit that provides a service was defined by Luck et al. (2003) as a Service Providing Unit. Consideration of the Ecosystem Service Provider (ESP), as suggested by Kremen (2005), integrates various levels of ecosystem organization: population, functional group and community. Several authors have attempted to establish the relationships between functional characteristics of ecosystems and ES supply (i.e. Diaz and Cabido, 2001; Diaz et al., 2007; Luck et al., 2009, de Bello et al., 2010, Harrison et al., 2014). At the landscape level, the presence of a wide variety of ES is strongly associated with the richness of different types of ecosystems (or e.g. Land Use classes) in the study area. Thus, some studies describing ES supply at this level involve the use of some indices as landscape metrics to analyze the spatial pattern of the ecosystems (e.g. Syrbe and Walz, 2012; Walz and Syrbe, 2013; Frank et al., 2013).

Spatial analysis of Ecosystem Services

The different types of assessment carried out or proposed for ES have always included a spatial component because of the spatial explicitness of ecosystems. For example, Costanza and colleagues included this type of analysis in their pioneering article (Costanza et al., 1997) and also in a recent update (Costanza et al., 2014), in which the type of ecosystems analyzed were geographically represented. Thus, several authors have highlighted the importance of carrying out spatial-based assessments of ES to integrate findings on the management and conservation of ecosystem landscapes (Hein et al., 2006; Naidoo et al., 2008; Daily and Matson, 2008; Albert et al., 2014). Mapping of ES is often mentioned in the European Biodiversity Strategy 2020 as a key element for achieving the objectives defined. Thus, several studies have focused on defining the supply and demand mapping processes (i.e. Hauck et al., 2013; Crossman et al., 2013).

One key aspect of this type of spatial analysis is the availability of geographical data that represent the ecosystems in the study area. Thus, global studies use ecosystem classifications that refer to the different types of biomes in the world or macro-climatic classifications. Other studies performed at European continental scale use datasets such as CORINE Land Cover and the European Forest Information Scenario Databases (EFISCEN), which provide information about land use classes or forest ecosystems. The CORINE Land Cover is often used at regional and local scales

(Burkhard et al., 2010; 2011; Frank et al., 2011). However, the level of detail of the analysis at both scales depends on the availability of high resolution data (spatial, thematic or temporal). For example, Kandziora et al. (2013) used different type of maps to assess some agroecosystem-related ES during 16 years in an area of northern Germany. Other authors combined information from remote sensors for a wide temporal range (1964-2004) to analyze the changes in land cover patterns in relation to ES supply (Lautembach et al., 2011). Other types of data (e.g. socio-economic information such as population data, number of head of cattle, etc.) may be useful for characterizing changes in ES supply at local scales (Moran-Ordoñez et al., 2013).

The most straightforward way of mapping ecosystems in order to identify potential or real service supply is to use Land Use/Land Cover (LULC) classes as a proxy for ecosystem representation. If the spatial or cartographic data include sufficient information, LULC data can be re-classified into ecosystem types depending on their structural and/or functional characteristics. Once an ecosystem map is constructed, a further step is needed to establish links between ecosystems and the services provided, or even the capacity for supply. A wide range of information can be used as the basis of such links (e.g. crop or forest productivity, structural characteristics, and dynamics). Such information can be obtained by literature searches, use of expert criterion, and (if sufficient resources are available) field research on the many aspects of the socio-ecological system. Once the cartographic information is established, other aspects of the ecosystems can be estimated by spatial analysis of the maps constructed. For instance, analysis of the spatial configuration of the landscape has been used successfully to provide information on ES supply (Frank et al., 2011; 2013; Syrbe and Walz, 2012; Turner et al., 2012).

In addition to categorical cartographic information, other sources of information, such as remote sensing imagery, have been increasingly used in recent years to analyze ES supply (Ayanu et al., 2012; Cabello et al., 2012). Indeed, studies involving ES analysis based on remote sensing data are increasingly common (De Araujo-Barbosa et al., 2015). The advantage of using remote sensing imagery relies on the capacity to provide spatial data over continuous time series and with homogeneous radiometric characteristics (if the data used is from the same sensor). Two main types of analytical approach can be used: one based on classification of the imagery to define ecosystems types and analyze the landscape structure, and another that combines environmental parameters related to ecological functioning of ecosystems in order to perform functional approaches (Alcaraz et al., 2006; Fernandez et al., 2010).

Supply and other characteristics of ES are strongly scale dependent. In this study, three main types of scale were considered: the *functional* or *operational scale* (spatial extension at which the essential structures or processes operate), the *observation scale* (the area comprised by the study) and the *scale of analysis* (scale at which the features are revealed from the analyzed data) (Lam and Quattrochi, 1992). Scale, together with its closely related concept of hierarchy, has been recognized as a central topic of ecology (Allen and Starr, 1982; O'Neill et al., 1986; 1989; King, 1997) and in ecological and environmental analysis (Wu et al., 2006; García et al., 2008). Scale is also an important source of uncertainty in ES analysis at the landscape level (Hou et al., 2013). For these reasons, several authors have recently focused on the analysis and detection of spatial scales in relation to ecosystem processes and derived services (e.g. Konarska et al., 2002; Hein et al., 2006; Martín-López et al., 2009).

The ES originate from different types of ecological processes with intrinsic characteristics, and they generate different spatial patterns. As a consequence, some ESPs may be widely distributed while others may be clustered within a few zones, with limited extension or distribution. Identification of the most appropriate scale for ES studies and characterization of the spatial patterns shown by ES are therefore key aspects, especially when the final goal is to include ES approaches in spatial planning at the appropriate spatial level. Characterization of ES patterns must also define the concepts of ES supply and demand. According to Burkhard et al. (2011),

- *"Supply of ecosystem services refers to the capacity of a particular area to provide a specific bundle of ecosystem goods and services within a given time period. Here, capacity refers to the generation of the actually used set of natural resources and services."*
- *"Demand for ecosystem services is the sum of all ecosystem goods and services currently consumed or used in a particular area over a given time period. Up to now, demands are assessed not considering where ecosystem services actually are provided."*

The spatial interactions between the different services have played a key role in ES studies in recent years (Mouchet et al., 2014). Thus, trade-offs, synergies[5] and similar concepts have been analyzed by several authors (i.e. Rodriguez et al., 2006; Raudsepp-Hearne et al., 2010; Martin-Lopez et al., 2014). Their importance for spatial planning has also been highlighted in different studies, e.g. in relation to forest

[5]Definitions following Raudsepp-Hearne et al. (2010):

- *Ecosystem service trade-offs: the simultaneous reduction in one ecosystem service and the enhancement of another.*
- *Ecosystem service synergies: the simultaneous enhancement of one ecosystem and another.*

ecosystem services (Onaindia et al., 2013; Rodriguez-Loinaz et al., 2013), in which analysis of different ES provided by native forest and fast growing species plantations in north Spain were compared. Another spatial characteristic often studied is the presence of areas with different densities of ES supply, defined as *hotspots* when the density is high, and *coldspots* when it is low. Identification of these (Gimona and Van der Horst, 2007) and analysis of how they are associated with areas of high biodiversity (Egoh et al., 2009) are important for spatial planning that is consistent with the ES concept. From the perspective of forest management, integration of the ES and the interactions between them has also been indicated as an important element of sustainable forest management (Fürst et al., 2013; García-Nieto et al., 2013). Nevertheless, the type of data and the characteristics are important for the analysis of spatial patterns and interactions (Eigenbrod et al., 2010a; 2010b), and aspects such as the detection of hotspots of one ES vary greatly depending on whether primary data or data proxies (e.g. Land Use/Land Cover map) are used.

In this study, we used data from different sources and also different approaches and methods to analyze the pattern of some ES and other ES-related concepts, such as the potential supply or the ESPs, from a spatial point of view (Figure 2).

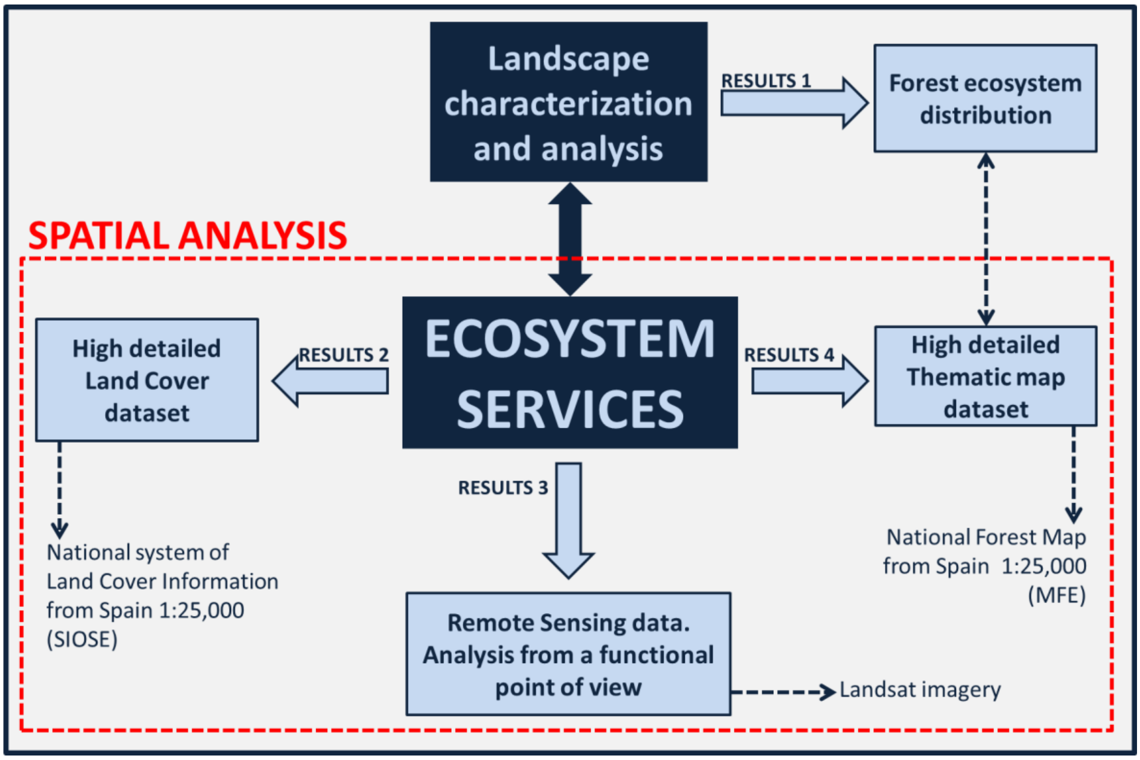

Figure 2. General workflow followed in this study.

In this study, we defined the environmental niches of the main forest ecosystems in the study area; these types of ecosystems are of key importance in relation to the ES that they provide (Harrison et al., 2010) and they comprise a major part of landscapes in the study area. These findings may help in estimating the potential supply or comparing the potential and current supplies of the ecosystems in a geographical area. We also used a database with high spatial resolution and based on the description of land cover types to analyze the pattern of some ESP and to indicate the spatial scales of the related ES. Taking into account that the ES and the process that generate them are strongly dependent on scale, this type of analysis may be helpful in future studies. We also used a combination of remote sensing information and socio-environmental variables to estimate ES supply and to detect the characteristic scales of their patterns. Although several authors have highlighted the potential use of this type of data for ES analysis, scientific studies based on remote sensing information for this purpose are scarce. Finally, the results obtained using a thematic forest map to assess the potential supply of some ES revealed the usefulness of this type of information for ES analysis. The map enabled inclusion of some information about the map features, such as forest species and cover, other than those included in classical proxies (e.g. LULC), thus enabling more detailed analysis of the ES and their spatial patterns.

Agricultural and forest landscape of northwestern Iberian Peninsula

The study area is located in the NW Iberian Peninsula and comprises the Autonomous communities of Asturias and Galicia. The total surface area of these regions is 40,200 km^2 and the total population is approximately 3.8 million inhabitants, distributed amongst some medium sized cites (several hundreds of thousands of people) and numerous rural centres. The study area is located in the European Atlantic Region (EEA 2011; Figure 3) and borders the Mediterranean Region. The elevation ranges between 0 and more than 2500 m, and the terrain is rugged - especially on the eastern side. The Cantabrian Mountains, which cross the country from east to west, determine the relief throughout the study area and show a marked gradient of elevations from the coast, especially in the eastern zone. The landscape has prominent slopes, which constitute one of the main restrictions to crop growing and similar types of use. The flattest areas at the bottom of the valleys are also the most populated areas.

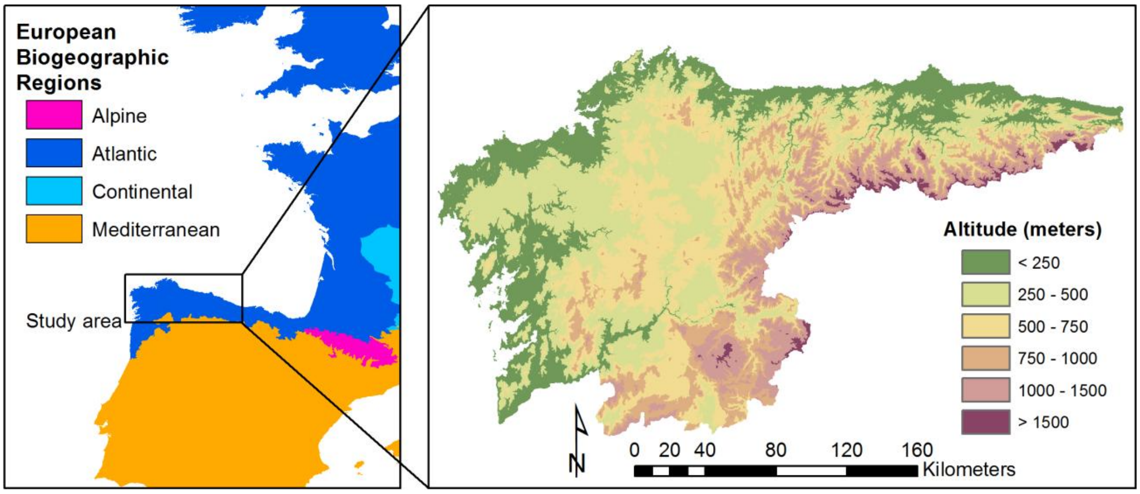

Figure 3. Location of the study area according to the classification of Biogeographic Region of Europe (source: EEA, 2011) and representation of the range of elevation in the area (source: IGN, 2015).

The prevailing climate throughout most of the area is oceanic, with mean precipitation exceeding 1000 mm/year (Ninyerola et al., 2005; Figure 4). Although the precipitation decreases in summer, physiological drought only occurs in a part of study area that is within the Mediterranean Region (and with a Mediterranean climate) and covering an area of approximately 5,000 km^2. The average temperature in the area is lower than in the Mediterranean zones. However, lower temperatures are reached at high elevations.

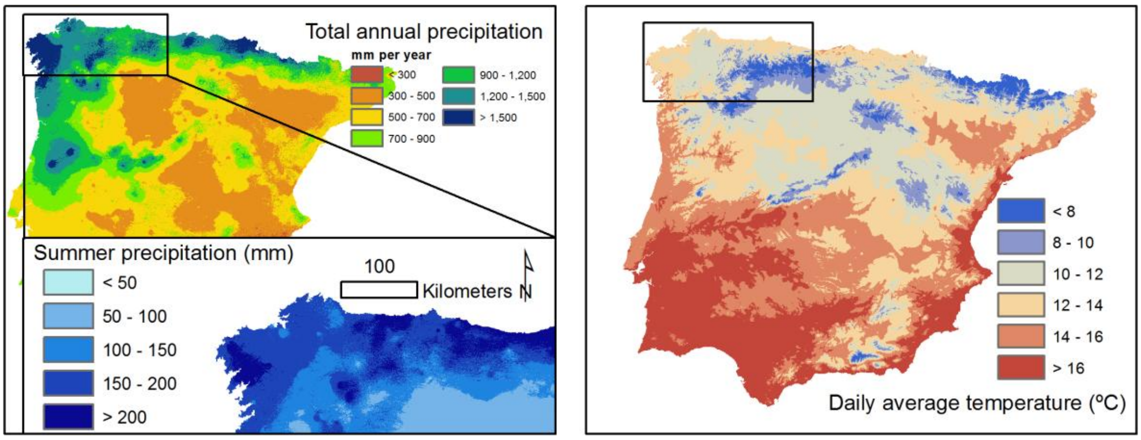

Figure 4. Precipitation throughout the year, and in the summer, and the daily average temperature in the study area (source: Ninyerola et al., 2005).

The area is one of the most densely forested regions (MAGRAMA, 2013), and also represents one of the most important carbon stocks in Spain (Doblas-Miranda et al., 2013). During the last century, human activity has greatly transformed the most accessible areas at low and medium elevations (< 1000 metres). Much of the low-lying land is used to produce fast growing species such as *Eucalyptus* spp. and *Pinus* spp. for timber production, and this has greatly modified the landscape of the area from a spatial point of view (Saura and Carballal, 2004). However, remnants of natural forests including *Fagus sylvatica* L., *Betula* spp. and *Quercus* spp. as the main species are found (Roces-Díaz et al, 2015). These forests are relatively more abundant in mountainous zones than in nearby areas (García et al., 2005), and the network of protected natural areas is strongly associated with these native forests. The forest ecosystems are also commonly scattered amongst habitats used to graze livestock (meadows and heathlands); the timber line is represented by deciduous forests and rarely exceeds an elevation of 1700 m (Díaz and Fernandez-Prieto 1987). Shrub and herbaceous communities are present in the sub-alpine zones. The vegetation in the area has been greatly affected by human activities during thousands of years. Thus, the lowlands include mixed patches of native species, such as *Quercus* spp. and *Castanea sativa* L., plantations of fast growing species and meadows, fields and crops. Mountainous areas have a higher cover of native forest but also shrub communities, mainly comprising *Erica* spp., *Ulex* spp., *Cytisus* spp. and *Genista* spp., which in the past were of outstanding importance for traditional agricultural uses. The socio-economic changes undergone in these rural zones during recent decades, in relation to the decreased population and aging of the remaining population, has involved important changes in the type of land use. For instance, many shrub communities used for grazing cattle have been replaced by woodland (Moran-Ordoñez et al., 2011; Alvarez-Martinez et al., 2014). Thus, the spatial pattern of the cultural landscapes in the area has undergone important changes (Calvo-Iglesias et al., 2006; Martinez et al., 2010). Such changes in the socioecological systems are associated with variations in ES supply (Moran-Ordoñez et al., 2013). Indeed, the main driver of changes in this geographic area identified in the Millennium Ecosystem Assessment of Spain (EME, 2011) is associated with changes in the type of land use.

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Objectives

General objective

The general objective of this research was to analyze the spatial distribution of Ecosystem Service supply by applying a multi-scale approach to spatial data from different sources, including categorical maps and remote sensed imagery, focusing on the agricultural and forest landscapes in the NW Iberian Peninsula.

Specific objectives

The specific objectives of the research are as follows:

- To identify the environmental factors that drive the spatial distribution of the main types of native forest ecosystems and to define the zones with greatest potential in relation to the presence of these ecosystems in the study area.
- To use available databases with high spatial resolution and based on the description of land cover types to analyze the spatial pattern of some Ecosystem Services Providers; then to analyze the spatial pattern by using a multi-scale, fractal-based spatial metric (lacunarity) to estimate the regularity of the distribution of the gaps in provision of the ES.
- To use Remote Sensed Imagery (Landsat) obtained in different seasons of a phenological year, in combination with some information of other socio-environmental variables, to provide a proxy for the supply of a selected set of ES; then to analyze the spatial patterns of the ES by using two multi-scale metrics: lacunarity and four term local quadrat variance.
- To use a forest thematic map, with a high spatial resolution, to characterize the potential supply of some forest ES; then to analyze the spatial patterns of the ES with special focus on the identification of hotspots and characterization of spatial relationships between ES.

Structure of the results of this research

The results presented here are also reported in four scientific articles written by the author and different colleagues. Three of the articles have been published and the fourth has recently been submitted. Further details regarding the methods used and the results obtained can be found in these articles:

- Roces-Díaz, J.V., Jiménez-Alfaro, B., Álvarez-Álvarez, P., Álvarez-García, M., 2015. Environmental niche and distribution of six deciduous tree species in the Spanish Atlantic region. iForest – Biogeosciences and Forestry Journal. 8, 224-231. doi:10.3832/ifor1183-008.
- Roces-Díaz, J.V., Díaz-Varela, E.R., Álvarez-Álvarez, P., 2014. Analysis of spatial scales for ecosystem services: Application of the lacunarity concept at landscape level in Galicia (NW Spain). Ecological Indicators. 36, 495–507. doi:10.1016/j.ecolind.2013.09.010
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Results and general discussion

This part of the document is organized in five sections: four concerning the specific results reported in each of the above-mentioned articles and one section providing a general discussion of the results.

Characterization and modelling of the distribution of the main types of forest ecosystems in Asturias (NW Spain)[6]

Presence and absence data for the main forest tree species in Asturias were used to develop six General Linear Models (by logistic regression). These models describe the environmental -climatic and topographic- factors that drive the distribution of these species. Thus, the main objective of this work was to define the ecological niches of the species in a spatially explicit way. The data were derived from the database of the Third National Forest Inventory[7] in Asturias (1877 plots).

The following species were considered:

- *Quercus robur* L.
- *Quercus petraea* (Matt.) Liebl.
- *Quercus pyrenaica* Willd.
- *Fagus sylvatica* L.
- *Castanea sativa* Mill.
- *Betula pubescens* Ehrh. *(*sometimes referred to as *B. pubescens* subsp*. Celtiberica* or *B. celtiberica*).

Of a previous set of nine variables, only five were used (because the models require input of independent variables, only those variables that were not closely correlated with others were considered). The following five variables were included:

- The average minimum daily temperatures in the coldest month (January) (ºC; TMIN).
- The slope (%, SLOPE).
- The solar radiation during one year (kJ m^{-2} $year^{-1}$; RADI).
- The rainfall during one year (mm; PRECI).

[6]For a complete description of the research, please refer to the following article included in the "Publications" section:

Roces-Díaz, J.V., Jiménez-Alfaro, B., Álvarez-Álvarez, P., Álvarez-García, M., 2015. Environmental niche and distribution of six deciduous tree species in the Spanish Atlantic region. iForest. 8, 224-231. doi:10.3832/ifor1183-008.

[7]Tercer Inventario Forestal Nacional (IFN3). Subdirección General de montes, Dirección General de Conservación de la Naturaleza, Secretaría General de Medio Ambiente, Ministerio de Medio Ambiente, Madrid.

- An estimation of the mineral fertility of soil (FERTI) calculated using a semi-quantitative variable between 1 (minimum) and 4 (maximum).

The GLM revealed differences between the variables that determine the presence of each tree species and the fitness of each. The values of the indicator Area Under ROC Curve were adequate for *F. sylvatica* (0.861) *Q. robur* (0.760), *C. sativa* (0.758) and *Q. petraea* (0.753) and lower for *B. pubescens* (0.627) and *Q. pyrenaica* (0.569). TMIN was the most important variable in these models. *Quercus robur* and *C. sativa* showed a preference for areas with higher values meanwhile *Q. petraea* and *F. sylvatica* preferred mountain areas with colder temperatures. FERTI was positively related to *F. sylvatica* and negatively related to *Q. robur* and *B. pubescens*. The first species occurs more typically on limestone soils with higher values on mineral fertility of the substrate.

The GLMs were used to construct six maps showing the habitat suitability (HS; between 0 and 1) for each species with a spatial resolution of 200 m. The species that preferred zones with high vales of TMIN (*Q. robur* and *C. sativa*) occur optimally in non-mountainous areas below 500 m above sea level. On the contrary, the most suitable areas for *F. sylvatica* and *Q. petraea* are mountainous zones over 1000 m. The correlations between the HS for these species (Pearson's correlation coefficient) also varied. Thus, *Q. petraea* and *F. sylvatica* showed a high value (0.87) and low values with the non-mountain species (*F. sylvatica* -0.876 with *Q. robur* and -0.834 with *C. sativa*; *Q. petraea* -0.839 with *Q. robur* and -0.938 with *C. sativa*). The models for *B. pubescens* and *Q. pyrenaica* (which performed less well) showed intermediate values relative to the models developed for the other species.

Spatial analysis of Ecosystem Services and associated scales using a Land Use/Land Cover dataset for NW Spain[8]

This section describes the analysis of a spatial land cover/land use database aimed at characterizing the pattern of some ES in an area about 2,000 km^2 in north-western Spain. The database was obtained from the System of Soil Information of Spain (SIOSE[9]), produced at a cartographic scale of 1:25,000. Conversely to other ES

[8]For a complete description of the research, please refer to the following article in the "Publications" section:
Roces-Díaz, J.V., Díaz-Varela, E.R., Álvarez-Álvarez, P., 2014. Analysis of spatial scales for ecosystem services: Application of the lacunarity concept at landscape level in Galicia (NW Spain). Ecol. Indic. 36, 495–507. doi:10.1016/j.ecolind.2013.09.010

[9]Dirección General del Instituto Geográfico Nacional works as National Reference Center on Land Cover and on Land Use and Spatial Planning.

assessments reported in the recent literature based on land use/land cover maps, the data used aallows an open classification of cover classes. SIOSE data enables classification based on the combination of different cover types for each spatial feature adapted to the needs of any given study case. In this study, we established a classification of the study area that included 38 land cover classes. We then identified those classes that acted as Ecosystem Service Providers (ESP) by an expert criterion process for six ES: food provision, materials provisions, energy provision, flow regulation, abiotic regulation and cultural services. Two types of ESP classification were used and maps were constructed: a binary type map that defined ESP and NO ESP zones, and a greyscale map that defined five categories of ES supply, ranging from No supply to Very high supply. The pattern of the ESP of each of the six ES and for both classification types were analyzed using a multi-scale spatial “lacunarity index”. This index provides an estimate of the regularity of the gaps (in this study, the gaps are NO ESP zones) with different sizes of scale of analysis. Scales ranging from 100 to 3,500 m were used to represent the lacunarity curves, which represent the changes in NO ESP areas with the increase of scale (extension).

The maps of binary type showed higher cover by NO ESP for the provisioning services (food 79.3%; materials 84.7%; energy 60.7%) than for the remaining ES (flow regulation 25.5%; abiotic regulation 20.2%; cultural 37.9%). The greyscale maps showed lower values for these NO ESP zones for the six ES (between the 19.7 and 31.4% of the landscape except for materials provision 54.8%). The lacunarity curves for the binary maps were clustered in two families of curves according to their values. The results of the Lakkis–Jones and non-linear extra sum of squares tests revealed that curves for flow and abiotic regulation are not statistically significantly different. Although the remaining curves are significantly different, the curve for cultural service, is similar in shape and values to the curve for regulating services, and therefore these three curves were clustered in the same group, designated Family 2. Although the curves for provisioning services are significantly different, they are very similar in shape and the values of the Lakkis–Jones test (L value) and nonlinear extra sum of squares test (F* value) coefficients indicated that they were closer to each other than to the curves in Family 2. Thus, these three curves were clustered in Family 1. In relation to the greyscale data, the lacunarity values were very similar for the six maps. The results of the Lakkis–Jones test and nonlinear extra sum of squares test showed that these six curves were not statistically different and could be clustered in the same group.

Several differences between families were also observed in landscape metrics. The maps that generated Family 1 curves produced low values for class ESP (presence of ESP on a cell) for three metrics: percentage of landscape (PLAND), mean shape index (AREA MN) and area-weighted shape index mean (SHAPE AM); these values are lower than those produced for ESP classes in the Family 2 maps. On the other hand, the number of patches (NP) metrics showed mismatched results, with higher values for each map with Family 1 than with Family 2 curves. The values of five landscape metrics were compared on the basis of null class results for six greyscale maps, revealing similar patterns.

The characteristic scales of each ES were analyzed by detection of slope breakpoints on the lacunarity curves. For binary data, the occurrence of these points revealed differences between services. The lacunarity curves for Family 1 show break-points at the same scale, corresponding with window sizes (i.e. extensions) of between 800 and 900 m. However, the breakpoints for Family 2 curves, which were of similar shape and with similar lacunarity values, occurred at different scales of between 400 and 800 m. The breakpoints for the greyscale curves occurred within a similar range of scales: for 500–700 m and windows larger than 700 m, the lacunarity values scarcely changed. Spatial interpretation of the identification of breakpoints in lacunarity curves is possible. For binary data of provisioning services (family 1 curves), the area associated with the window size including the breakpoint was 72 ha, and thus a mean area of 72 ha is required to enable identification of a regular pattern in these services. This was the largest area identified in this work and is associated with a high proportion of gaps in binary maps of these services. However, in binary maps with few gaps (regulating services), the surface area associated with breakpoints in their curves was 20–25 ha. Finally, greyscale curves generated a similar range of surface area for six services, of 30–42 ha, despite the wide range of gaps, ranging from 20 to 54%.

Spatial analysis of Ecosystem Services and their scales identified using a functional proxy based on Remote Sensing data[10]

In this section, we analyzed the supply of some ES by using a combination of five remotely sensed images of an area of 2,134 km^2 in the NW Iberian Peninsula as the main information source. We selected a time series of images from sensor Landsat-5 TM[11] (spatial resolution 30x30 m) with low cloud coverage and spanning a

[10]For a complete description of the study, please refer to the following article in the “Publications” section:

Roces-Díaz, J.V., Díaz-Varela, R.A., Álvarez-Álvarez, P., Recondo, C., Díaz-Varela, E.R., 2015. A multiscale analysis of ecosystem services supply in the NW Iberian Peninsula from a functional perspective. Ecol. Indic. 50, 24–34. doi:10.1016/j.ecolind.2014.10.027

[11]Landsat imagery was obtained from the following agencies:

-PNT (Plan Nacional de Teledetección).

-ESA (European Space Agency).

recent phenological year. The first image selected corresponds to autumn (2010/10/18), the second to winter (2011/03/11), the third to spring (2011/06/24), the fourth to summer (2011/09/12) and the fifth again to autumn (2011/10/30), thus covering the entire phenological cycle. The normalized difference vegetation index (NDVI) was calculated for each image, and the five maps obtained were combined to produce a proxy of the potential productivity of the zone during a cycle of 365 days. The new index calculated was called ∑NDVI and was combined with another three variables (terrain slope, human population density and the presence of environmentally protected areas) to yield a spatial model of five ES: food provision, materials provision, energy provision, mass flow regulation and climate regulation.

The maps produced show the supply capacity of each ES based on the biomass amount and the other variables considered. Use of these weighted mask layers for the three provisioning services (food, materials and energy) implies a relative reduction in the values in the areas with steeper slopes. In contrast, the mass flow regulation service yielded high values for steep slopes with a high risk of erosion, and low or even zero values for flat areas. The maps of provisioning services (food, materials and energy) showed clustered patterns. Wide areas of no supply were more frequent in the central zone, while areas of high supply occurred in the east and west sides, where low slopes and high population densities occur. On the other hand, the regulating services (mass flows and climate) generally showed a non-clustered pattern, with high and low values evenly distributed throughout the study area (with the exception of the climate regulation service) and high values within the protected area.

These maps were analyzed using two multi-scale methods: lacunarity and four term local quadrat variance (4TLQV). The lacunarity analysis enabled quantitative assessment that was complementary to the visual interpretation of ES spatial pattern. Overall, the appearance of the five lacunarity curves is similar, with the highest values corresponding to the smallest window size (100 m), followed by a sharp decrease for larger windows, resulting in concave curves. The five curves have an asymptote close to the lacunarity's minimum value (1). In this study, the patterns corresponding to the provisioning services (food, materials and energy) generally showed higher lacunarity values that were more closely clustered than for the regulating services. Food provision showed the highest lacunarity values within the provisioning services, and the curve differed significantly in shape from the other curves. The values for supply of materials and energy were lower than for supply of food but still much higher than for regulating services. The provisioning services also reached a larger area of no supply (>26%).

-USGS (United States Geological Survey).

Both regulating services (mass flow and climate regulation) that showed a small area of no supply in their patterns – 8.06 and 2.37% of study area – yielded the two lowest lacunarity values and they were more widely scattered throughout the study area. Despite the differences in lacunarity statistics and curves, the position of the breakpoints (i.e. window size values recording abrupt changes in slope of the lacunarity curves) was similar for all ecosystem services. Thus, the five curves showed a characteristic spatial scale of gaps around window sizes of 2400 and 3300 m, which are relatively small in comparison with the range tested (100–23,000 m). This means that the lacunarity metric, and therefore the gap distribution, is more scale-dependent for window sizes smaller than those breakpoints. For larger window sizes, the lacunarity values are independent of the scale, and the ES gaps are more homogeneously distributed.

In general, the 4TLQV values increased more or less homogeneously from minimal levels in the smallest window sizes and then followed different patterns as the window size increased, depending on the particular ES considered. Nonetheless, the curves for the provisioning services tended to be similar. The values reached maximum levels of 162,553, 170,903 and 151,774 for provision of food, materials and energy respectively, corresponding to window sizes in the interval between 12,000 and 14,400 m. Thereafter, the curves tended to decrease, although new relative increments and peaks appeared for the largest window size (23,000 m). The mass flow regulation service was associated with the lowest 4TLQV values and the flattest curve. In fact, the maximum value is three times lower than the maximum value for the other ecosystem services and corresponds to a relatively large window size (21,300 m). Finally, the curve for the climate regulation service showed intermediate values between the provisioning and mass flow regulation services, with a smoother and more gradual increase and a maximum value (120,430) for the relatively large window size of 20,900 m.

Spatial analysis of Ecosystem Services using a forest map of the NW Iberian Peninsula[12]

The final section of results describes analysis of the potential supply of some ES with a forest spatial database for the NW of Iberian Peninsula as the main data

[12]For a complete description of the research, please refer to the following article in the "Publications":
Roces-Díaz, J.V., Burkhard, B., Kruse, M., Müller, F., Díaz-Varela, E.R., Álvarez-Álvarez, P. Use of forest data to analyze the potential supply of forest ecosystem services and their spatial relationships in NW Spain. Under revisión in Forest Ecology and Management. Reference number: FORECO15379.

source. This database corresponds to the most recent version of the National Forest Map of Spain for the Regions of Asturias and Galicia and has a spatial scale of 1:25,000[13]. The ES selected for this study were strongly associated with forest ecosystems (Forest Ecosystem Services, FES): food provision, materials provision, energy provision, climate regulation, erosion regulation and provision of cultural services. Different sources of information (forest harvest statistics, scientific articles and technical reports, etc.) were used to classify the potential supply of the ES for the different features of the study area based on the forest attributes of the spatial units (species, percentage cover, etc.)

The patterns of the ES showed different distributions of the potential supply classes. For instance, food provision was associated with the largest no supply area (88.8%) and erosion regulation with the smallest no supply area (<10%). On other hand, zones near to the coast were the most valuable for materials provision, but not for energy provision, climate regulation or cultural services, which mainly occurred in inland areas. Spatial analysis of the maps of potential supply was carried out using different methods: Moran's I/Incremental Spatial Autocorrelation and Getis-Ord Gi* statistic. All of the ES showed similar values of spatial autocorrelation by the Moran´s I index, indicating that the patterns were clustered in a similar way. Spearman correlation coefficients were used to analyze the correlation between services, yielding positive values for the six ES. Some pairs of ES are closely correlated (e.g. materials and energy provision with climate regulation) while others are less closely correlated (e.g. food provision with materials provision and erosion regulation).

A multiscale analysis of Incremental Spatial Autocorrelation, based on the Moran's I statistic, was also performed in order to detect the characteristic scales of each pattern. The z-score values of Moran's I statistic were plotted against increasing calculation distances and the corresponding curves showed peaks for the more intense clustered areas, thus defining scale domains. The curves for services providing food were similar up to a calculation distance of 20,000 m, and thereafter higher values were obtained for food provision with no clear peak, while materials provision showed a small peak at 95,000 m (these distances can be interpreted as the radius of a calculation window, which defines the extension or scale). The curves for the remaining ES have lower values, with a small increase for the smallest distances and a flat shape for larger distances. The energy provision and climate regulation curves have similar shapes up to 75,000 m without any marked slope. For distances greater than 100,000 m, the climate regulation curve shows similar values to the cultural services curve and

[13] MAGRAMA (Ministerio de Alimentación, Agricultura y Medio Ambiente).

the values of energy provision decreased slightly. The cultural services and erosion regulation curves show a similar shape for short distances (up to 35,000), with lower values than in the curve for food and materials provision and higher than for the remaining ES.

Finally, the Getis-Ord Gi* statistic was used to identify hotspots and cold spots of supply of the six ES, at two different spatial levels: i) regional, using the database from the original forest map; and ii) at municipal level for the study area. These hotspots/cold spots comprise zones with spatial clustering of features with high/low values of potential supply and with different spatial distributions. Hotspots of food provision are clustered in the central and eastern zones, while hotspots of materials provision occur on the coast of the central and west zones. The hotspots of energy provision and climate regulation are similar distributed, especially in the central area, but are also distributed throughout the study zone. Hotspots of erosion regulation service occurred in the eastern side of the study area, distributed along the direction of the Cantabrian Mountains. Finally, hotspots of cultural services followed the direction of the Cantabrian Mountains, especially on the eastern side and in the central area. Analysis of the potential supply of the six FES for the 393 municipalities in the study showed different results from those obtained at regional level. The food provision service occurred in the municipalities with highest values on the eastern area, where the hotspots also occur, while most of the western side is a large coldspot. On the other hand, the highest values for materials provision, and thus the hotspots, occur in zones close to the coast. The remaining four FES showed similar patterns in relation to the municipalities with highest values, most of which occur in interior eastern zones, and also in relation to the hotspots, which mainly occur in the Cantabrian Mountains zone. The distribution of coldspots was more variable, with a larger presence in coastal areas for cultural services.

General Discussion

The results of this study were based on the use different sources of spatial data to analyze ES supply: SIOSE digital categorical LULC maps; Landsat 5TM derived maps; inventory forest data and MFE digital categorical forest cover maps. These data sources were used in combination with specific methods of spatial analysis (lacunarity, four term local quadrat variance, Generalized Lineal Models, Moran's I and the associated Incremental Spatial Autocorrelation, and the Getis-Ord Gi* statistic) to characterize the pattern of the ES, the distribution of the main types of ecosystems providing them, and the spatial characteristic scales at which the provision occurs.

Although the ES were assessed independently of each other (Roces-Díaz et al., 2014; 2015b; 2015c), similar sets of ES were considered. Thus, the food, materials and energy provisioning was considered along with climate and erosion regulation in the three studies, while cultural services were considered in two studies.

The environmental niches of major native forest species of the study area were first characterized and defined (Roces-Díaz et al. 2015a). Several authors have highlighted forest ecosystems in relation to their biodiversity and the wide range of ES that they provide (i.e. Harrison et al., 2010; García-Nieto et al., 2013). However the supply of ES is strongly related to the different characteristic of these ecosystems, such as the type of management, which drives the species composition or the harvesting regime. In the study area, the ES provided by forest plantations of exotic species (mainly *Pinus* spp. and *Eucalyptus* spp.) are different from those provided by native forest in which management is also less intensive (Rodriguez-Loinaz et al., 2013). On the basis of this idea, we accurately defined the ecological niches of the major native tree species of this area, which are important for the supply of regulating and cultural services (Roces-Diaz et al., 2015c). The spatially explicit models of species or ecosystems distributions are useful tools for habitat management (Moran-Ordoñez et al., 2011). In addition, this type of data has great potential for analysis of the influence of management strategies on the forest ES supply at regional scale (Fürst et al., 2013; Frank et al., 2015).

The influence of the different types of data sources on the results on the ES spatial assessment was also taken into account in the analysis. The importance of the spatial scale and its effects on ES assessment have been addressed in depth elsewhere (i.e. Hein et al., 2006; Martín-López et al., 2009; Grêt-Regamey et al., 2014). The supply and other characteristics of ecosystems related to their services are strongly dependent on the scale. Thus, the internal characteristics of the data, such as the spatial resolution (Konarska et al., 2002; Grêt-Regamey et al., 2014) and the thematic resolution (Kandziora et al., 2013) affect the results obtained. Other factors such as the type of map used and some uncertainties and bias associated with ES assessment (such as the over-simplification of the types of ecosystems and the landscape) have also been highlighted by other authors (Eigenbrod et al., 2010). For these reasons we explored the use and the influence of different sources on ES spatial assessment in this study.

We used a land cover database with high spatial resolution (cartographic scale 1:25,000; minimum mapping unit 0.5-2 ha depending on the cover type) (Roces-Díaz et al., 2014). This database did not enable establishment of a closed classification of land cover classes. However, it provides information about the different types of cover in each patch of the study area and enabled classification of each case study. Thus, the different types of ecosystems of the study area were accurately defined and problems associated with the use of LULC data (Eigenbrod et al., 2010; Hou et al., 2013) were minimized. On the basis of the ecosystem classification, we identified the Ecosystem Service Providers of some ES. One type of bias is related to the presence of ecosystems covering a small area and acting as ESPs that are omitted on low resolution Land Use/Land Cover (LULC) maps. The high spatial resolution of the database used can also help to minimize this problem. Establishing this link between the type of ecosystem and the supply of ES yields a supply pattern for each service. The supply is associated with the type of ecosystems of a landscape (landscape composition) and also with the spatial distribution of the ecosystems (landscape configuration; Frank et al., 2011; 2013; Syrbe and Walz, 2012). The use of lacunarity index in ES research has previously been addressed relation to the characterization of no supply areas (Syrbe and Walz, 2012). Thus, the use of this metric, which depends on the total surface area of the no supply areas (Plotnick et al., 1993) and also on their regularity at different scales, was useful for analysis of the relationships between supply and landscape configuration and composition.

The lacunarity analysis was based on information that described the patches of the study area according to the structural characteristic of the ecosystems, and it is thus called a structural approach. However, a functional approach was used to analyze data related to the ecological functioning of the ecosystems (Roces-Díaz et al., 2015b). These types of approaches, based on remote sensing data, were studied in depth by several authors to describe the spatial heterogeneity of the landscape (e.g. Paruelo et al., 2001; Alcaraz-Segura et al., 2006). In this case, we used data from the Landsat 5-TM sensor. Previous studies (e.g. Ayanu et al., 2012; Cabello et al., 2012) have recommended the use of remote sensing data in ES assessment by some characteristics (e.g. high spatial and temporal resolution, and continuous data). However, in recent years assessments based on remote sensing data have proliferated (De Araujo-Barbosa et al., 2015). The combined use of an index based on a proxy for the Primary Net Production during a phenological year of the ecosystems (∑NDVI) and other sociological and environmental variables enabled development of a spatially explicit model of the supply of five ES. The patterns of these ES models were analyzed using two multi-scale metrics: lacunarity and 4TLQV. Based on the idea that ES supply is neither a homogeneous nor a static process (Fisher et al., 2009), this method enabled identification of the most important areas of ES supply. The provisioning services showed a clustered pattern, while the regulating services were more widely distributed throughout the study area. These findings are similar to those obtained with the land cover database of Roces-Díaz et al. (2014). In addition, the lacunarity was useful for detect thresholds at local scales, while 4TLQV was more sensitive at larger scales.

These scale thresholds were analyzed by the shape and the position of breakpoints on the lacunarity curves. The patterns of the binary maps (with only ESP or NO ESP areas) showed a threshold for the provisioning services with a window size of 900 m, but a larger window size for the remaining ES (Roces-Diaz et al. (2014). Subsequent findings at higher scales showed window size ranging between 2,400 and 3,300 m for the five ES (Roces-Diaz et al., 2015b). These values can be understood as the window size where the pattern of no-supply areas is regular and from which their supply is stable. On the basis of these findings, we recommend that ES analysis includes a study area larger than this range of surface areas obtained.

Once both structural and functional approaches were used to characterize the general aspects of ES provision, specific forest data were integrated to perform specific, more detailed forest ES provision analysis. We used a thematic digital forest map, which includes structural information (species composition, percent cover, etc.) and its associated database, as the main data source (Roces-Díaz et al., 2015c). This database was further combined with forest harvest statistics, information from other scientific works and expert criterion to assess the potential supply of six ES strongly associated with forest ecosystems (Forest Ecosystem Services, FES). Combined use of the different types of information enabled more accurate definition of forest ecosystems than use of other cartographic datasets. The analysis revealed differences between the spatial patterns of the provision of the six FES. For example, food provision and cultural services showed more clustered patterns, while regulating services were more widely distributed throughout the study area. These types of patterns were similar to those obtained in previous analyses (Roces-Díaz et al., 2014; 2015b). Analysis of the spatial relationships between the FES identified two types of forest ecosystems and the spatial structure of associated areas: i) fast growing plantations (with *Pinus* spp. and *Eucalyptus* spp.), which are common in the study area, have a high potential supply of materials provision services, but their potential to supply other FES is comparably low; and ii) native deciduous forests have lower growth rates, but a higher potential supply of FES such as climate regulation and cultural services. These effects are consistent with previous findings (i.e. Rodriguez-Loinaz et al., 2013; Onaindia et al., 2013; Palacios-Agundez et al., 2014). Areas of high interest in relation to their potential supply (hotspots) were identified using the Getis-Ord Gi* statistic. Although analysis of hotspots and cold spots is very common in ES analysis (i.e. Egoh et al., 2009; García-Nieto et al., 2013), only local scale studies (Homolova et al., 2014) or studies based on point data (Timilsina et al., 2013) have used the Getis-Ord Gi* statistic. This may be because this statistic has only relatively recently been included in GIS software. This statistic enables accurate definition of the type of area and is potentially useful for identifying priority conservation areas in relation to ES supply.

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Conclusions

The major conclusions of this work are as follows:

1. After definition of the environmental niches of the major native tree species in the study area, it can be concluded that the major environmental variable that drives the distribution of these species is related to the minimum temperature in the winter months.
2. The spatial delimitation of these niches and the areas with higher values of habitat suitability can be applied to ES analysis. Thus, analysis of the potential supply of these ecosystems or the comparison between potential and real supply could be performed using these types of maps.
3. The application of the multi-scale lacunarity index to a high-detailed land cover map enabled analysis of the spatial pattern of the provision of six ES. Two types of maps (binary and greyscale) were produced for these ES on the basis of expert criterion.
4. The binary maps showed that provisioning services were clustered relative to regulating and cultural services. The greyscale maps showed a similar pattern for all six ES. The classification based on expert criterion apparently worked better for the two categories of the binary maps than for five categories of the greyscale maps.
5. The use of the lacunarity metric enabled identification of functional scales in which the supply of these ES was theoretically warranted. These scales were similar for the provisioning services and showed differences from the regulating and cultural services with the binary maps. This scale analysis did no show differences from the greyscale maps.
6. The combination of remote sensing images and socio-environmental variables on a GIS enabled development of models of five ES with a high spatial resolution and based on the primary production of the ecosystem of the study area.
7. The patterns of these ES showed clear differences when analyzed using two metrics: lacunarity and four term local quadrat variance (4TLQV). Provisioning services showed clustered patterns and a higher variability at larger scales, while the regulating services were more widely distributed throughout the study area.
8. Lacunarity analysis was useful for detecting scale thresholds at the local level and for indicating whether the scale domains imply self-similarity in the

supply pattern. However, 4TLQV was more sensitive to scale thresholds at larger spatial levels.

9. The use of a forest thematic cartography integrating information about species structure and composition enabled highly accurate assessment of forest ES, although only related to forest ecosystems

10. These forest ES showed four different patterns of spatial clustering and scales: supra-regional (food provision), intermediate sub-regional (materials provision), low sub-regional (energy provision and cultural services); and two-level (climate and erosion regulation).

11. Identification of hotspots of potential supply of these forest ES based on the Getis-Ord Gi* statistic enabled precise delimitation of the areas of particular interest for each type of ES. Thus, areas close to the coast are more important for provision of materials by forest plantations. However, mountainous zones with greater presence of native forest ecosystems are more important for other services such as regulating and cultural services.

Publications

Environmental niche and distribution of six deciduous tree species in the Spanish Atlantic region.

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Environmental niche and distribution of six deciduous tree species in the Spanish Atlantic region

Jose V Roces-Díaz [(1)], Borja Jiménez-Alfaro [(2)], Pedro Álvarez-Álvarez [(1)], Miguel A Álvarez-García [(3)]

(1) GIS-Forest Group, Department of Organisms and Systems Biology, University of Oviedo, E-33993 Mieres (Spain); (2) Department of Botany and Zoology, Masaryk University, CZ-61137 Brno (Czech Republic); (3) INDUROT, Department of Organisms and Systems Biology, University of Oviedo , E-33993 Mieres (Spain)

@ Jose V Roces-Díaz (jvroces@gmail.com)

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Understanding the influence of environmental factors on the distribution of tree species is essential for developing management actions at regional level. We developed species distribution models for six European tree species to determine their potential niche in the Spanish Atlantic region, where deciduous forests are relatively well preserved. Data from the national Forest Inventory and topo-climatic and soil variables were used to construct distribution models by using Generalized Linear Models. The main factor accounting for the current geografic distribution of the selected species were minimum winter temperature and mineral fertility of soils. Suitable habitats for *Quercus petraea* and *F. sylvatica* were mainly high-altitude areas with low minimum temperatures. In contrast, *Q. robur* and *C. sativa* were restricted to low altitudes and warmer conditions. *Betula pubescens* was not influenced by the elevation, probably because its adaptation to Atlantic conditions, though its distribution was associated with low fertility soils. Although the submediterranean *Q. pyrenaica* was positively influenced by the slope, model performance was poor for this species, possibly because of the truncated environmental range of the species in the study area. The findings suggest that temperature rather than moisture is shaping the distribution of deciduous trees at the southern limit of the Atlantic biogeographic region. Strong elevational difference between the warm coast and the cold mountains may determine the geographical disjunction between *Q. robur* and *Q. petraea* in southern Europe.

Keywords: Species Distribution Models, Topo-climatic Variables, *Quercus* species, *Fagus sylvatica*, *Castanea sativa*, *Betula pubescens*, Iberian Peninsula, Deciduous Forests

Introduction

The temperate mid-latitude ecozone of the northern hemisphere is mainly distributed in the Atlantic regions of North America and Europe and also in central Europe (Schultz 2005). The climax vegetation of this ecozone consists of temperate deciduous forests, which dominate from sea level to the subalpine zone. These ecosystems comprise some of the main components of European landscapes (Meeus 1995) and provide the society with important flow of services (MA 2005, Harrison et al. 2010). The main ecosystem services provided by forests are regulation processes, such as soil protection, climate, etc., although provision of cultural services is also important.

The distribution of tree species in Europe is mainly determined by climatic factors (Svenning & Skov 2004, 2007), despite the effect of historical factors such as the presence of glacial refuges (Muñoz Sobrino et al. 2006, Willner et al. 2009) and naturalization of species beyond their former range. The dominant forest tree species in the temperate mid-latitude ecozone are taxonomically related, most belonging to the *Fagaceae* family. These species require a minimum of 120 days per year with an average temperature above 10 °C, and most of them grow in areas where winter is shorter than 4 months (Walter 1979) and frost damage is a secondary factor. Although it has been suggested that minimum temperature is one of the main determinants for the growth and development of native trees (Sykes et al. 1996), other climatic variables and soil factors are also expected to shape the distribution of tree species (Ashcroft et al. 2011).

Several attempts have been made to characterize the ecological niche and spatial distribution of forest tree species in Europe (Sykes et al. 1996, Brus et al. 2011, Casalegno et al. 2011). However, biogeographical regions differ in terms of historical and climatic factors. A better understanding of species-environment relationships requires data sources spanning over large areas with high spatial resolution (*e.g.*, National Forest Inventories - NFI), to be used for the development of climatic models, with the aim of analyzing particular areas and assessing the influence of environmental conditions. Computing species distribution models (SDMs - Guisan & Thuiller 2005, Elith & Leathwick 2009) applied on such data may be especially useful for defining the environmental niche of tree species and for assessing their potential distribution at regional scales.

In this study, we applied SDMs on species occurrence data from the Spanish NFI to compare the climatic niche of six European tree species in the Atlantic region, at the southern distribution limit of temperate deciduous forests in Europe. The studied region is characterized by an oceanic and relatively warm climate and representing a unique environmental zone in Europe (the *Lusitanian* zone, according to Metzger et al. 2005). The study area was the Autonomous Community of Asturias, one of the most densely forested areas of the Iberian peninsula, where deciduous forests are relatively well preserved. Asturias is characterized by an elevational gradient ranging from the sea level to altitudes often higher than 2000 m a.s.l., by far the strongest altitudinal gradient found across the entire European Atlantic region. According to local vegetation surveys, the distribution of tree species is determined by strong climatic gradients and soil conditions (Díaz & Fernández-Prieto 1994), although it is unknown whether local environmental gradients affect the ecological niche of forest trees. Thus, Asturias provides a good study system for investigating the environmental niche of European tree species in oceanic temperate climates with high topographic heterogeneity.

Understanding the ecological determinants that affect the distribution of forest tree species in this region is important for planning appropriate management actions aimed at preventing the potential impacts of climate

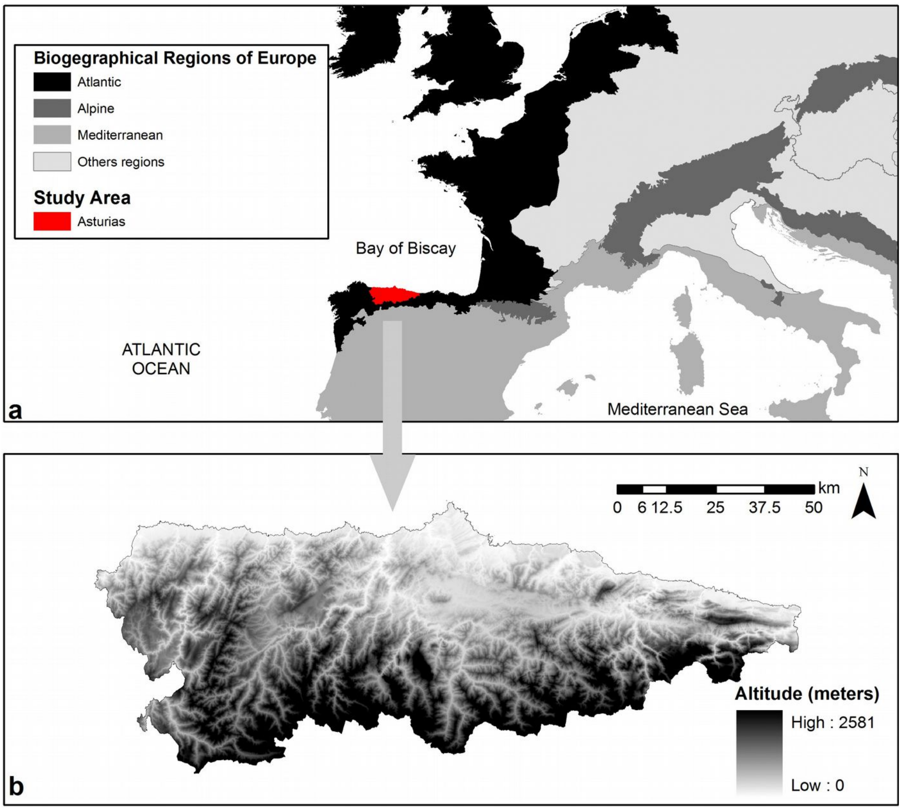


Fig. 1 - Map of the study area. (a): location of Asturias in the European Biogeographical Atlantic Region (source: EEA 2011). (b): Digital elevation model of Asturias (source: IGN 2013).

change in southern Europe (Benito Garzón et al. 2008). It is worth noting that native forests from this area are rarely monospecific, including one or more dominant species, and mixtures of different tree structures as well. Niche overlapping is therefore possible for these species, and the analysis of such overlap could help improve our understanding of forest distribution.

The main aims of this study were: (i) to investigate how environmental factors determine the distribution of main tree species in deciduous forests; and (ii) to delineate the potential distribution ranges of these species at high-resolution scale. In addition, we discuss whether the factors driving the forest tree species' occurrence in the Spanish Atlantic Region are similar to those previously reported for other European regions.

Material and Methods

Study area and species

The Autonomous Community of Asturias is part of the European Atlantic Region (EEA 2011) at the border with the Mediterranean Region (Fig. 1), and covers about 10 600 km^2 of which approximately 40% are forests. The area is one of the most densely forested regions in Spain (MMA 2003).

The climate is oceanic, with mean precipitation exceeding 800 mm year^{-1} and reaching more than 2000 mm year^{-1} at highest elevations. Precipitation decreases in summer in some areas, but physiological drought does not occur in any part of the study area. Forest wildfires in this region are less intense and affect smaller areas than in the Mediterranenan region (Álvarez & Marquínez 2007).

Human impacts on woodlands in Asturias began two thousand years ago (Muñoz-Sobrino et al. 2005), but during the last century human activity has deeply transformed most accessible areas at low and medium altitudes (< 1000 m a.s.l.). Nowadays, timber production using fast growing species such as *Eucalyptus* spp. and *Pinus* spp. are widespread at low altitudes, while remnants of natural forests are scattered amongst meadows and heathlands used for livestock. In montane areas, forests are more abundant though fragmented (Garcia et al. 2005). Timber line is represented by deciduous forests and rarely exceeds 1700 m a.s.l. (Díaz & Fernández-Prieto 1987).

In this study, six main native tree species occurring in the study area were chosen (Tab. 1): *Quercus robur* L., *Q. petraea* (Matt.) Liebl., *Q. pyrenaica* Willd., *Fagus sylvatica* L., *Castanea sativa* Mill., and *Betula pubescens* Ehrh (sometimes referred to as *B. pubescens* subsp. *celtiberica* or *B. celtiberica*). These species may be found as dominant trees (except *C. sativa*) in mixed forests, along with other minor species such as *Fraxinus excelsior* L., *Salix* spp., *Ilex aquifolium* L. and *Acer pseudoplatanus* L.

Data collection

Information on species cover was drawn from the Spanish National Forest Inventory (NFI - MMA 2003), based on a regular grid of 1×1 km covering the whole forested territory. For each grid node, data on the presence and cover of tree species in circular plots (radius 25 m) were available. Presence/absence of the six target species for 1877 plots falling within the study area were then imported in a GIS database (ArcGIS 9.3, ESRI, Redlands, CA, USA). The minimum distance of 1 km between plots was chosen to prevent the inclusion of spatially autocorrelated data.

Climatic and topographic data were compiled from the Climatic Digital Atlas of the Iberian Peninsula (Ninyerola et al. 2005), available in grid format with a cell size of 200 m. Climatic data consisted of the following variables (Tab. 2): (i) annual precipitation (PREC); (ii) annual mean temperature (T); (iii) mean temperature of the coldest month (TMIN); (iv) index of continentality (IC), *i.e.*, the difference between the mean temperatures of hottest and coldest months (Tuhkanen 1980); and (v) potential evapotranspiration for July (ETP), representing the maximal evaporation in a given area without water limitation in the driest month (Thornthwaite 1948). Three topography-related variables were also considered: (vi) altitude

Tab. 1 - Mean values (and standard deviation) of the parameters used to describe the structure of forest stands analyzed in this study. Data from plots with more than 50 stems ha^{-1} and coverage by the dominant species > 60% (source: MMA 2003).

Dominant species	Tree density (stems ha^{-1})		Basal area (m^2 ha^{-1})		Quadratic mean diameter (cm)		Dominant height (m)	
	mean	SD	mean	SD	mean	SD	mean	SD
Q. robur	449.52	396.8	15.33	10.05	23.39	10.41	12.17	4.18
Q. petraea	342.04	243.5	18.92	12.7	28.27	13.88	12.89	4.46
Q. pyrenaica	543.26	600.15	14.25	12.54	19.3	8.39	10.96	4.73
F. sylvatica	526.43	420	26.13	10.64	29.77	12.48	17.18	4.21
C. sativa	785.1	668.61	24.73	17.91	23.61	14.07	13.99	3.64
B. pubescens	645.7	560.32	15.02	10.1	17.80	6.86	12.19	4.72

Tab. 2 - Description of the variables considered as possible predictors of the geographic distribution of the six target species. (a): Semiquantitative classification from 1 (lowest) to 4 (highest).

Variable	Description	Unit	Source	Cell size (m)
ALT	Altitude based on a Digital Elevation Model	m	IGN 2013	10
SLOPE	Slope based on a Digital Elevation Model	%	IGN 2013	10
RAD	Accumulated radiation during one year	kJ m^{-2} $year^{-1}$	Ninyerola et al. 2005	200
PREC	Accumulated precipitation during one year	mm	Ninyerola et al. 2005	200
TEMP	Mean annual temperature	°C	Ninyerola et al. 2005	200
TMIN	Mean temperature of daily minimum during January	°C	Ninyerola et al. 2005	200
IC	Difference between monthly temperatures of hottest month and coldest month	°C	Ninyerola et al. 2005	200
PET	Maximum evaporation occurring on ground totally covered by vegetation and without water limitations during the driest month	mm	Ninyerola et al. 2005	200
FERTI	Soil fertility based on lithological factors	1 to 4 [(a)]	Fernández-Menéndez 2002	200

(ALT); (vii) slope (SLOPE); and (viii) solar radiation (RAD); and one variable related to soil pH: (viii) fertility (FERTI), determined for the study area by combining geological and lithological digital maps to reflect the amount of carbonates and soil depth (Fernández-Menéndez 2002).

Pairwise Pearson's correlation coefficients (*r*) were calculated between variables to assess their collinearity, excluding those with *r*>0.6. FERTI, SLOPE, RAD and PREC were not significantly related to any other variable. ALT and TEMP were closely correlated with several of the other factors and therefore discarded from further analysis. TMIN, IC and ETP were correlated with each other. As TMIN is a meaningful factor related to the winter temperatures and frost probability, it was preserved as a more informative predictor, and the other two factors then discarded.

Distribution models

In order to model the spatial distribution of each of the six target species analyzed, Generalized Linear Models (GLMs) were constructed using a binomial distribution with a logistic link function in SPSS 17.0 for Windows (SPSS Inc. 2008). The dependent variable was binary and reflects the presence (1) or absence (0) of each species in each plot. The dataset of each species was implemented in ArcGIS 9.3 to built an equal proportion of presences and absences (50%). Using a random selection procedure, we selected 80% of the grid points for model calibration and the remaining 20% for the next validation step. The sample size was 1816 for *Q. robur*, 508 for *Q. petraea*, 630 for *Q. pyrenaica*, 832 for *F. sylvatica*, 1690 for *C. sativa*, and 1588 for *B. pubescens*.

Independent variables in GLMs were selected using the Wald's backward stepwise procedure. The performance of each model was assessed by a confusion or error matrix that crosstabulates the observed and predicted presence/absence patterns (Fielding & Bell 1997). Model validation was performed using the Area Under the ROC Curve (AUC - Fielding & Bell 1997). AUC values can range from 0.5 (performance equal to random) to 1.0 (perfect fit). For assessing distribution models, AUC values in the range 0.5-0.7 were considered low, 0.7-0.9 were moderate and >0.9 were high, suggesting poor, good and very good model performances, respectively (Swets 1988). For each of the six models considered, Moran's *I* statistic was also computed to evaluate the spatial autocorrelation of residuals after accounting for the effect of the environmental variables, using the Spatial Analyst tool in ArcGIS (Elith & Leathwick 2009).

The coefficients from the GLMs obtained were used to predict the probability of occurrence of the target species in the whole study area at a grid size of 200×200 m. Predicted values ranging from 0 to 1 were interpreted in terms of habitat suitability, *i.e.*, the probability of finding suitable environmental conditions for each species according to the set of variables included in the models. Finally, Pearson's correlation coefficients between predicted and observed data were calculated for each species using a random selection of 1000 grid points over the study area.

Results

The results from the GLM analysis revealed differences among those environmental variables that determine the occurrence of the analyzed species (Tab. 3). The model for *Q. robur*, which included all the variables considered, revealed that the presence of this species was positively related to TMIN, RAD and PREC, and negatively related to

Tab. 3 - Results of the GLM modeling for each of the six target species. (B): coefficients of the model; (Wald): statistics used in the variable selection process; (AUC): accuracy parameter used for validation.

Model	Variable	B	Range	Mean	Wald	AUC
Quercus robur	TMIN	0.039	4-13.2	9.6	98.232	0.76
	FERTI	-0.182	1-4	2.64	13.568	
	SLOPE	-0.021	0.5-40.6	15.2	6.505	
	RADI	0.001	1134-2369	1920	16.403	
	PREC	0	714-2034	1273	2.91	
	constant	-6.101	-	-	38.029	
Quercus petraea	TMIN	-0.035	4.6-13.2	9.2	34.088	0.753
	constant	3.243	-	-	33.314	
Quercus pyrenaica	SLOPE	0.042	0.4-37.9	15.8	11.755	0.569
	PREC	0	755-1767	1258	5.524	
	constant	0.746	-	-	1.647	
Fagus sylvatica	TMIN	-0.084	4.0-13.1	9.1	133.138	0.861
	FERTI	0.707	1-4	2.93	52.607	
	RADI	-0.003	1145-2369	1874	37.96	
	constant	11.783	-	-	98.443	
Castanea sativa	TMIN	0.07	4.0-13.2	9.6	262.284	0.758
	PREC	0	636-2034	1276	7.49	
	constant	-5.474	-	-	69.797	
Betula pubescens	FERTI	-0.424	1-4	2.61	68.993	0.627
	SLOPE	-0.037	0.1-39.8	15	20.94	
	RADI	0	1134-2360	1919	5.689	
	PREC	0	636-2034	1272	8.7	
	constant	4.345	-	-	77.087	

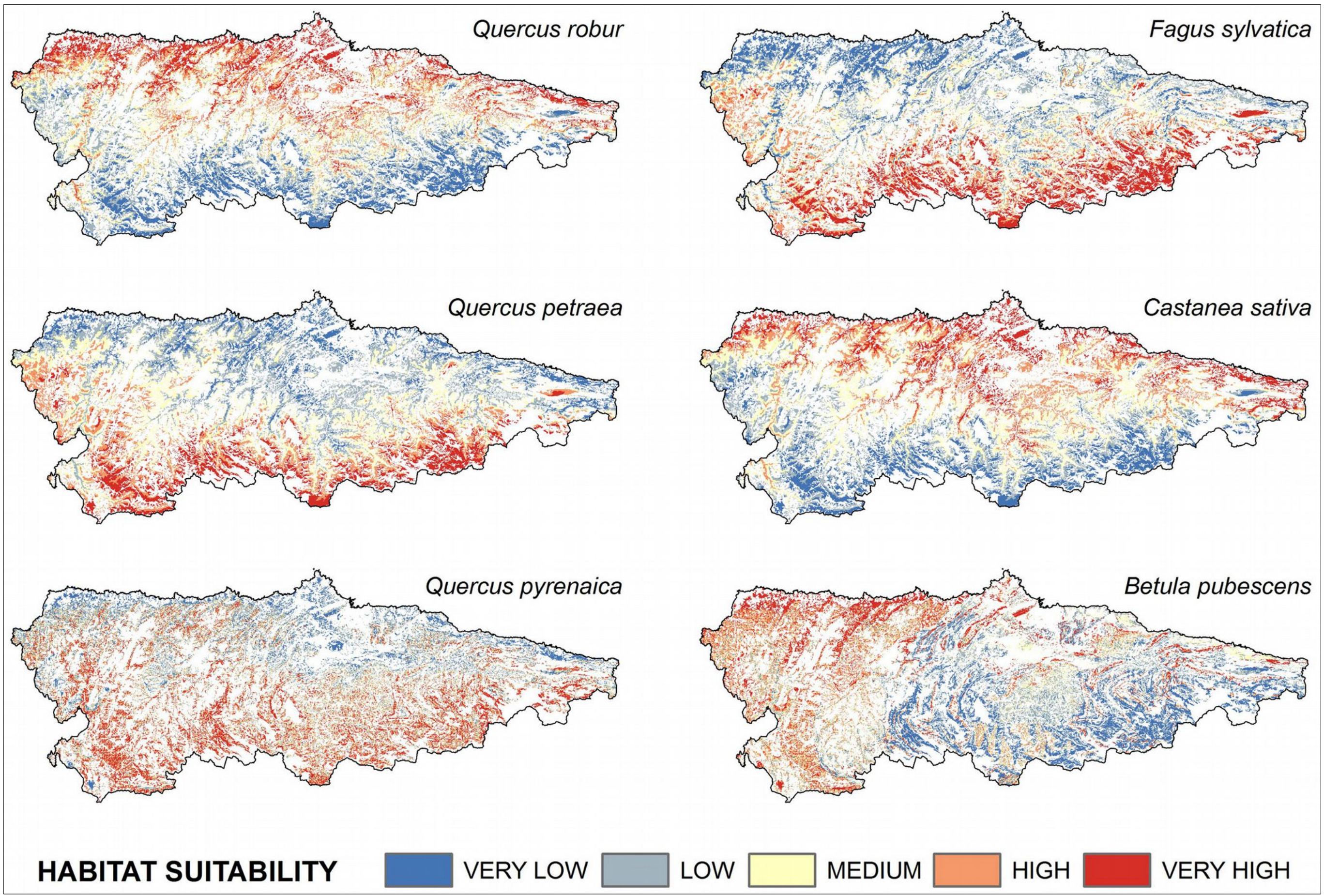


Fig. 2 - Results of the modeling of habitat suitability for the six species analyzed. Non-forest areas were excluded from the analysis (displayed in white in the maps).

FERTI and SLOPE. The AUC value for this model (0.760) indicates a good performance. The *Q. petraea* model provided a similar accuracy (AUC = 0.753), although in this case the only variable included was TMIN and its effect was negative. Although the *Q. pyrenaica* model was the least accurate (AUC = 0.569), it revealed that the presence of this species was positively related to SLOPE and PREC. The *F. sylvatica* model was the most accurate (AUC = 0.861), showing that the presence of this species was positively related to FERTI and negatively related to TMIN and RAD. For *C. sativa*, model performance was similar to that obtained for *Q. robur* and *Q. petraea* (0.758), revealing that the species presence was positively related to TMIN. Finally, for *B. pubescens* model performed rather poorly (AUC = 0.627), showing that the presence of this species was negatively correlated with FERTI and SLOPE.

Tab. 4 - Probability thresholds for the five habitat suitability classes.

Model	Suitability classes				
	Very Low	Low	Medium	High	Very High
Q. robur	<0.10	0.10-0.19	0.19-0.29	0.29-0.41	0.41-0.79
Q. petraea	<0.31	0.31-0.39	0.39-0.51	0.51-0.65	0.65-0.96
Q. pyrenaica	<0.75	0.75-0.79	0.79-0.83	0.83-0.87	0.87-0.98
F. sylvatica	<0.13	0.13-0.26	0.26-0.51	0.51-0.83	0.83-0.99
C. sativa	<0.46	0.46-0.74	0.74-0.88	0.88-0.93	0.93-0.99
B. pubescens	<0.88	0.88-0.92	0.92-0.94	0.94-0.96	0.96-0.99

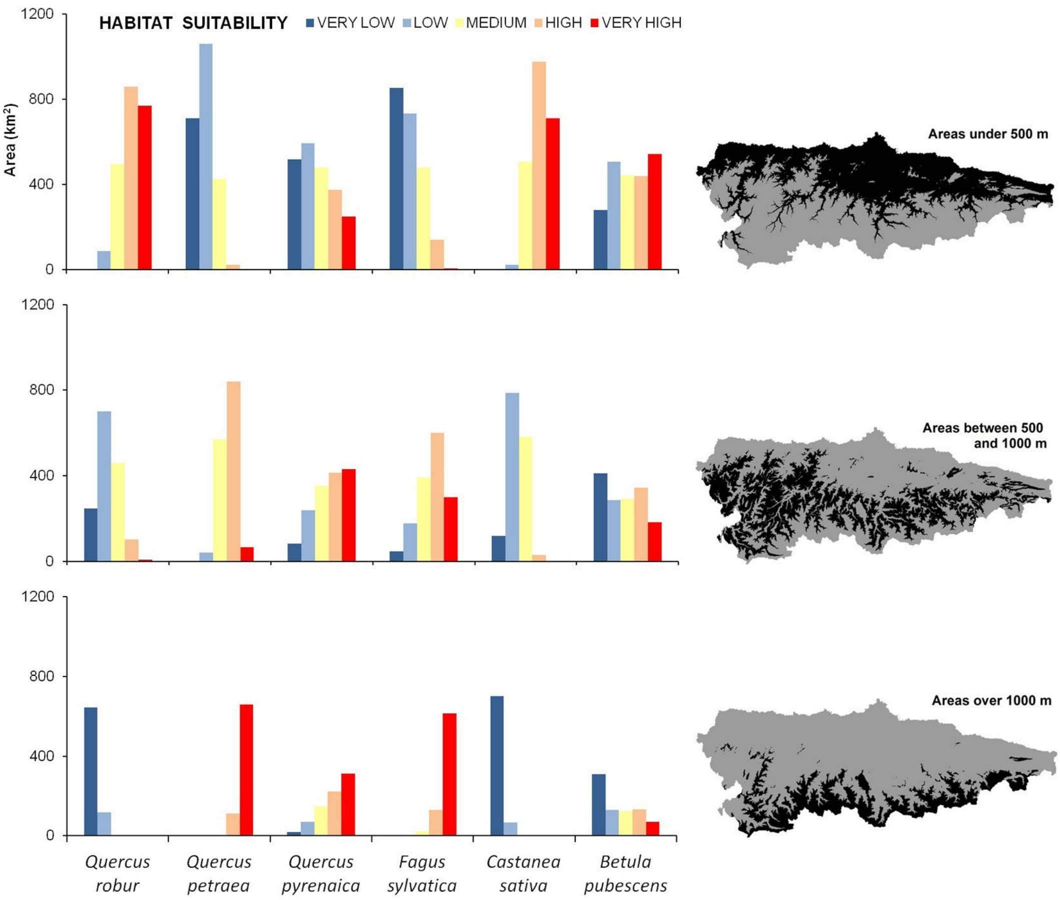
Tab. 5 - Results of the Pearson's correlation analysis between habitat suitability for the different species analyzed. (**): p< 0.01.

Pearson *r*	*Q. petraea*	*Q. pyrenaica*	*F. sylvatica*	*C. sativa*	*B. pubescens*
Q. robur	-0.839 **	-0.44 **	-0.876 **	0.81 **	0.35 **
Q. petraea	-	0.404 **	0.87 **	-0.938 **	0.057 **
Q. pyrenaica	-	-	0.38 **	-0.283 **	0.14 **
F. sylvatica	-	-	-	-0.834 **	-0.11 **
C. sativa	-	-	-	-	0.102 **

The predicted spatial pattern of habitat suitability clearly differed among species, although some similarities were observed (Fig. 2 and Tab. 4). Habitat suitability of *C. sativa* and *B. pubescens* was "high" to "very high" over more than 50% of the area, with a wide range of variation, while for the other species the range was narrower (10 to 28%). Calculations of Moran's *I* detected positive values of spatial autocorrelation of residuals for *Quercus petraea* (I = 0.543, P = 0.00) and *Betula pubescens* (I = 0.51, P = 0.03) models, and a stronger clustering for *Castanea sativa* (I = 0.81, P = 0.00). The remaining species were randomly distributed.

Highest suitability values for *Q. robur* and *C. sativa* were observed in the northern half of the study area, mainly at low altitudes (Fig. 3). Analogously, the least suitable areas for both species were the elevated mountain

Fig. 3 - Area (km²) of the five habitat suitability classes for each species based on three different altitudinal ranges: <500 m; 500-1000 m; >1000m.



slopes at the southern limit of the study area (Fig. 3). By contrast, the highest suitability values for *F. sylvatica* and *Q. petraea* ranged from intermediate altitudes to approximately 1300 m a.s.l. The suitability values for *Q. pyrenaica* were quite similar to those obtained for *F. sylvatica* and *Q. petraea*, as they showed a certain preference for intermediate altitudes (Fig. 3). However, suitable areas for *Q. pyrenaica* were less continuous than for other species.

The correlations between habitat suitability for the different species analyzed clearly revealed two main groups of species: those associated with low altitudes (*Q. robur* and *C. sativa*) and those preferring mountainous areas (*F. sylvativa* and *Q. petraea* - Tab. 5). Correlation coefficients between suitability of *Q. pyrenaica* and *B. pubescens* and suitability for any of the other species were always < 0.5, suggesting the presence of different ecological niches across the study area.

Discussion

The findings of this study reveal the main environmental factors driving the distribution of six European tree species in Asturias, a region characterized by a temperate oceanic climate and a unique elevational gradient in the context of the Atlantic biogeographic region in Europe. The study area represents the southern margin of the distribution for *Fagus sylvatica, Quercus petraea, Quercus robur* and *Betula pubescens*, which are common in the Atlantic region but not in the Mediterranean region.

We found that the minimum temperature (TMIN) had a strong influence on species distribution. Such factor has been considered critical in shaping the geographical distributions of plants (Ashcroft et al. 2011). Indeed, minimum temperature can be used as a surrogate for winter conditions, reflecting the ability of some species to resist frost damage. Given the Atlantic influence in the study area, it is not surprising that precipitation (PREC) had scant influence on the distribution of the analyzed species, unlike other studies carried out in the Mediterranean region, where this is critical factor affecting the transitions between forest types (*e.g.*, *Quercus ilex* and *Quercus faginea* forests - Ninyerola et al. 2010). Soil fertility (FERTI) was also found to be an important predictor of the spatial distribution of species, according to previous studies that used soil properties as predictors in species distribution models (Gaston et al. 2009).

Model performances were generally satisfactory, except for *Quercus pyreanica* and, to a lesser extent, *Betula pubescens*. As we discuss below, the poor model performance of *Q. pyrenaica* can be explained by the scarce representation of the species in the study area, which generates a truncated niche. In contrast, the poor model performance for *B. pubescens* may be explained by the common occurrence of such species in the whole study area, regardless the changes in the factors analyzed along the enviromental gradients considered. We also detected spatial autocorrelation of model residuals for few species, in particular for *Castanea sativa*. However, spatial effects in species distribution models has been shown not to influence results in large datasets (Record et al. 2013). In our study, spatial autocorrelation in the *C. sativa* dataset suggests that the distribution of this species is closely related to factors not included in the current analysis. Considering that our sampling was based on well-separated spatial units (1 km), this effect is possibly related to human activities favoring the development of chestnut in particular areas.

Fagus sylvatica and *Quercus petraea* showed a strong preference for montane areas. These species are widely distributed and predominant in cool regions of central Europe (Sykes et al. 1996), where they often share environmental niches. Recent distribution models based on different climatic scenarios have predicted in the next few decades an enlargement of their range in northern Europe (European Commission 2012), as a consequence of the expected increase in minimum winter temperatures. Our results confirm that winter temperature affects the distribution of both species in the Spanish Atlantic region, and therefore similar shifts to higher altitudes (rather than higher latitudes) are expected in the future.

The geographic distribution of *F. sylvatica* has traditionally been related to a relatively long vegetative period, high moisture and high degree of continentality (Fang & Lechowicz 2006), variables that are negatively related to TMIN. Sánchez et al. (2003) reported an optimal distribution for this species (in an area close to the present study area) on northern slopes above 600 m a.s.l. with mean annual temperature ranging between 6.1 and 10.5 °C. The optimal conditions described for beech by these authors imply annual rainfall higher than 950 mm with no drought and an upper altitudinal limit of approximately 1500 m a.s.l., *i.e.*, similar to the maximum altitude of forests in the Spanish Atlantic region (Díaz & Fernández-Prieto 1987). At northern latitudes, the species shows a preference for temperate areas where extremely low winter temperatures are rarely occurring. However, it is also one of the few tree species that resists the most severe winter conditions in northern Spain. The distribution of *F. sylvatica* was also positively correlated with soil fertility, suggesting that the species prefers basic substrates. As *F. sylvatica* is known to grow in basic and acid soils in the study area, this distribution probably reflects the location of remnant beech forests in rich (calcareous) substrates.

Muñoz-Sobrino et al. (2008) identified an increase in the niche of *F. sylvatica* from the late Medium Holocene in the northwest of the Iberian Peninsula, which they attributed to the progressive warming in the area and the increased elevation of the tree line in the Cantabrian mountains. Our results are consistent with these previous findings, as *F. sylvatica* shows a clear preference for montane sites. Under such conditions (mountain climate at mid latitudes), *F. sylvatica* is highly competitive and is one of the main forest species in the Atlantic Region. The distribution of *Q. petraea* was established about 7000 years ago, as a result of the long-range recolonization after the last glaciation, according to fossil pollen data (Huntley & Birks 1983). Similar to other deciduous oaks, during the Last Glacial Maximum this species was limited to small refugia in the Mediterranean region (Bennett et al. 1991), from where its spread northbound began. It is possible that similar shifts towards cool areas affected the distribution of this species in northern Spain, thus explaining its current distribution range at high elevations.

The geographic distribution of *Quercus robur* and *Castanea sativa* is mainly correlated with low-altitude areas and high minimum temperatures. Although *Q. robur* extends to high latitudes (up to 60° N - Repo et al. 2008), it is often limited by short vegetative periods and cold damage (Jensen 2000). Our findings are consistent with those of Attorre et al. (2012) who reported that the presence of *Q. robur* was correlated with the warm temperatures occurring in temperate areas of Italy, which suggests a preference of the species for relatively low altitudes. In our study, this results in a geographical disjunction between *Q. petraea* (restricted to cold sites) and *Q. robur* (dominating warm areas at low and medium altitude). Such disjunction is fairly uncommon in other European regions, where both species have similar distribution ranges, and their environmental niches are differentiated by soil moisture (EEA 2007). We also found that *Q. robur* was negatively correlated with fertility and positively correlated with the presence of acid soils.

Castanea sativa is less common in oceanic regions than *Q. robur*, mainly occurring in permanent forests of the Mediterranean region. The distribution of chestnut has been closely associated with human activity over the last 2000 years, as it has been intensively planted and harvested in the Iberian peninsula since Roman times, and its fruit was an important food in Medieval Ages as well (Conedera et al. 2004). Interestingly, the distribution of *C. sativa* has been related to low altitudes with annual rainfall between 700 and 1100 mm in both Mediterranean (Rubio et al. 2002) and Atlantic regions (Blanco et al. 2000). Our findings suggest that this species formed refugia in warm areas of temperate regions, which are probably more similar to the wettest areas of the Mediterranean regions. Indeed, the study area is considered a refuge for this species during several glacial events (Krebs et al. 2004) and pollen evidence demonstrates its presence prior to human impacts. In addition, we also detected spatial aggregation of such species, suggesting that its spread may have been locally favored to some extent by human intervention.

Although *B. pubescens* was positively correlated with the presence of acid soils, we did not find any clear geographical pattern in relation to the distribution of this species. These findings confirm the acidophilous nature of *B. pubescens* in the Atlantic region, unlike other biogeographical regions where birch can grow in different conditions along a soil mineralization gradient (EEA 2007). *Betula* species have been studied from different perspectives in botanical studies (Peinado & Moreno 1989, Ceballos & Ruíz de la Torre 2001), but no studies have focused on the ecological niche of these species in the Iberian peninsula. The relatively poor performance of the distribution models indicates that there are no clear climatic constraints to the local distribution of this species, which occurs on acid soils at any altitude in the study area. *Betula pubescens* is widely distributed in the Atlantic Region (Sykes et al. 1996), and its historical importance in northern Spain is often emphasized as it played a role as a colonizer after the Last Glacial Maximum (Muñoz Sobrino et al. 2006).

Finally, the model performed very poorly for *Q. pyrenaica* in the study area. In biogeographical terms, this species occupies intermediate zones between Atlantic forests of *Q. robur* and Mediterranean xerophytic forest dominated by *Quercus ilex* L. (Castaño-Santamaria et al. 2013), and this species may not be sufficiently well represented in the study area for a good characterization of its niche. Such specific conditions - commonly referred as submediterranean climate - are not frequent in the study area, where *Q. pyrenaica* shows a scattered distribution on acid and dry soils in both mountain and coastal areas. This species also occupies a wide altitudinal range in Galicia (which is also part of the Spanish Atlantic region) in between 300 and 1300 m a.s.l., and in areas with low precipitation (750 mm $year^{-1}$ - Diaz-Maroto et al. 2006, 2007). According to these authors, *Q. pyrenaica* requires lower summer precipitation (115 mm from June to August) than *Q. robur* (165 mm) and it is located in colder areas further from the sea. This is consistent with the location of the optimal area for this species in the Mediterranean region of the Iberian peninsula (Sánchez de Dios et al. 2009).

Conclusions

This study analyzed the strong altitudinal gradient of the Spanish Atlantic region and identified the minimum annual temperature as the main factor affecting the geographic distribution of tree species. Soil fertility was also an important predictor, as suggested by the good performance of distribution models for other forest species (Gaston et al. 2009).

Although landscapes in the Iberian peninsula have been greatly modified by human activities, the study area still comprises important portions of the remnant Atlantic deciduous forests (Garcia et al. 2005). Forest ecosystems are well represented, and the sampling carried out was larger enough to ensure the environmental niche assessed to be sufficiently representative of the species requirements. Nonetheless, we also recognize that in some cases historical reasons may underlie the current species distribution, especially at low altitudes (*e.g.*, *Quercus robur*) and for those species most influenced by human activities (*e.g.*, *Castanea sativa*), therefore puzzling the interpretation of the model outputs. In particular, the distribution of *C. sativa* appears to be spatially clustered, possibly due to the effect of past human influence (Conedera et al. 2004). On the other hand, we found meaningful explanations for the observed distributional patterns of the other species, in most cases fully consistent with their autoecological requirements. In addition, we also detected divergent niches for *Q. petraea* and *Q. robur* that have not previously been reported in Europe. Suitability of oceanic and humid-cool conditions was also confirmed for *Betula pubescens* and *Fagus sylvatica*, respectively. Overall, the information provided contributes to a better understanding of the distribution of deciduous forests in the European Atlantic biogeographical region.

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Analysis of spatial scales for ecosystem services: Application of the lacunarity concept at landscape level in Galicia (NW Spain)

Jose V. Roces-Díaz[a,b,*], Emilio R. Díaz-Varela[b], Pedro Álvarez-Álvarez[a]

[a] GIS-Forest Group, Department of Organism and Systems Biology, University of Oviedo, Spain
[b] Research Group 1716 – Projects and Rural Planning, Department of Agro-Forestry Engineering, University of Santiago de Compostela, Spain

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ABSTRACT

Ecosystem services research has become important in fields such as ecology and land planning in recent years. Several authors have emphasized the need to evaluate these services from a spatial perspective. The spatial distribution of the resources and processes that provide ecosystems have also been considered in relation to landscape. Because ecosystem services are provided by different ecological processes, the spatial scales probably also differ; this aspect may be of interest for analyzing the provision flow. In this study, we analyzed the spatial pattern of six services that are important in the study area (in Galicia, NW Spain). We first identified the landscape elements associated with these services, defining them as ecosystem service providers (ESP). To represent the ecosystem, we initially used cartographic information based on land use/land cover (LULC) and then generated two different raster ESP data sets: (i) binary and (ii) greyscale. We then explored the spatial patterns of ESP by lacunarity analysis, which is often used to study fractal elements, and by selecting landscape metrics. The results suggest that the spatial patterns of ecosystem services occur at different scales. We observed a strong relationship between lacunarity values and the different distribution patterns of ESP. Multiscale effects were also associated with changes in lacunarity values. Application of different spatial analysis techniques to study the relationships between landscape structure and service providers should provide a better understanding of service provision and enable evaluation of the ecological integrity of landscapes.

1. Introduction

During the last decade, ecosystem services (ES) have attracted much interest, especially after the huge international effort to classify and assess these services (MA, 2005). Such efforts have enabled the identification of a series of topics that must be addressed in order to enhance the potential of the ES approach for developing meaningful land planning and suitable management strategies (Egoh et al., 2008). For example, analysis of the provision of ES from a spatially explicit, multiscale perspective has been reported to be essential (Daily et al., 2009; Müller et al., 2010) to further our knowledge of the spatial distribution, characteristic scales and the relationships between ES and biodiversity, landscape and human use (Nelson et al., 2009). Studies carried out from such perspectives, combined with the development of appropriate indicators, could provide useful tools for evaluating ecosystem services in land planning processes.

Several studies have dealt with spatial perspective of ES. Thus, some studies have used land use/land cover (LULC) information as a proxy for the spatial arrangement of ecosystems (Frank et al., 2012; Burkhard et al., 2012), while others include additional sources of spatial information and combine them to develop spatially explicit models (Raudsepp-Hearne et al., 2010; Sherrouse et al., 2011). Such models may also consider supply and demand, both essential factors in the analysis of ES (Syrbe and Walz, 2012).

Some authors have analyzed spatial patterns in relation to ES and have emphasized the need to identify areas that are important to society in relation to biodiversity and provision of services (e.g. Chan et al., 2006; Egoh et al., 2008). Identification of such areas should take into account the presence of trade-offs between services at landscape level, derived from their spatial interactions (Raudsepp-Hearne et al., 2010). Despite the usefulness of these contributions, several limitations have been identified in the approaches used to date. For instance, Eigenbrod et al. (2010) indicated some common problems in studies of this type: (i) generalization over the whole study area values for a given variable sampled in few locations; and (ii) assumption of invariance over different spatial scales. More detailed study of the relationships between the spatial distribution of LULC and the provision of ES across different landscape scales is therefore essential.

* Corresponding author at: GIS-Forest Research Group, Department of Organism and Systems Biology, Polytechnic School of Mieres, 33993 Mieres, Asturias, Spain. Tel.: +34 985 103000x5857.
E-mail address: jvroces@gmail.com (J.V. Roces-Díaz).

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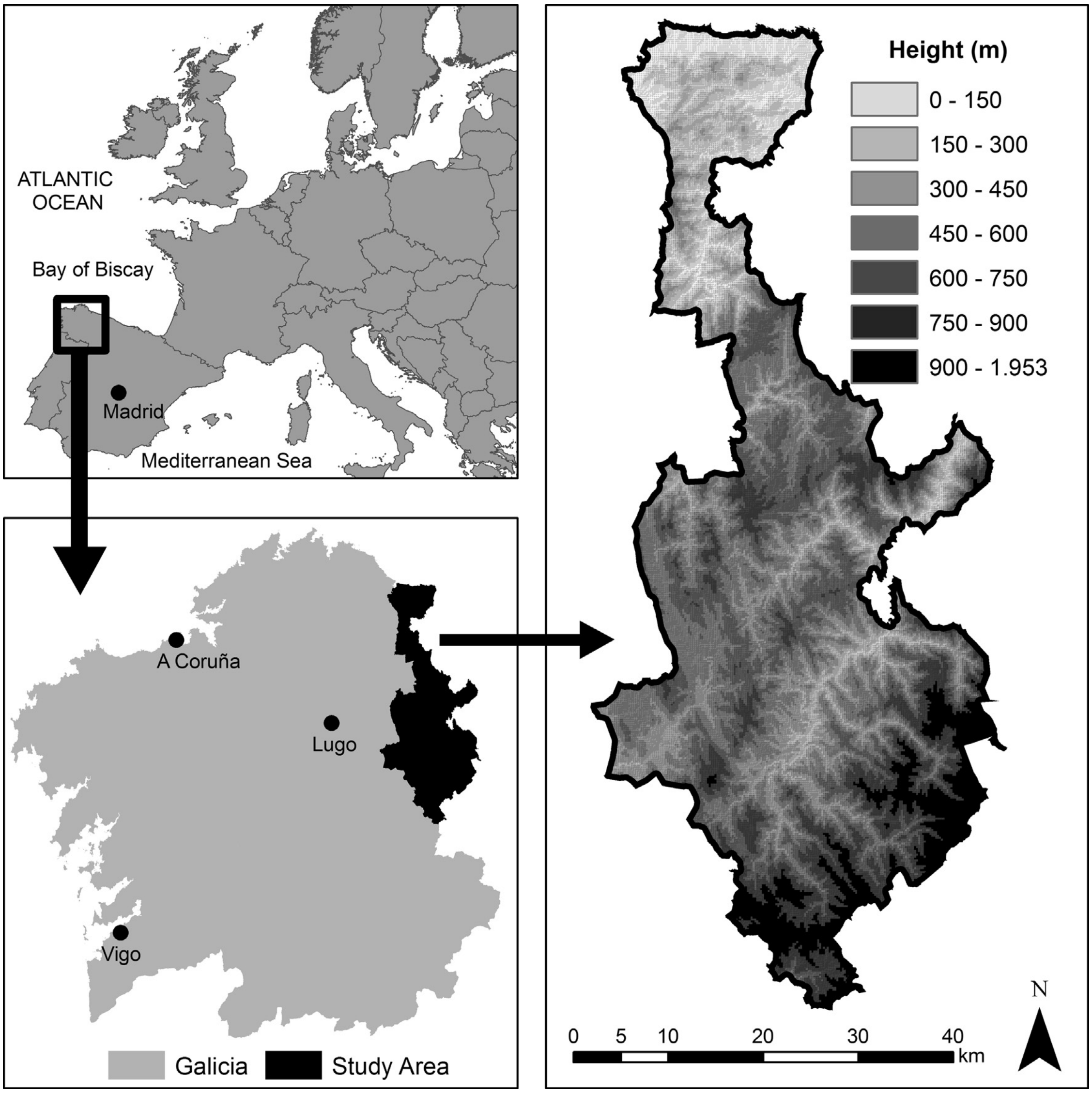

Fig. 1. Location of Galicia and the study area.

In addition to the spatial component, ES analysis should integrate the relationship between the flow of services and the presence of elements that act as a source of the services. Such elements have been defined as ecosystem service providers (ESP; Kremen, 2005). Functional inventories should focus on ESP and how their efficiency is affected by the spatial arrangement at different scales (Balvanera et al., 2005) and by the different types of impact and disturbance involved (Petrosillo et al., 2010).

Although several studies have approached the analysis of services at landscape scale in recent years, the relationship between the provision of services and spatial structure and heterogeneity must be thoroughly explored (Meyer and Grabaum, 2008). In this sense, several authors have proposed the use of landscape metrics to quantify diversity and heterogeneity (Burkhard et al., 2012; Frank et al., 2012; Syrbe and Walz, 2012). The general idea that emanates from these studies is that a high diversity of landscape elements will be associated with a wide range of service providers. This is probably due to the fact that a diverse landscape produces a more complex flow of ecological processes than a landscape with few elements (Fischer et al., 2006). As landscape diversity depends on the scale considered (Díaz-Varela et al., 2009), and ecological processes operate at several spatial and temporal scales (Hein et al., 2006) and generate different ES at each scale (Martín-López et al., 2009), the provision of each service will have a characteristic spatial scale. Several authors (e.g. Fisher et al., 2009; Syrbe and Walz, 2012) have recently considered the spatial relationships between landscape elements from the point of view of ES. Accurate information about these relationships and the spatial characteristic scales of elements and processes that are relevant to ES provision would improve evaluation of the flow of services, aimed at maintenance of their provision and impact assessment.

In this study, we developed a methodology for the identification of characteristic scales in the ES pattern, based on lacunarity calculations. The concept of lacunarity, which was introduced by Mandelbrot (1983), is used to show differences in spatial patterns between objects that have a similar fractal dimension (e.g. their capacity to replicate the same pattern at different scales is comparable). The terms are derived from the latin "lacunar", referring to gaps that exist in the spatial pattern (Fortin and Dale, 2005). According to Gefen et al. (1983), lacunarity measures the deviation of an object, such as a fractal, from a translational invariance (Plotnick et al., 1993). Lacunarity has been used extensively in landscape ecology as a scale dependent metric for the characterization of spatial patterns (Plotnick et al., 1993), and it can be considered as a scale-dependent measure of heterogeneity or texture of an object, whether or not it is fractal (Allain and Cloitre, 1991). Lacunarity

Table 1
Final LULC classes classification.

Artificial classes	Vegetation classes	Bare soil	Humid classes	Mosaics
101.Traditional rural settlement	201. Herbaceous crops	301. Firewall (areas cleared to prevent wildfire propagation)	401. Marshland	501. Mosaic formed by trees and shrubs
102. Rural and urban center	202. Meadows	302. Bare soil	402. Estuary	502. Mosaic formed by trees and crops
103. Urban discontinuous	203. Crops and meadows mixed	303. Burnt soil	403. River	511. Mosaic formed by rocks, bare soil and forest elements
104. Other urban and rural areas with low population density	204. Crops and meadows with forest elements	304. Rocky areas		512. Forest elements without trees
111. Areas for agricultural, forest and livestock practices	211. Pasturelands	305. Coastal elements		521. Mosaic formed by crops and other elements
112. Mining areas	221. Shrublands			
121. Industrial areas	222. Shrublands formed after timber harvest			
131. Tertiary sector areas	223. Shrubland predominant with trees			
141. Building for public services	231. Coniferous plantations			
151. Road	232. *Eucalyptus* plantations			
152. Railway	233. Deciduous woodland			
161. Equipments for energy production	234. Woodlands mixed with coniferous and *Eucalyptus* plantations			
	235. Woodland with shrubs			

analysis can be applied to data of any dimension and to binary or quantitative data, and both fractal and non-fractal patterns can be analyzed. It therefore enables determination of scale-dependent changes in spatial structure (Plotnick et al., 1996). The importance of lacunarity analysis has increased during the last decade, particularly in relation to multi-scale analysis and modeling of different subjects, e.g. earth sciences, environment and ecology (Dong, 2009).

In the present study, we used lacunarity to analyze the spatial distribution of some ecosystem services providers across a wide range of scales. We identified several providers associated with important ES, using digital cartographic information. We then used lacunarity analysis to analyze the spatial distribution of provision gaps for each map. We also determined any relevant spatial scales at which the provision gaps are revealed. Differences and affinities among the spatial distribution of providers were reflected in the spatial pattern, as reported both by landscape metrics and lacunarity analysis, allowing us to define ‘families’ of ES provision.

The main aims of the study were as follows: (i) to test the capacity of the lacunarity methodology to estimate the functional scale of some ecological process at different spatial levels of analysis; and (ii) to test whether the supply of ES can be revealed at different scales depending on the origin and the spatial pattern of the providers.

2. Materials and methods

2.1. Study area

The study area, which is located in the Autonomous Community of Galicia (NW Spain), is formed by 13 municipalities divided into three subregional administrative units (called “comarcas”): “A Mariña Oriental”, “A Fonsagrada” and “Os Ancares” (Fig. 1). The population of the study area comprises 35,311 inhabitants (INE, 2012), and the area spans 2128 km^2.

The N–S altitudinal gradient in the area ranges from sea level on the northern coast to 1800 m in the southern mountains. The climate is oceanic, with mean precipitation exceeding 1000 l/m^2/year throughout the study area and reaching more than 2000 l/m^2/year at the highest points; there is no relevant summer drought. The landscape is typically European Atlantic, with strong anthropogenic influences and a decline in woodland during the last two thousand years (Muñoz-Sobrino et al., 2005), and several of the remaining elements are related to livestock use (e.g. meadows, pastures and heathland). During the last few decades, the northwest Iberian peninsula has suffered from intensification of the use of the most fertile land and abandonment of marginal areas. This, combined with a strong rural depopulation, has resulted in a decline in traditional agricultural and forestry activities, and important changes in land use (Jongman, 2002) with associated changes to the traditional landscape (Martínez et al., 2010).

2.2. Spatial data sources

The spatial model for ecosystem representation was based on SIOSE (Spanish System for Land Uses) land use/land cover (LULC) information IGN (2012), developed at the national scale by the Spanish Government. This map shows LULC information retrieved from aerial photographs dated from 2004 to 2006, combined with Landsat 5TM and SPOT5 (panchromatic and multispectral) images from 2005. The map scale used was 1:25,000. Minimum Mapping Units (MMU), which depend on the type of land cover, were as follows: (i) 0.5 ha for beaches, and vegetation associated with rivers, wetlands and greenhouses, (ii) 1 ha for artificial areas and water bodies and (iii) 2 ha for cultivated areas, forest and shrub vegetation.

Information is structured on a database in which 12,297 polygons were identified and spatially located for the study area. Each polygon includes defined information about different types of land cover and vegetation. An estimation of the percent surface area contributed by each type was also included within these polygons. Thus, each polygon is formed by a combination of different types of cover defined in the SIOSE spatial model. As a result, the model is formed by different combinations of 37 simple types of cover, each characterized by a single type (e.g. vegetation cover) and 42 complex types of cover, each showing combinations of individual types of LULC.

2.3. Ecosystem types and spatial model

From the original SIOSE information database, we developed an operative legend by grouping the original LULC classes into fewer groups. The criteria used were based on the establishment of threshold values for the proportion of classes within each group of polygons. Those polygons with more than 70% covered by one of the types of cover defined in the legend were clustered and a single class was created for each (we considered that 70% cover represents a value that is high enough to describe the main characteristics of the polygon). The remaining polygons were clustered on the basis of the LULC combinations: where cover comprised more than 50% of one type, a class was created on the basis of this type

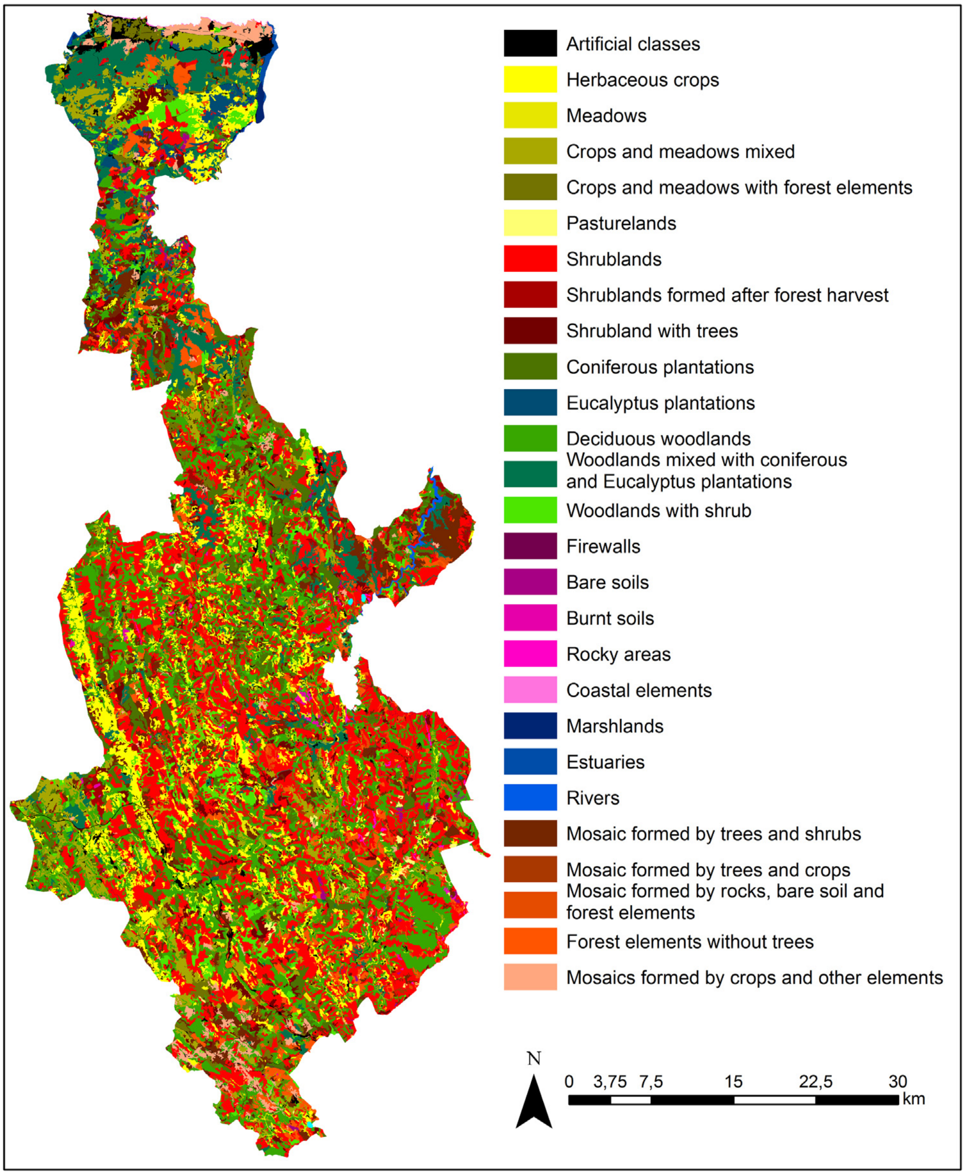

Fig. 2. Spatial model for the ecosystem spatial distribution, based on modified SIOSE information (IGN, 2012).

– considered as dominant – and the other type of cover present within the polygons [e.g. "woodland (>50%) with shrub"]. When more than one dominant type was present, the mixed class was denominated "mosaic". Mosaics include a combination of two or three types and the sum of their cover occupies more than 50% of the surface area of a polygon. Finally, we produced a map legend with 38 classes (Table 1). Five classes were defined on the basis of the origin of cover: (i) artificial classes (12 classes, e.g. villages, industries, etc.), (ii) vegetation classes (13 classes, e.g. grasslands, shrublands, forests, etc.), (iii) bare soil (5 classes), (iv) wet classes (3 classes, e.g. marshes, etc.), (v) and mosaics (5 classes). We processed the cartographic data with ArcGIS 9.3 software (Fig. 2).

2.4. Classification of ecosystem services and their providers

The classification of ecosystem services is based on the "Common International Classification of Ecosystem Goods and Services" (CICES) hierarchical classification (Haines-Young, 2010), completed with elements from other studies (Costanza et al., 1997; de Groot et al., 2002; Nielsen and Müller, 2009). We selected six main types of service based on available information and the potential for identification of the ecosystem services providers (ESPs): (i) provision of food – goods used directly or indirectly as food. (ii) Provision of materials – elements with uses other than food and energy for human consumption. (iii) Provision of energy – elements that can be used to generate energy for human use. (iv) Flow regulation services are defined as those in which the structural elements of the ecosystem (soils, vegetation, landscape arrangement) function as a physical or chemical barrier for aerial or hydrological flows and their associated organic or inorganic particles, thus avoiding the potentially harmful effects coupled to their transference to other ecosystems. Soil retention in erosive processes, or hydrological regulation are examples under this category. (v) Abiotic regulation services are those which characterize the functioning of Earth as a system, supporting the general conditions under which the human populations are developed. Climatic regulation – temperature and precipitation regimes – or atmosphere regulation – Uvb-protection by O_3 – would be included under this category. (vi) Symbolic, experimental and intellectual services – cultural services, which include the non-material and usually non-consumptive outputs of ecosystems that affected the physical and mental states of people.

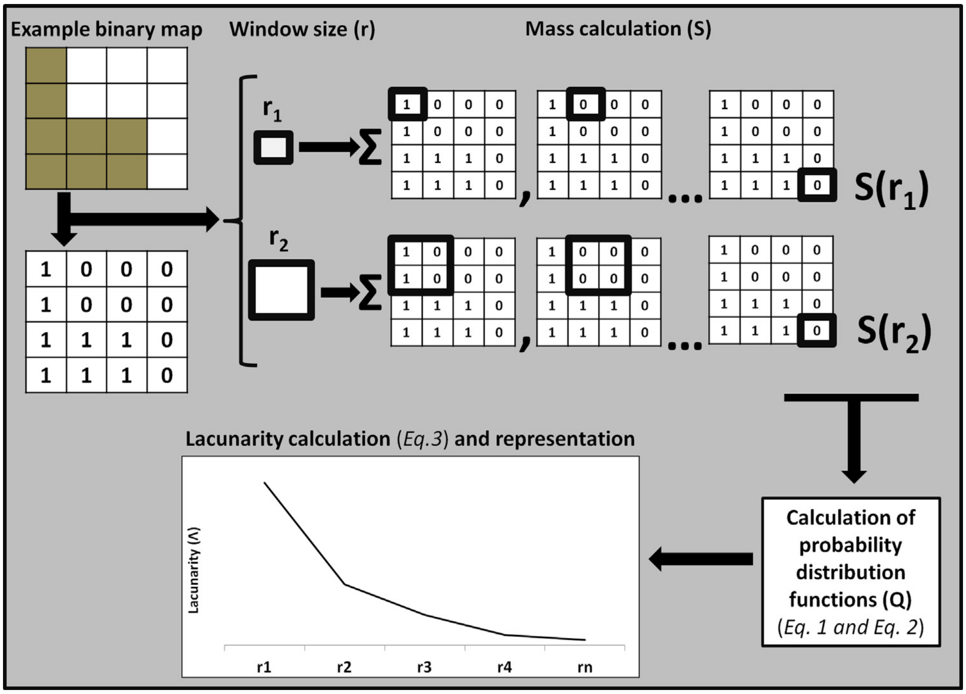

Fig. 3. Scheme of lacunarity calculation for a binary map.

Once the ES groups were established, we proceeded to identify and characterize the different ESPs associated with each type of ES, in accordance with previous studies (Kremen, 2005; Balvanera et al., 2005; Quijas et al., 2010). Relationships between the provider units and the LULC classes previously defined in the maps were then identified. These relationships were based on the following: the composition of LULC classes, as reflected by GIS databases; the LULC-ES relationship criteria defined in previous studies (e.g. Vihervaara et al., 2010; Fürst et al., 2010; Burkhard et al., 2012; Lautenbach et al., 2011; Koschke et al., 2012; Syrbe and Walz, 2012); the results of several services assessments, included those related to or including the study area (MA, 2005; EME, 2011); and the expert criteria of the authors.

As a result, we developed two LULC-ES relationship tables. The first is based on a binary variable, where 1 represents the providers of each service and 0 the other classes. To model local differences in the provision capacity of the landscape, we included a second table showing a gradient of provision intensity, with 5 categories between 0 and 1 (0; 0.25; 0.50; 0.75 and 1) where 0 represents "no provision" and 1 represents "maximum provision". A similar number of categories has been used by other authors, such as Burkhard et al. (2010, 2012), to estimate the capacity of LULC classes to provide different ecosystem services. By applying the relationship to the previously developed spatial model, we generated 12 maps (one for each service [6 maps] and one for each type of data [=2 × 6 maps]).

2.5. Analysis of variation in ESP spatial patterns

2.5.1. Lacunarity

To detect large spatial scales in the pattern of ecosystem services provision, we used a methodology based on lacunarity estimation. As explained in the introduction, the lacunarity concept can be used as a scale-dependent measure or estimation of heterogeneity. Lacunarity values depend on the following: (i) the size of window used for the calculations, (ii) the fraction the map analyzed that is occupied by the habitat or elements of interest and (iii) the geometry of the map (Plotnick et al., 1993). The algorithm most frequently used, which was proposed by Allain and Cloitre (1991), is used extensively in landscape ecology (e.g. Plotnick et al., 1993; With and King, 1999; McIntyre and Wiens, 2000). Calculation of lacunarity was initially developed for binary maps, but can also be extended to maps with several scale legends, e.g. greyscale maps (Dong, 2000).

In binary maps, calculation of lacunarity involves applying a squared window of radius "*r*" to a raster map representing a given spatial pattern, starting at the top left pixel. The "Mass (*S*)", which consists of the sum of all the values of the cells contained inside the window, is calculated at this position. The window then moves to the second column of the same row and "*S*" is calculated. This process is repeated for all the pixels of the image. Using these data, it is possible to build a frequency distribution and a probability distribution $Q(S,r)$. Thus, the first moment (Eq. (1); $Z(1)$) and the second moment (Eq. (2); $Z(2)$) of the distribution probability can be expressed as follows:

$$Z(1) = S\,S\,Q(S, r) \tag{1}$$

$$Z(2) = S\,S^2\,Q(S, r) \tag{2}$$

where r is the radius of the squared window for the calculation; S is the sum of values of those cells contained in this window; Q is the distribution probability of S; Z is the first ($Z(1)$) and the second ($Z(2)$) moment of the distribution probability.

The lacunarity [Eq. (3); Lacun (r)] is the ratio of these two moments:

$$\text{Lacun}(r) = \frac{Z(2)}{Z^2(1)} \tag{3}$$

The radius of the window will be increased successively, so that the calculations will be repeated for every window size. The lacunarity calculation process is shown in Fig. 3.

We calculated the lacunarity values for greyscale maps by using a method developed by Dong (2000), which uses the gliding-box algorithm introduced by Allain and Cloitre (1991) and the differential box counting method in fractal dimension estimation proposed by Sarkar and Chaudhuri (1992). In both binary and greyscale maps, the outcome is represented by an accumulation curve representing the increase in the lacunarity values in relation to window size.

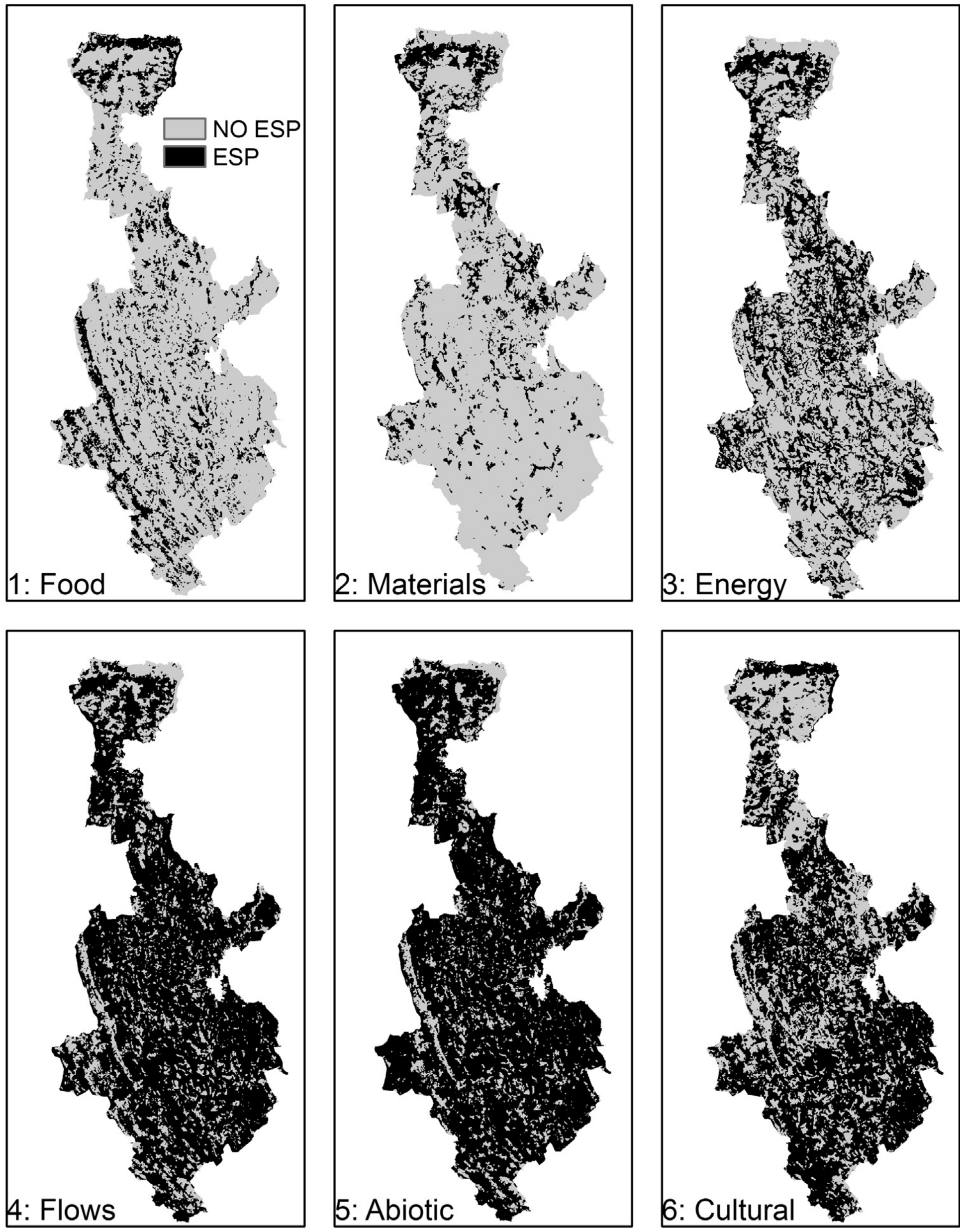

Fig. 4. Binary map of ecosystem services. Black: areas categorized as Ecosystem Service Providers (ESP); gray: areas categorized as non-ESP.

We generated 12 maps (6 + 6) in total, as binary and greyscale versions of each of six ESP types. The calculations were done with the Lacunarity Extension created by Dong (2009) for ArcGIS software. This tool enables analysis of binary or greyscale maps in raster (e.g. image) formats. Calculations were done for a range of moving window sizes from 1 to 35 map cells that with a cell size of 100 meter supposes a range from 100 to 3500 m.

We tested different cell sizes for the input grid maps, to optimize the time required for calculations. This grid size determines the number of rows and columns in the matrix used for lacunarity estimation. The results of several tests showed that a cell size of 100 m was the best ratio between grid resolution and calculation time.

We analyzed the resulting lacunarity curve for each service, searching for two main characteristics: (i) changes in lacunarity values, and (ii) the slope of the curve, from which it is possible to find some break points that are related to characteristic spatial scales (Elkie and Rempel, 2001). For this purpose, we identified the scale at which the percent decrease in the dependent variable (lacunarity) becomes lower than the increase in the independent variable (window size), using Eq. (4):

$$p_i = \left| \left(\frac{\Delta V_i}{\Delta W_i} \right) \right| - 1 \qquad (4)$$

where ΔV_i is the percent change in lacunarity with respect to the range of values adopted in the study area and ΔW_i is the percent change in window size. The value of window size that supposes a change of p_i from positive to negative, occurs at a characteristic spatial scale. Thus, two different zones can be defined on each curve: (i) $p_i > 0$, where lacunarity values depend strongly on spatial scale and (ii) $p_i < 0$, where lacunarity is almost independent of the window size (Diaz-Varela et al., 2008).

We obtained twelve different lacunarity curves (one for each distribution pattern) and proceeded to compare six curves

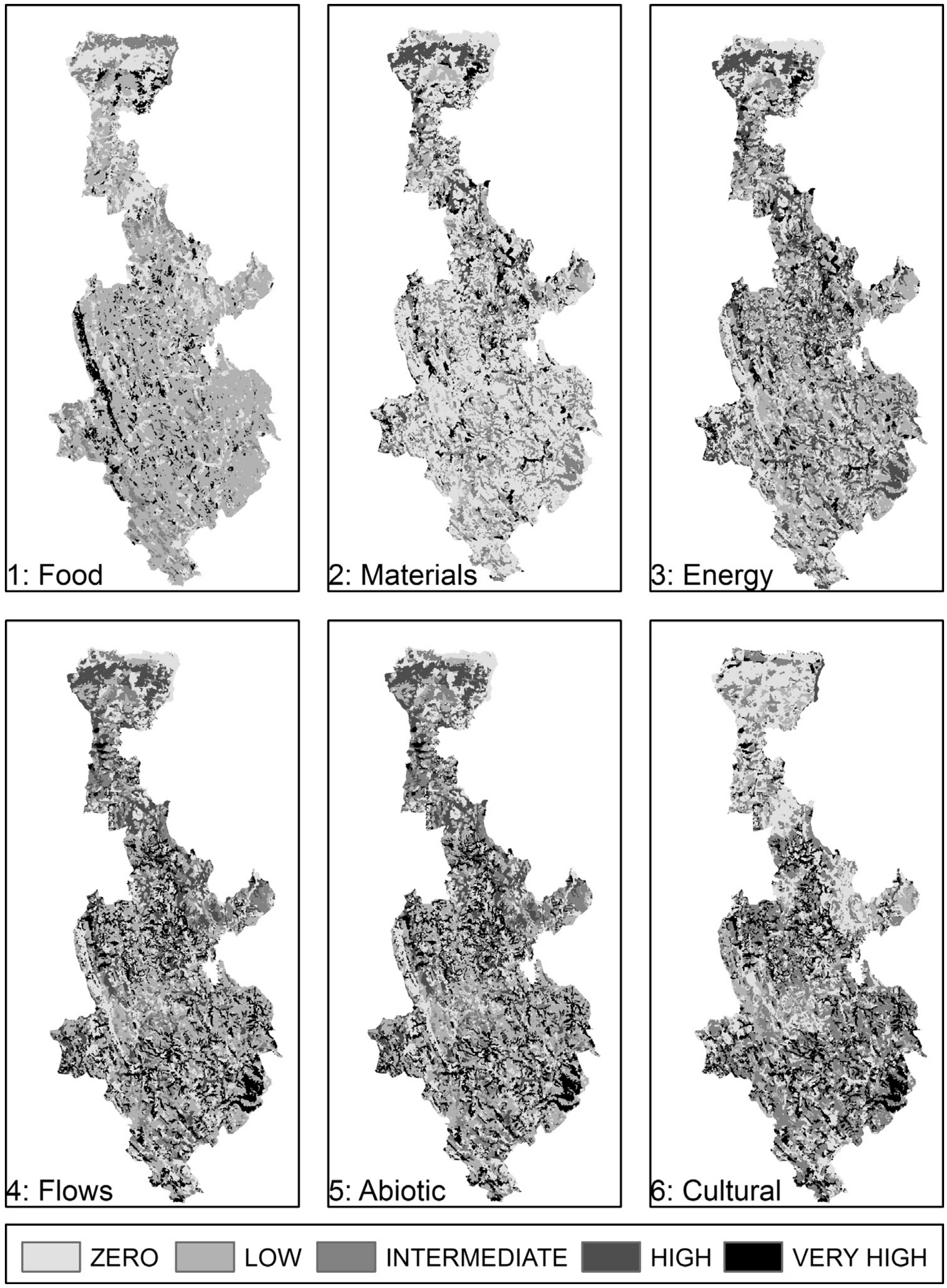

Fig. 5. Greyscale map of ecosystem services. The level of provision ranged in five classes from zero to very high.

comprising each type of data (binary and greyscale) with each other. We also compared six pairs of curves, so that the lacunarity curve of service *i* for binary data was compared with the corresponding curve for greyscale data. We used the lacunarity values to analyze the spatial pattern of ecosystem service providers.

To explore differences between these lacunarity curves, we applied two statistical tests based on the simultaneous detection of homogeneity among the regression coefficients of these models, using SAS software (SAS Institute Inc., 2004): the χ^2-test proposed by Lakkis–Jones (Eq. (5)) (Khattree and Naik, 1999), and the nonlinear extra sum of squares (Eq. (6)) (Bates and Watts, 1988). The aforementioned methods require fitting of reduced and full models. While the reduced model has the same set of parameters for all lacunarity curves (binary and greyscale), the full model corresponds to different sets of parameters for each curve and is obtained by expanding each parameter through an associated parameter and a dummy variable to differentiate the lacunarity curves. The expressions are as follows:

$$\text{Lakkis–Jones test}: L = \left(\frac{\text{SSE}_\text{F}}{\text{SSE}_\text{R}}\right) \exp\left(\frac{n}{2}\right) \quad (5)$$

$$\text{Nonlinear extra sum of squares}: F* = \left[\frac{\text{SSE}_\text{R} - \text{SSE}_\text{F}}{\text{d.f.R} - \text{d.f.F}}\right] \times \left(\frac{\text{d.f.F}}{\text{SSE}_\text{F}}\right) \quad (6)$$

where SSE_R is the sum of squared errors of the reduced model, SSE_F is the sum of squared errors of the full model, d.f.F and d.f.R are the degrees of freedom for the full and reduced model, respectively.

2.5.2. Landscape metrics

To enhance the interpretation of the relationship between spatial pattern and lacunarity values, we calculated a set of landscape metrics at class level for each of the twelve maps generated by FRAGSTATS 3.4 software (McGarigal et al., 2002), as follows: (i) PLAND (Percentage of landscape), (ii) NP (Number of Patches), (iii) AREA_MN (Mean Patch area), (iv) SHAPE_MN (Shape Index Mean) and (v) SHAPE_AM (Shape Index area-weighted mean). For detailed information about the calculation procedure, see McGarigal et al. (2002).

3. Results

3.1. Spatial ecosystem model and reclassification process

The binary identification of ecosystem services providers generated two different classes on maps: ESP class (positive values, presence of a ESP in a cell) and NO_ESP class (null values, absence of ESP; Fig. 4). The area covered by ESP was different from the areas with low ESP values (Food Provision, service 1, 20.7%; Material Provision, service 2, 15.3%). However, on three of the maps, a large portion of the area was covered by ESP (Flow Regulation, service 4, 74.5%; Abiotic Regulation, service 5, 79.8%; Cultural, service 6, 62.1%) and one map displayed intermediate values (Energy Provision, service 3, 36.6%).

On greyscale maps (Fig. 5), five classes were generated by a reclassification process. Zero provision classes have different values on these maps. Thus, services 1, 4 and 5 have values lower than 25% (respectively 22.4; 19.7 and 19.7%), Services 3 and 6 have values higher than 25% (26.3 and 31.4%) and only service 2 has very high values (54.8%). The remaining classes were distributed differently: service 1 has a high portion of its area covered by classes of low and medium provision (58.8 and 10.3%), while services 3, 4 and 5 have more than 30% covered by high and excellent classes of provision.

3.2. Lacunarity results from binary and greyscale datasets

Six lacunarity curves produced by binary data were analyzed (Fig. 6). The results of the Lakkis–Jones and non-linear extra sum of squares tests revealed that curves for services 4 (flow regulation) and 5 (abiotic regulation) are not statistically different. Although the remaining curves (services 1, 2, 3 and 6) are statistically significantly different, the curve for service 6 (cultural) is similar to the curves for services 4 and 5, and therefore these three curves were clustered in the same group, designated Family 2.

Although the curves for services 1 (food), 2 (materials) and 3 (energy) are significantly different, they are very similar in shape, and the values of the L and F^* coefficients indicated that they were closer to each other than to the curves in Family 2. Thus, these three curves were clustered in Family 1.

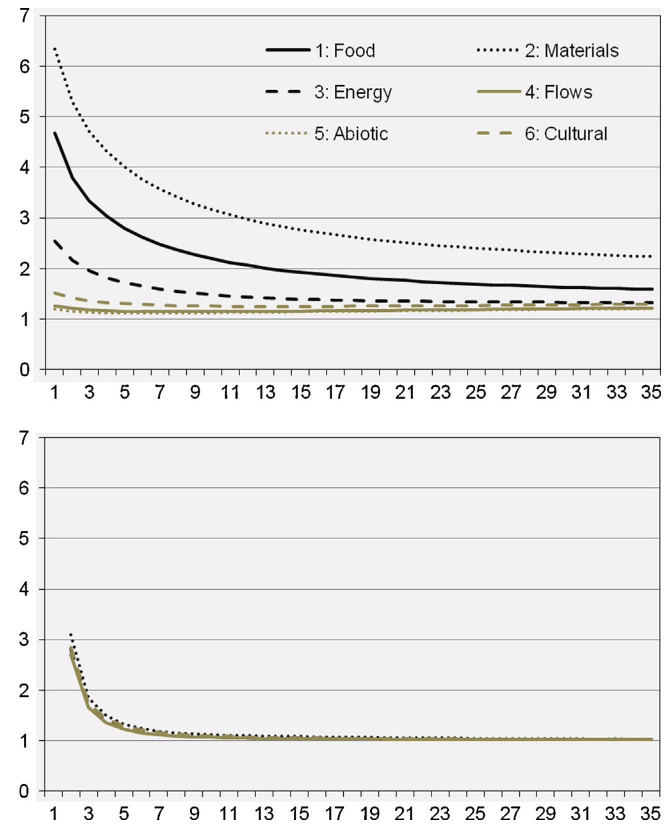

Fig. 6. Lacunarity variation (Y) for binary data and greyscale data based on window size (X, ×100 m).

The values of ESP class cover for the curves in Family 1 were low and therefore these curves produced the highest lacunarity values (Table 2). The mean lacunarity values are higher than for the other curves (2.110 for service 1; 2.997 for service 2; 1.489 for service 3) and the shapes are very similar, so that their maximum values appear at the smallest windows used. The values decreased greatly (by about 25%) with an increase in window size from 100 to 200 m. On the other hand, values were minimal (1.5916, 2.2387 and 1.3312 respectively) with the largest windows used (3500 m).

Finally, Family 2 is formed by curves for services with high values of ESP cover: flow regulation (4), abiotic regulation (5) and cultural services (6). Therefore, the lacunarity values for these curves are low. The mean values are 1.183 (service 4), 1.163 (5) and 1.288 (6). The decrease in lacunarity values of the curves with smallest windows was very marked. Thus, lacunarity values decreased by more than 40% with an increase in window size from 100 to

Table 2
Maximum values (MAX LACUN), minimum values (MIN LACUN) and mean values (MEAN LACUN) of lacunarity curves for the twelve maps of binary and greyscale type. Identification of breakpoint position where the decrease in lacunarity is lower than the increase in window size (ABS($\Delta\%Y/\Delta\%X$) < 1).

		MAX LACUN	MIN LACUN	MEAN LACUN	ABS($\Delta\%Y/\Delta\%X$) < 1
Binary data	1: Food	4.6748	1.5916	2.110	8–9
	2: Materials	6.3468	2.2387	2.997	8–9
	3: Energy	2.546	1.3312	1.489	8–9
	4: Flows	1.2671	1.1491	1.183	5–6
	5: Abiotic	1.2116	1.1238	1.163	4–5
	6: Cultural	1.5236	1.2535	1.288	7–8
Greyscale data	1: Food	3.8836	1.0466	1.272	6–7
	2: Materials	3.0991	1.0318	1.179	5–6
	3: Energy	2.814	1.0225	1.135	5–6
	4: Flows	2.7099	1.022	1.126	5–6
	5: Abiotic	2.7105	1.0219	1.126	5–6
	6: Cultural	2.848	1.0254	1.150	5–6

Table 3
Landscape metrics at class level for binary maps. Metrics are as follows: PLAND (Percentage of landscape), NP (Number of Patches), AREA_MN (Mean Patch area), SHAPE_MN (Shape Index Mean) and SHAPE_AM (Shape Index area-weighted mean).

	1: Food		2: Materials		3: Energy		4: Flows		5: Abiotic		6: Cultural	
	NO ESP	ESP	NO ESP	ESP	NO ESP	ESP	NO ESP	ESP	NO ESP	ESP	NO ESP	ESP
PLAND	78.6102	21.3898	84.2367	15.7633	60.718	39.282	21.0792	78.9208	16.2389	83.7611	34.3708	65.6292
NP	214	1469	133	805	575	875	1573	141	1438	91	1281	385
AREA_MN	781.5327	30.9789	1347.4962	41.6609	224.6609	95.5131	28.5105	1190.8369	24.0257	1958.3077	57.0851	362.6753
SHAPE_MN	1.2565	1.3328	1.3701	1.3805	1.4219	1.4825	1.3077	1.2929	1.2829	1.3290	1.3739	1.3908
SHAPE_AM	26.5222	3.6187	13.4917	3.6960	19.1720	14.8162	3.0294	26.8773	2.6252	21.9421	5.8961	23.9685

200 m. The minimum values for family 2 curves were obtained with intermediate sized windows: for service 4, a value of 11,491 with a window of 900 m; for service 5, a value of 11,238 with a window size of 700 m, and for service 6 a value of 12,535 with a window size of 1400 m.

Several differences between families were also observed in landscape metrics (Table 3). The maps that generated Family 1 curves produced low values for class ESP (presence of ESP on a cell) for three metrics: PLAND, AREA_MN and SHAPE_AM; these values are lower than those produced for ESP class in maps of Family 2. On the other hand, the NP metrics showed mismatched results, with higher values for each map with Family 1 than Family 2 curves.

In relation to the greyscale data, the lacunarity values were very similar for the six maps (Fig. 6). The results of the Lakkis–Jones test (L value) and nonlinear extra sum of squares test (F^* value) showed that these six curves were not statistically different and could be clustered in the same group. The maximum values (2.7099–3.8836) and mean values (1.126–1.272) of these curves are within a similar range (Table 2). The shape of six curves is very similar, with a very marked high value for the smallest window, which decreased by more than 50% with the first increase in window size in six curves.

The values for five landscape metrics were compared on the basis of null class results for six greyscale maps (Table 4), revealing a similar pattern. Similar results were obtained for four landscape metrics (PLAND, AREA_MN, SHAPE_MN and SHAPE_AM): low values for services 4 and 5, intermediate values for services 1 and 3 and high values for services 6 and 2.

Finally, comparison of lacunarity curves for binary and greyscale data revealed several differences (Fig. 7). For example, the values of the binary curves for services 1 and 2 are higher than those of the greyscale curves, so that the decrease in lacunarity values was more evident in the greyscale than in binary data. On the other hand, the lacunarity values of the curves for service 3 were intermediate between the highest (services 1 and 2) and remaining curves. Although the mean value of service 3 with binary data is closer to mean values of services 4, 5 and 6, the change of scale is similar to that observed for services 1 and 2. Lacunarity curves for services 4, 5 and 6 are similar in shape for both binary and greyscale data. The greyscale curves have marked maximum values with the smallest window size that do not exist on binary data and these greyscale curves decline sharply with the increased window size. For windows larger than 600 m, the shape of greyscale curves is the same

Table 4
Landscape metrics at class level for greyscale maps. Metrics are as follows: PLAND (Percentage of landscape), NP (Number of Patches), AREA_MN (Mean Patch area), SHAPE_MN (Shape Index Mean) and SHAPE_AM (Shape Index area-weighted mean).

	Class	PLAND	NP	AREA_MN	SHAPE_MN	SHAPE_AM
1: Food	Zero	22.3732	1136	41.9014	1.3553	4.5364
	Low	58.7812	497	251.6298	1.3519	28.9764
	Intermediate	10.2987	760	28.8303	1.3351	2.9524
	High	0.5589	200	5.945	1.1525	1.4842
	Very high	7.9881	938	18.1183	1.2808	2.4450
2: Materials	Zero	54.837	648	180.0432	1.4149	29.0552
	Low	13.7379	1284	22.7632	1.3030	2.6170
	Intermediate	16.7127	1137	31.2726	1.4637	3.8949
	High	7.2224	372	41.3065	1.3957	3.8673
	Very high	7.4899	740	21.5338	1.3133	1.9415
3: Energy	Zero	26.2531	1567	36.0108	1.3735	3.4183
	Low	38.0458	1180	68.5966	1.4430	6.8346
	Intermediate	3.1008	398	16.5754	1.3061	2.1429
	High	24.7483	1196	44.0242	1.5206	4.7660
	Very high	7.582	741	21.7692	1.3250	1.9337
4: Flows	Zero	19.7148	1494	28.075	1.3251	2.9068
	Low	33.6957	1216	58.9548	1.4533	7.0237
	Intermediate	14.0543	1283	23.3055	1.3170	2.6394
	High	15.3454	844	38.6825	1.4014	3.6877
	Very high	17.1898	1077	33.9573	1.4975	4.3079
5: Abiotic	Zero	19.7162	1494	28.077	1.3250	2.9047
	Low	33.2957	1228	57.6857	1.4440	7.1250
	Intermediate	14.4087	1365	22.4579	1.3071	2.6174
	High	15.3388	848	38.4835	1.3992	3.6847
	Very high	17.2406	1076	34.0892	1.4974	4.3138
6: Cultural	Zero	31.3896	1133	58.9435	1.4141	6.8958
	Low	15.3609	1264	25.8552	1.3298	2.5050
	Intermediate	34.5468	1281	57.377	1.4362	6.4060
	High	1.0796	255	9.0078	1.1883	2.3717
	Very high	17.6231	1122	33.4171	1.4807	4.2852

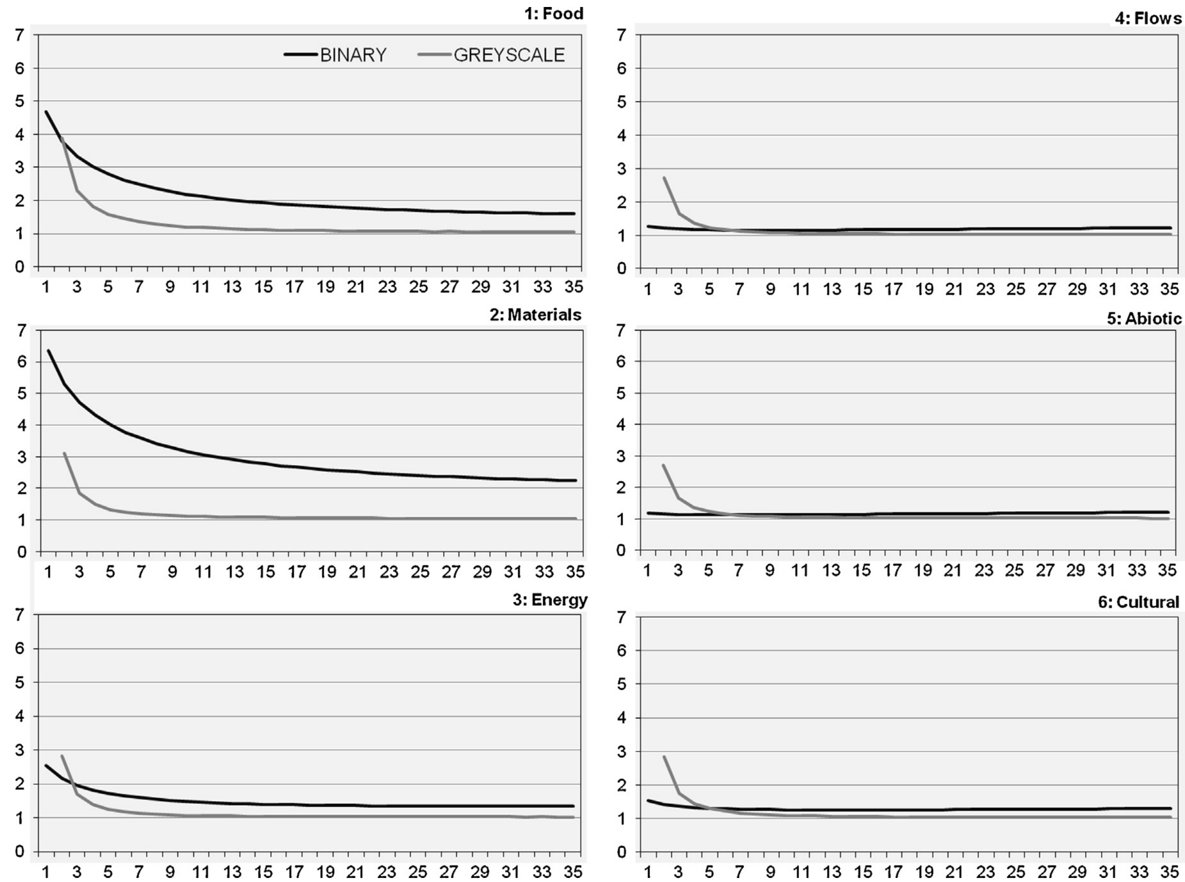

Fig. 7. Lacunarity curves of binary and greyscale maps for six services. Lacunarity variation (*Y*) based on window size (*X*, ×100 m).

as that of binary curves and the values are very similar. Only a small increase in lacunarity values of services 4 and 5 for binary data was noted.

3.3. *Identification of relevant scales*

Finally, we analyzed breakpoints in lacunarity curves and took into account differences among types of maps. For binary data, the pattern of these points revealed differences among services. The lacunarity curves for Family 1 (services 1, 2 and 3) show breakpoints at the same scale, for window sizes of between 800 and 900 m. However, the breakpoints for Family 2 curves, which were of similar shape and had similar lacunarity values, occurred at different scales: service 4 with 500–600 m, service 5 with 400–500 m and service 6 with 700–800 m.

The breakpoints for the greyscale curves occurred within a similar range of scales: for 500–700 m and windows larger than 700 m, the lacunarity values scarcely changed. Therefore, six curves were almost horizontal for the remaining values of window size that were used (up to 3500 m).

Comparing binary and greyscale data, breakpoints appeared at a smaller window size in greyscale curves (500–700 m) than in binary curves (800–900 m) for services 1 and 2. Minimum lacunarity values were also higher in binary curves than in greyscale curves, in which the minimum values were close to 1.

Identification of breakpoints in lacunarity curves has a spatial interpretation. For binary data of services 1, 2 and 3, an extension of 72 ha is related to the window size where the breakpoint is, thus an mean extension of 72 ha is required to enable identification of a regular pattern in these services. This was the largest extension found and is related to a high proportion of gaps in binary maps of these services (79% service 1; 84% service 2; 71% service 3). On the other hand, in binary maps with few gaps (service 4, 21% and service 5, 16%) the surface area associated with breakpoints of their curves was 20–25 ha. Finally, greyscale curves generated a similar range of surface area for six services, of 30–42 ha, despite the wide range of gaps, ranging from 20 to 54%.

4. Discussion

4.1. *Spatial variation in ecosystem service provision*

The location of the spatial origin of the ES is important for analysis of the provision and consumption of services (Burkhard et al., 2012). In the approach presented here, we considered this as a compromise between the ready availability of LULC cartographical data, and the reliability of the information derived from its analysis. Despite the limitation pointed out by Eigenbrod et al. (2010) in relation to LULC cartographical information, which may omit small ecosystems by oversimplification of landscapes and thus overlook the flow of services that are generated (Koschke et al., 2012), the present results demonstrate the usefulness of LULC information as a proxy for service assessment, especially when a legend with a large number of LULC classes is used. Therefore, the risk of oversimplification was overcome by careful consideration of the following: (i) spatial and thematic resolutions; (ii) the composition of classes represented in the thematic legend; and (iii) the translation of LULC classes into the ecosystems for which they are proxies. This procedure also minimizes the risk of generalization, as ecosystem types were defined by a combination of LULC types at well-specified percentages. Accurate representations of LULC also help to explicitly identify the provision of a specific service from several ecosystems with the adequate reclassification procedure. In addition, convergence of several ecosystem classes into a specific service provision allows integration of the probability of the contribution of each ecosystem in the analysis by the use of greyscale approaches. As a result, the maps show specific spatial behavior for each service provision, as well as spatial relationships between ecosystems. Two main aspects that directly affect the provision of ES can be emphasized: (i) the relationship between the spatial distribution of ES and the spatial arrangement of the LULC that they are associated with; and (ii) the similarity of spatial patterns due to overlapping.

For the former, a clear example is provided by the relationships between different but complementary land uses. For instance, services 1 (food provision) and 2 (material provision), which are related to different ESP, showed a high degree of similarity in the binary data curves, and they were therefore included in the same family. The spatial pattern of this group of services does not extend throughout the study area and is clustered at some points associated with the presence of the ESP. This may be related to the transformation of the traditional agricultural-forestry landscape (Martínez et al., 2010), from a highly diversified production system (food and material) to a more homogeneous landscape in which the distribution patterns for crop production and forest plantations are similar and of comparable extension. The transformation of traditional landscapes has previously been analyzed in a zone adjacent to the study area (Calvo-Iglesias et al., 2009). These authors pointed out that changes during the second half of the 20th century have transformed spatial pattern and functionality of traditional “bocage” landscape of this area into more homogeneous modern landscapes. Thus, changes in cultural landscape elements are not only associated with provision of services (principally food), but also with cultural aspects. In addition to this, the family 1 of curves represents a degree of clustering of the service providers that is highly dependent on a “patchy” distribution of the ecosystems. Variance in such spatial arrangement will be determinant on the scale-dependence of the service availability, as will be shown in the next section.

For the latter, an example is given by service 4 (flow regulation) and service 5 (abiotic regulation), which are related to similar LULC and also show similar spatial patterns in both binary and greyscale data. It is known that a single type of ecosystem acts as source of several services, thus generating spatial overlapping of ESP identified during analysis of service distribution (e.g. Egoh et al., 2008, 2009). The present study revealed that different provision and regulation services were strongly associated with forest ecosystems. In fact, variations in the surface area of this type of ecosystems have been related to significant changes in service flow at a regional scale (Frank et al., 2012).

4.2. Scale effects

For the six services analyzed, we determined the spatial scales associated with ESP patterns of distribution. Differently shaped lacunarity curves were associated with the spatial patterns of services distribution, and differences in the values and scale effects were related to the window size used in the estimation. In general, curves were logistically shaped, with maximum values for the smaller window sizes. This is consistent with the findings of most previous studies, in which higher values were related to a clustering of habitat of interest (ESP class) or a wide range of gaps sizes (e.g. Plotnick et al., 1993; McIntyre and Wiens, 2000; Dong, 2009). Therefore, maximum lacunarity value is closely related with gap densities in the map but not with curves shape (Plotnick et al., 1996).

The main utility of the multiscale behavior of lacunarity, as described by the different families of curves, is to detect the scale at which the service provision is guaranteed at a given probability. As the maps on which the analysis is based are a spatial representation of the ES providers, the gaps in the lacunarity analysis indicate the absence of provision for any given ES. Consequently, the breakpoints on lacunarity curves can be interpreted as scale thresholds for such provision. For example, the scale threshold was 72 ha for services 1, 2 and 3 (binary type data), clustered in Family 1 of lacunarity curves. For the other services on binary maps, the threshold was 20–25 ha. On the other hand, analysis of greyscale data reveals a fixed scale threshold of 30–42 ha. This may be due to the complexity of the differentiation among intensity classes in the greyscale pattern. As the gap density is not related to shape but to maximum values, the contribution of different intensities to the overall results creates an averaging effect, possibly masking the scale effects at each intensity. Such masking effects could be overcome by adding functional analysis of remote sensed data in future assessments.

In both cases, scale thresholds can be taken as a reference for the characteristic scale of each ecosystem service. They can be interpreted as the size of the area for which the probability of provision of the service is highest. This has a straightforward application for ES planning and management and changes the spatial analysis of the distribution of ES from being simply descriptive to being informative of the degree of provision at a given space and scale.

In general terms, the results of landscape metrics and lacunarity estimation are related. As regards PLAND, services 1 and 2 tend to be awarded low values, service 3 intermediate values, and services 4 to 6 high values, which is consistent with the family grouping in the lacunarity analysis. A similar trend can be seen for AREA_MN, and inversely, for NP. SHAPE_MN does not differ greatly in the different services, and SHAPE_AM is a better choice due to the area weight. Thus, the proportion of ESP on the map is more important than the shape, which is consistent with the conclusions of Plotnick et al. (1993). The mean lacunarity values are between 1 and 1.52 for those services with a surface are of map higher than 60%. Consequently, metrics reporting for direct and straightforward characteristics of landscape composition (e.g. PLAND, AREA_MN) can be used to support ES planning and management. They can be used to evaluate the ES flow in a territory based on the structural characteristics of the ecosystem components of the landscape or to highlight zones that are rich in ESP.

Thus, the definition of areas of influence for each ESP will establish the basis for demand analysis from a spatial perspective, in order to develop sustainable planning and management of ecosystem service flows (Syrbe and Walz, 2012). This can be done by relating service demand to the amount of interest habitat (see e.g. McIntyre and Wiens, 2000), e.g. by using metrics that measure the relative percentage of the target ecosystem.

5. Conclusions

The proposed methodology allowed definition of functional scales for the provision of ecosystem services, by the use of the multi-scale approach inherent in lacunarity analysis. Such functional scales can be interpreted as the spatial level at which the provision of a specific service is warranted for a given probability. The results of this study also highlight differences in the spatial distribution of the provision of ecosystem services, based on the differences of the spatial pattern of the ecosystem service providers. Such differences are revealed by the relationships between the spatial patterns of land use/land cover and ecosystem service providers, which also differ at different scales.

The usefulness of the methodology is related to the support generated for the identification of the level of provision of ecosystem services, and the scale at which this level is revealed, in planning and management processes. We expect that this will constitute an important aid to the correct treatment of the spatial explicitness of the behavior of ecosystem services and their provision. However, factors such as the divergence between the location of service provision and its demand are not addressed by the methodology. In this respect, further research should include a more detailed analysis of the relationships between provision areas, their size, and service demand.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2013.09.010. These data include Google maps of the most important areas described in this article.

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A multiscale analysis of ecosystem services supply in the NW Iberian Peninsula from a functional perspective

Jose V. Roces-Díaz [a,*], Ramón A. Díaz-Varela [b], Pedro Álvarez-Álvarez [a], Carmen Recondo [c,d], Emilio R. Díaz-Varela [e]

[a] GIS-Forest Group, Department of Organisms and Systems Biology, University of Oviedo, Mieres, Spain
[b] Department of Botany, GI-1934-TB, IBADER, University of Santiago de Compostela, Lugo, Spain
[c] Area of Cartographic, Geodesic and Photogrammetric Engineering, University of Oviedo, Mieres, Spain
[d] Institute of Natural Resources and Territorial Planning – INDUROT, University of Oviedo, Mieres, Spain
[e] Research Group 1716 – Projects and Rural Planning, Department of Agro-Forestry Engineering, University of Santiago de Compostela, Galicia, Spain

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A B S T R A C T

In recent years, the assessment of ecosystem services (ES) supply has been based on the use of Land Use/Land Cover (LULC) data as proxies for spatial representation of ecosystems. Nevertheless, some shortcomings of this method, such as uncertainties derived from generalization of the ecosystem types and assumptions of invariance across spatial scales, indicate the need for new approaches. Such approaches could be aimed at improving knowledge of the relationships between ecosystem services and landscape structure and the spatial characteristics of ES patterns. In this study, we propose an integrative approach that involves the generation and analysis of continuous maps representing the supply of five ES potentially related to the amount of biomass. Five remote sensing images of the Northwestern Iberian Peninsula, obtained with Landsat-5 TM, were used to generate a proxy for net primary production by combining the normalized difference vegetation index (NDVI) of each image to calculate a ΣNDVI index that could act as a potential indicator of some ecosystem services. This information was combined with three variables – terrain slope, population density and occurrence of protected areas – to produce spatial models for the five ES and eventually a series of five supply maps. Food, materials and energy provision services showed a clustered pattern, with high supply values in flat zones and areas with high population densities. In contrast, mass flow and climate regulation services were more widely distributed throughout the study area. The five ecosystem service patterns were analyzed at different scales by two methods: lacunarity and four term local quadrat variance (4TLQV) analysis. These methods revealed differences in the spatial pattern: lacunarity analysis was useful for detection of scale thresholds at the local level, whereas 4TLQV was more sensitive to scale thresholds at larger spatial levels. Thus, the variance analysis yielded higher values for larger windows sizes, particularly for provisioning services. The results demonstrated the suitability of the proposed approach for the spatially explicit modeling of ecosystem services, avoiding the uncertainty of other assessments such as those based on LULC data, and for the exploratory analysis of ES supply from a spatial point of view.

1. Introduction

Analysis of ecosystem services (ES) has been addressed in many scientific articles and research projects during the last few decades (e.g., MEA, 2005; EME, 2011). Despite the advances made in gathering a theoretical body of information and in the analysis and classification of ES, there is still a general lack of information and standardized approaches for integrating ecosystem services analysis in land planning and management (de Groot et al., 2010; Koschke et al., 2012). There is also a need for methods of quantifying the supply and the demand of ES from a spatial perspective (Burkhard et al., 2012, 2014). Therefore, the development of methods for accurate mapping and correct quantification of ecosystem services is considered a key requirement for implementation of the ES concept in environmental policies and land use decision making (Daily and Matson, 2008).

* Corresponding author at: GIS-Forest Research Group, Department of Organism and Systems Biology, Polytechnic School of Mieres, Mieres, Asturias 33600, Spain. Tel.: +34 985103000x5857.
E-mail address: jvroces@gmail.com (J.V. Roces-Díaz).

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Assessment of ES is often based on Land Use/Land Cover (LULC) data (e.g., Frank et al., 2012; Koschke et al., 2012; Kandziora et al., 2013). This approach enables the assessment of large areas and development of multi-scale analysis. However, some common problems have been detected in this type of assessment (Eigenbrod et al., 2010a): first, the generalization over the whole study area of standard values for a given variable sampled in a location and, second, the assumption of invariance across different spatial scales. In addition, the map resolution may not be sufficient for location of some ecosystem services, particularly when such ES are associated with ecosystems that cover small areas or that are fragmented in small patches barely identified in the LULC datasets (Kandziora et al., 2013). In this respect, Hou et al. (2013) also identified a series of uncertainty sources commonly found in assessment of spatial ecosystem services. These authors highlighted the uncertainties associated with the use of LULC data, particularly missing data, scale issues or imprecise function/ecosystem service classifications or definitions.

Analysis of ES should not rely solely on identification of the relationships between the ecosystem services and a given LULC class (Frank et al., 2012), as some ES may be associated with several classes at the same time and/or depend on complex relationships between LULC classes. Different ecosystem services might show multiple spatial scales because they originate in ecological processes revealed at a wide range of spatial levels (Roces-Díaz et al., 2014), and therefore the multi-scale perspective should also be taken into account in such ES analysis (Burkhard et al., 2012). Similarly, the relationships between landscape pattern and the supply and demand of ecosystem services should also be addressed, along with improvement of the spatial representation of ES supply.

The availability of datasets with spatially explicit information obtained from sources other than extrapolation or generalization processes may prevent the above-mentioned problems identified by Eigenbrod et al. (2010a). Thus, some authors have emphasized the use of remote sensing (RS) data to overcome some of the traditional flaws of ES assessments (Ayanu et al., 2012; Burkhard et al., 2013; Cabello et al., 2012). Indeed, some recent studies analyzing ES supply from a functional perspective have used RS datasets for quantifying energy flows as a proxy for ecosystem services distribution (Petrosillo et al., 2013). In other studies, RS data have been used to characterize the territory structure and the landscape pattern and eventually to define functional types of ecosystems (Paruelo et al., 2001, 2004; Alcaraz et al., 2006; Fernandez et al., 2010); furthermore, Kandziora et al. (2014) combined RS data and the ES approach to identify the spatial and temporal dynamics of ES. Most such studies are based on the analysis of spatial heterogeneity of some parameters associated with vegetation structure (such as the normalized difference vegetation index (NDVI)) and energy distribution (such as the albedo and land surface temperature). The use of vegetation indices – such as the aforementioned NDVI – is common in several fields of environmental research. In fact, different authors have associated this index with vegetation structure and other parameters, e.g., primary production and carbon balance (Running et al., 1999; Huete et al., 2002), which are relevant in ES analysis.

Net primary production (NPP) is often assumed to be a key process in the study of the relationships between ecological functioning and ES supply (MEA, 2005) because it drives the amount of biomass in an ecosystem. NPP is defined as the balance between the carbon fixed in photosynthesis and the carbon lost by plant respiration (both due to growth and maintenance respiration) and is generally considered a type of organization of the energy essential for the maintenance of natural capital and the well-being of society (Odum, 1971; Costanza et al., 1998). For this reason, different ES assessments (i.e., Richmond et al., 2007; Petrosillo et al., 2013) established the NPP as a proxy for quantifying different ecosystem services, such as provision of food and timber. Thus, the combination of different methods of ES analysis, such as those based on LULC data with RS information, may be useful for reducing some of the typical errors that appear in assessment of the ecosystem services.

Taking all the above into account, we propose a method for the analysis of five key ecosystem services from a functional perspective. For comparison of the five ES models obtained from a spatial point of view, we applied two methods of spatial analysis that depend on the scale. First, we used lacunarity (Mandelbrot, 1983; Plotnick et al., 1993; Fortin and Dale, 2005), which analyzes the regularity of the pattern of the gaps (in our case they are the no supply zones), and second, we used the four term local quadrat variance (4TLQV; Dale, 1999; Fortin and Dale, 2005), which analyzes the increase in variance with increasing scale of analysis. More precisely, the objectives of this study were as follows: (i) to estimate the supply of five ecosystem services associated with biomass production, by using remote sensing data and spatially explicit models; and (ii) to analyze the differences between these models by establishing the characteristic spatial scale of each ES pattern.

2. Material and methods

2.1. Study area

The study area (which covers an area of 2134 km^2) is located in the northwest of the Iberian Peninsula (Fig. 1) and is included in the European Atlantic Biogeographic Region (EEA, 2013). The climate of the area is defined as oceanic, with average annual rainfall values higher than 1000 l/m^2 and with no summer drought (Ninyerola et al., 2005). The area is mountainous, with an elevation ranging from sea level to 2000 m (Fig. 1). The mean slope is steeper than 40% and only 5% of the area has a slope lower than 10%.

The landscape of the area has been subject to strong anthropogenic influence and a general decline in woodland surface during the last two thousand years in relation to the increase in agricultural and livestock use (Muñoz-Sobrino et al., 2005). The areas with the most fertile and deepest soils are often used for agricultural crop production and dairy farms. These uses are mixed with scattered patches of woodland of native species (*Quercus robur* L. and *Castanea sativa* Mill.) and forest plantations for timber production (*Eucalyptus globulus* Labill., *Pinus pinaster* Ait. and *Pinus radiata* D. Don). In the highlands, the slope aspect plays a key role in the distribution of vegetation, and shady slopes are usually covered by forest comprising *Q. robur*, *Quercus petraea* (Matt.) Liebl., *Fagus sylvatica* L. or *Betula pubescens* Ehrh., while scrubland is more common on south-facing slopes. The anthropogenic influence is also associated with the occurrence of scrub communities (mainly heath, gorse and broom) at a wide range of elevations (Diaz and Fernández-Prieto, 1994).

2.2. Data collection and pre-processing

The different stages of data collection, pre-processing and data analysis are summarized in Fig. 2. Remote sensing analysis was based on imagery from the Thematic Mapper (TM) sensor of Landsat-5 satellite. These images have an original spatial resolution of 30 m and provide information about six spectral bands in the visible electromagnetic spectrum (blue, green and red channels: 1, 2 and 3, respectively), near infrared (channel 4), short wavelength infrared (channels 5 and 7) and thermal infrared (channel 6).

We selected a time series of images with low cloud coverage spanning a recent phenological year (covering all four seasons). The first image selected corresponds to autumn (2010/10/18), the

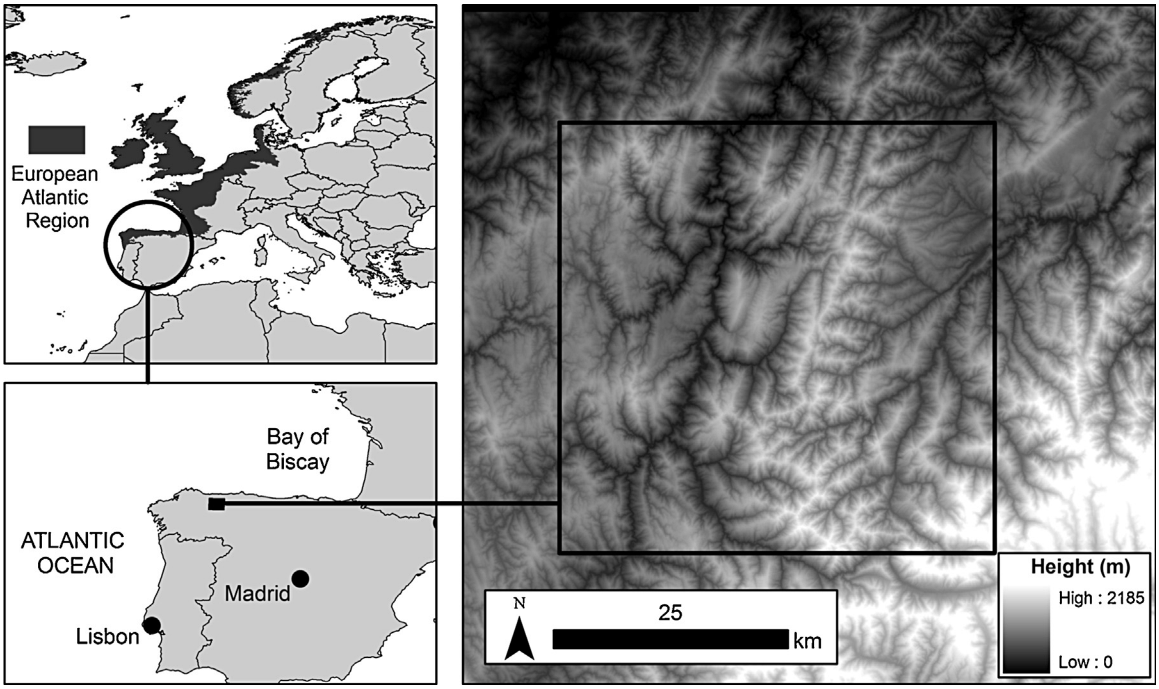


Fig. 1. Location of the study area and its elevation distribution. Sources: EEA (2013); IGN (2014).

second to winter (2011/03/11), the third to spring (2011/06/24), the fourth to summer (2011/09/12) and the fifth again to autumn (2011/10/30), thus covering the phenological cycle. The five images were atmospherically and topographically corrected using the ATCOR v3 module implemented in the Geomatics Focus v9.1.0 package (PCI Geomatics, 2003). The ATCOR3 procedure is based on the MODTRAN-4 radiative transfer code (Berk et al., 1998, 2003). The atmospheric correction parameters of scene acquisition (date, solar zenith angle and mean elevation) and calibration data (gain and offset values) were obtained from the metadata imagery by introducing minor modifications in the gain and offset values following the criteria proposed by Chander et al. (2009). The topographic data were obtained from a Digital Elevation Model (DEM) with a pixel size of 25 m, provided by the National Geographic Institute of Spain (IGN, 2014) (Fig. 1). The model used by ATCOR3 for the topographic correction is a modified Minnaert model, which integrates a correction factor G based on information relative to the vegetation cover, wavelength and solar zenith angle (Balthazar et al., 2012). It is expressed as follows (Eq. (1)):

$$G = \left(\frac{\cos i}{\cos t}\right)^b \quad (1)$$

where i is the incident solar angle, i.e., the angle between the normal to the ground and the sunrays; t is a threshold value depending on the solar zenith angle; and b is a parameter that is a function of the vegetation cover and wavelength. Following Balthazar et al. (2012), parameter t was adjusted to a range between 47° and 69°.

The NDVI (Rouse et al., 1973) was the main parameter used for the remote sensing analysis. Calculation of this index is based on the normalized difference between near infrared and red bands (Eq. (2)):

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{RED})}{(\mathrm{NIR} + \mathrm{RED})} \quad (2)$$

where RED and NIR are the measurements of spectral reflectance in the red (RED) and near infrared (NIR) wavelength intervals. NDVI has been widely used for different applications in agriculture, forestry and environmental sciences (Chuvieco and Huete, 2009). Various authors have related this index to vegetation structures, such as vegetation cover, biomass and leaf area index, as well as some functional characteristics, such as primary production and carbon balance (Running et al., 1999; Stoms and Hargrove, 2000; Huete et al., 2002; Kerr and Ostrovsky, 2003), some of which are the important features in ES analysis.

We computed a proxy for the amount of biomass as the sum of the area under the curve of NDVI throughout a phenological year. First, the NDVI corresponding to each image was calculated using the ENVI 5.0 package (Exelis VIS, 2012) by choosing an output spatial resolution of 100 m, which is the final pixel size for ecosystem service maps (see details in Section 2.3). A time series of NDVI values was then generated, corresponding graphically to a curve with the NDVI value on the vertical axis and the time on the horizontal axis, assuming that the variation in NDVI follows a straight line between correlative dates (Fig. 2). The accumulated area under the curve was then calculated for each image cell. This yielded a continuous image of the accumulated NDVI value throughout a phenological cycle (hereafter referred to as ΣNDVI). We used the ArcGIS 9.3 software (ESRI Inc., 2008) for this and further GIS analysis. The calculation is expressed as follows (Eq. (3)):

$$\sum \mathrm{NDVI} = \sum_{i=1}^{4}\left[(t_{i+1} - t_i) \times \frac{(\mathrm{NDVI}_i + \mathrm{NDVI}_{i+1})}{2}\right] \quad (3)$$

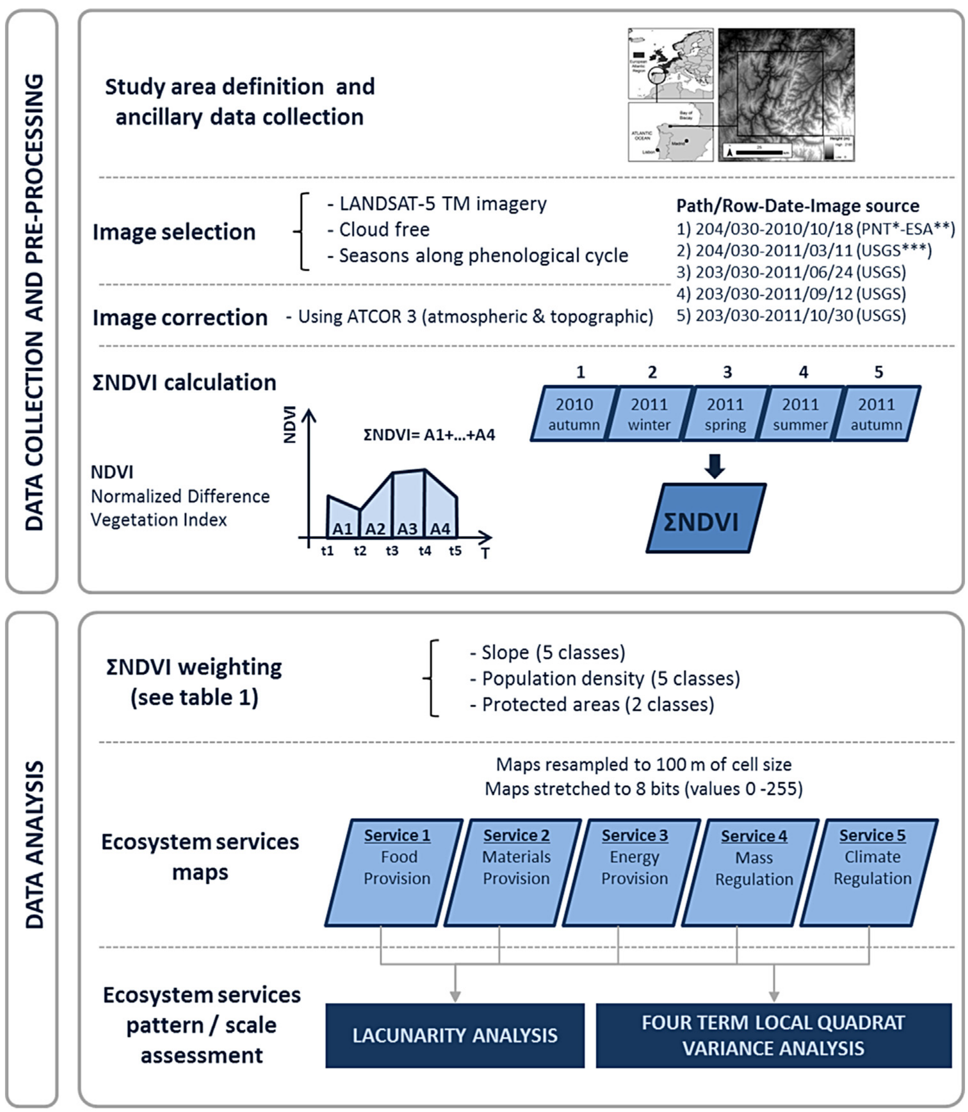
where t is the Julian date for the images, i and $i+1$ refer to one image ($i = 1$ to 4, in this case) and the correlative image ($i + 1 = 2$ to 5, in this case), respectively. The ΣNDVI is expressed as NDVI × day (the product between the non-dimensional value of NDVI and the number of days).

Five ES associated with biomass production (Ayanu et al., 2012) were analyzed following the guidelines for the CICES

V4.3 classification (Haines-Young and Potschin, 2013) of such ecosystem services. The following ES were selected: (i) food provision; (ii) materials provision (from biomass, e.g., wood for construction or pulp for paper); (iii) energy provision, as wood for fuel or energy crops; (iv) mass flow regulation, as protection against soil erosion; and (v) climate regulation and carbon storage.

For a more realistic estimation of how the effective ecosystem services supply were related to biomass production, we included three additional variables in the analyses, namely terrain slope, population density and occurrence of natural protected areas, as these may constrain the provisioning or accessibility to a certain ES. Raster layers of these variables were calculated and used as masks in further analyses in order to fine-tune the calculation of ecosystem services, as detailed below. Each mask layer was reclassified in discrete values to produce the ES models closest to their real supply. The ΣNDVI map was weighted by the resulting mask values for each ecosystem service according to the values detailed in Table 1. These values were based on expert assessment and on the findings of previous studies of ecosystem services assessment and territorial analysis in NW Spain (EME, 2011; Blanco-González et al., 2013). The three mask layers were constructed with a spatial resolution of 100 m, which is the final pixel size for ES maps. The map for each ecosystem service was obtained by multiplying the ΣNDVI map by the three mask layers, which have different weights for each ES (Table 1).

Terrain slope is a key factor that determines the effective use of resources. A slope map was generated from the DEM with a pixel size of 25 m and was then reclassified in five slope intervals by adapting a previously described procedure performed by the Food and Agriculture Organization of the United Nations (FAO, 2006) in accordance with the potential to provide the ecosystem services analyzed. The areas with the lowest slopes are more appropriate for harvesting products associated with provisioning services (Jack et al., 2008), i.e., provision of food, material and energy, while the mass flow regulation service is only provided in those zones with erosion risk, which is related to the slope.



*PNT: Plan Nacional de Teledetección (in English: National Remote Sensing Program; http://www.ign.es/PNT/) enables free access to and downloads of Landsat and other images (only free to Spanish public universities or organizations) from the PNT online archive (ftp://ftp.pnt.ign.es/). **ESA: European Space Agency.
***USGS: United States Geological Survey. The Landsat images search was made through the USGS Global Visualization Viewer (GloVis) (http://glovis.usgs.gov/) and Earth Explorer (http://earthexplorer.usgs.gov), which are online tools that allow visualization and free downloads of Landsat and other images from archives.

Fig. 2. Description of the workflow including data collection, pre-processing and data analysis.

Table 1
Weight coefficients assigned to the classes of the three mask layers for calculation of ecosystem service maps. In an expert assessment procedure, the values were discussed and assigned by six experts from different fields (landscape ecology, remote sensing, forest ecology and forest modeling and silviculture) and with detailed knowledge of the area vegetation and land use characteristics.

Mask layers		Food provision	Materials provision	Energy provision	Mass flow regulation	Climate regulation
Slope, range of values (%)	0–5	1.00	1.00	1.00	0.00	1.00
	5–15	0.75	0.80	0.80	0.25	1.00
	15–30	0.50	0.60	0.60	0.50	1.00
	30–60	0.25	0.40	0.40	0.75	1.00
	>60	0.00	0.00	0.00	1.00	1.00
Population density, range of values (population/km^2)	0–20	0.25	0.50	0.50	1.00	1.00
	20–35	0.50	0.75	0.75	1.00	1.00
	35–50	0.75	1.00	1.00	1.00	1.00
	50–65	1.00	1.00	1.00	1.00	1.00
	>65	1.00	1.00	1.00	1.00	1.00
Protected area	Inside	1.00	0.50	0.75	1.00	1.00
	Outside	1.00	1.00	1.00	1.00	0.75

The logic behind overlaying the population density on the map is that, because of the rural character of the area (i.e., absence of large cities or settlements), the supply of provisioning services is more likely to be found when a minimum threshold of population density is reached. To construct a population density map, point data representing population data was generated using data from the National Geographic Institute of Spain (IGN, 2013). The data were processed using the density kernel option in the Spatial Analyst extension of ArcGIS 9.3. Eight kernel sizes ranging from 1000 to 8000 m were used to choose the most representative density raster map. The map resulting from the 4000 m kernel was selected, as this was the size from which the variance in results for the whole area became asymptotic.

Finally, the mask layer for protected areas is related to potential restrictions for certain land uses and activities, indicating a reduction in some provisioning services or enhancement of others, such as climate regulation services due to the low land use intensity and lower carbon turnover rates (Table 1).

As a result, maps were obtained for each of the five ecosystem services analyzed. In order to convert these maps into a format that enables analysis of spatial scales, decimal values were removed and the raster maps were stretched to 8 bits (range of values from

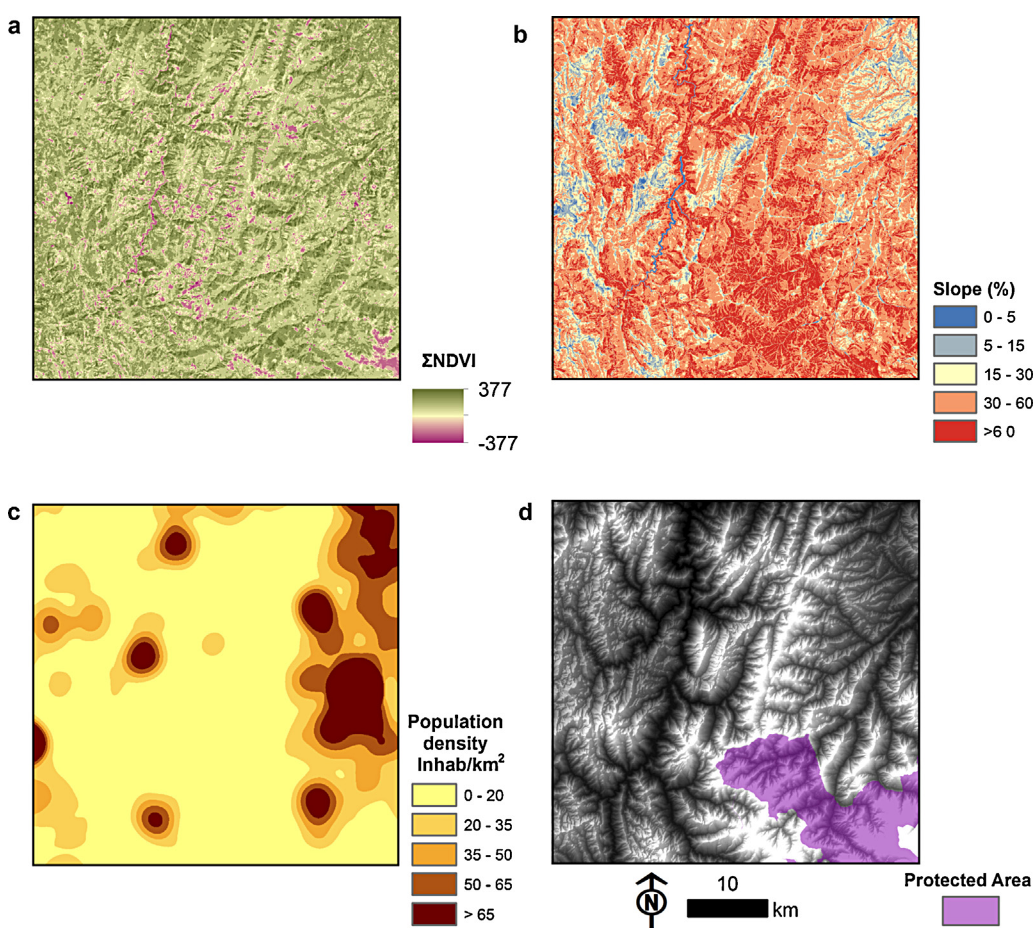


Fig. 3. Representation of (a) ΣNDVI map, (b) slope layer, (c) population density layer, and (d) protected area layer.

0 to 255) pixel depth, considered wide enough to span the variability and heterogeneity of the ES analyzed.

2.3. Data analysis

Several spatial statistical analyses were then conducted using PASSaGE V2 software (Rosenberg and Anderson, 2011) as detailed below (for a more detailed description of the methods, see e.g., Dale, 1999; and Fortin and Dale, 2005). As the original spatial resolution of the layers generated a large matrix data, data were resampled to a cell size of 100 m (a grid of 465 cells × 465 cells).

Different windows sizes from 100 to 23,000 m were then used in the multiscale pattern analysis detailed below, where the smallest window corresponds to the grid resolution and the largest to a quarter of the study area.

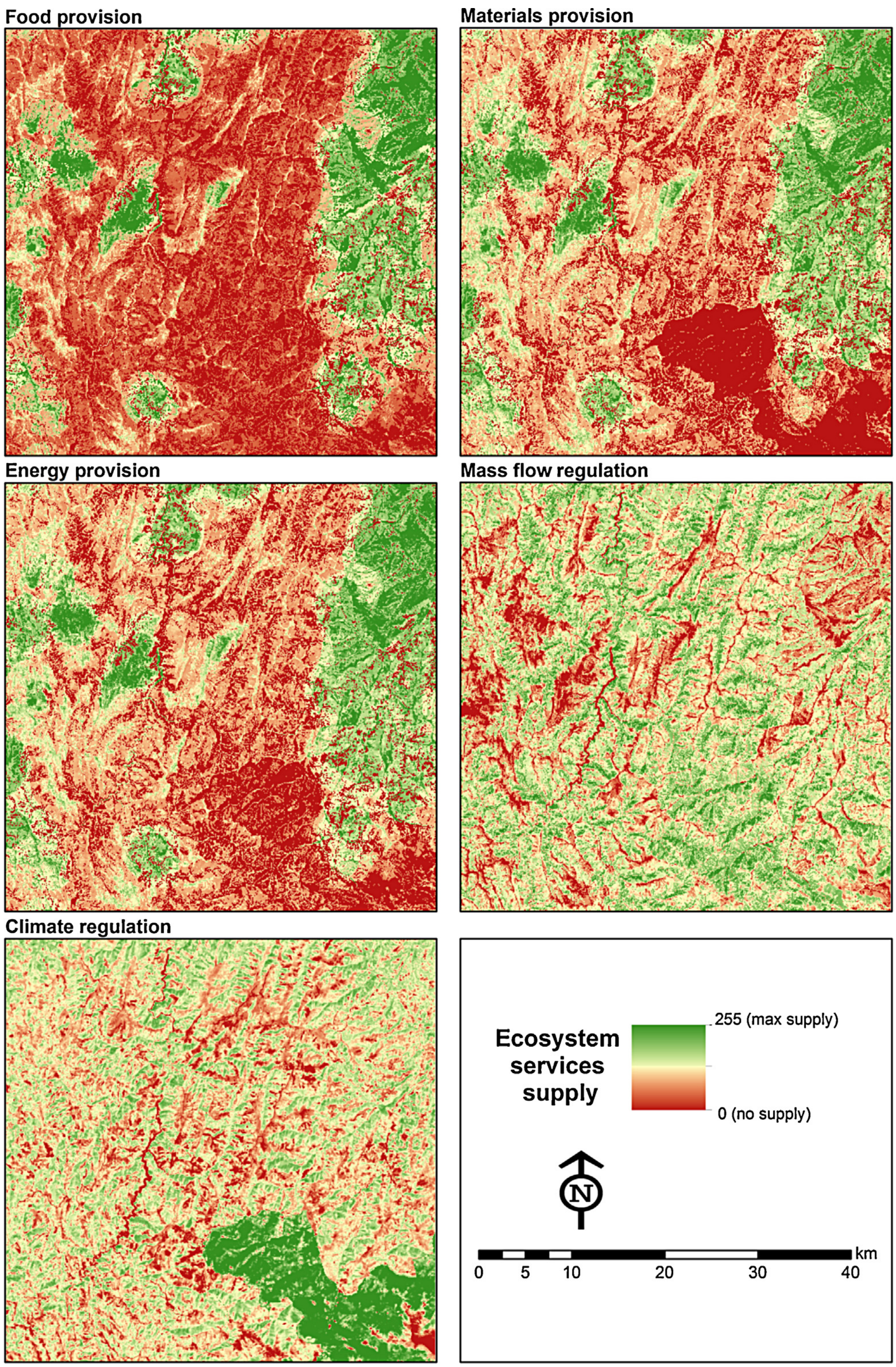


Fig. 4. Supply maps obtained for the five ecosystem services analyzed.

2.3.1. Lacunarity calculation

Lacunarity analysis of the five ES maps was performed in order to identify the characteristic spatial scales of each ecosystem service. Lacunarity can be considered as a measure of the heterogeneity or the texture of an object (Allain and Cloitre, 1991), and it has been extensively used in landscape ecology as a scale dependent metric for characterizing spatial patterns (Plotnick et al., 1993). In our study approach, it provides an estimation of the regularity of gap pattern in the ES supply maps, in this case corresponding to areas of no supply.

Lacunarity values were calculated for each window size, and these variables were then plotted in a bivariate graph, generating a curve for each ecosystem service. In these curves, we identified the window sizes linked to major changes in the slope (breakpoints) by comparing the change percentage of lacunarity value (vertical axis) with the percentage increase in the window size (horizontal axis). The minimum possible value of lacunarity metric is 1.

2.3.2. Quadrat variance analysis

As an alternative way of exploring the spatial pattern and identifying characteristic scales of the ecosystem services maps, we used four term local quadrat variance (4TLQV) analysis. This method consists of a two dimensional analysis of variance that divides a search window of a given size into four equal quadrants and compares the variance of the first with the variance with the three remaining quadrants. The value of 4TLQV changes as the window size increases, so that it is possible to plot both variables in a curve and to identify the characteristic spatial scales of the pattern analyzed as 4TLQV peaks (Dale, 1999). For a complete description of the method, see Dale (1999).

3. Results

3.1. Calculation of variables

Maps constructed with data from the four sources used for the ecosystem services calculation are shown in Fig. 3. The ΣNDVI map for the study area is represented in Fig. 3a, with values ranging from −377 (areas with low or null coverage of green vegetation throughout the year) to 377 (areas with high coverage of green vegetation throughout the year), as the time elapsed between the first and the last image was 377 days. This image represents an estimation of the spatial distribution of the amount of green biomass, and hence of potential productivity, in the study area. Despite the relatively even distribution of high and low values of this variable, low values are more frequent in some areas, such as the south east zone.

The slope map shows a clear dominance of steep slopes across the whole study area (slopes >30%), while relatively flat areas are confined to the lowest parts of valleys (Fig. 3b). The population distribution is shown in Fig. 3c, in which the highest densities of inhabitants are clustered in the NE zone (>65 inhabitants/km^2) while most of the area has fewer than 20 inhabitants/km^2. Finally, the protected areas layer (Fig. 3d) reflects the location of the Natural Park of Fuentes del Narcea, Degaña e Ibias, the only protected site in the study area.

3.2. Ecosystem services maps

Five ecosystem services maps were produced (Fig. 4) by overlaying the ΣNDVI map and the three mask layers affected by weighting factors (see Table 1). These maps show the supply capacity of each ES based on the biomass amount and the other variables considered: slope, population density and protected areas.

Use of these weighted mask layers for the three provisioning services (food, materials and energy) imply a relative reduction in the values in the areas with steeper slopes. In contrast, the mass flow regulation service yielded high values in steep slopes with a high risk of erosion, and low or even zero values in flat areas.

The maps of provisioning services (food, materials and energy) showed clustered patterns. Wide areas of no supply were more frequent in the central zone, while areas of high supply occurred in the east and west sides, where low slopes and high population densities occur. On the other hand, the regulating services (mass flows and climate) generally showed a non clustered pattern, with high and low values evenly distributed throughout the study area (with the exception of the climate regulation service) and high values within the protected area.

3.3. Differences in spatial patterns

The lacunarity analysis enabled quantitative assessment complementary to the visual interpretation of ES spatial pattern. The values of this metric and the curves generated by plotting this variable against different window sizes are shown in Table 2 and Fig. 5, respectively. Overall, the appearance of the five curves is similar, with the highest lacunarity values corresponding to the smallest window size (100 m) and a clear decrease for larger windows, which produce concave curves. The five curves have an asymptote close to the minimum value (i.e., 1).

In this study, the patterns corresponding to the provisioning services (i.e., supply of food, materials and energy) generally showed higher lacunarity values that were more closely clustered than for the regulating services. Food provision showed the highest lacunarity values (maximum of 2.1796 and mean of 1.3265) within the provisioning services, and the curve differed significantly in shape from the other curves. The values for supply of materials (maximum value, 1.7002 and mean value, 1.1746) and energy (maximum value, 1.6549 and mean value, 1.1522) were lower than for supply of food but still much higher than for regulating services. The provisioning services also reached a larger area of no supply

Table 2
Values of lacunarity and four term local quadrat variance (4TLQV) for the five ecosystem services analyzed.

		Food provision	Materials provision	Energy provision	Mass flow regulation	Climate regulation
Lacunarity	Maximum	2.1796	1.7002	1.6549	1.2707	1.2327
	Minimum	1.0629	1.0322	1.0270	1.0029	1.0072
	Mean	1.3265	1.1746	1.1522	1.0217	1.0394
	Breakpoint position (m)	3200–3300	2400–2500	2500–2600	2900–3000	2500–2600
4TLQV	Maximum	162553	170903	151774	44764	120430
	Minimum	1881	2473	2576	2022	1057
	Mean	104358	121748	103909	28126	64082
	Maximum position (m)	12000	14400	13000	21300	20900
Land surface with no ES supply (%)		28.65	28.26	26.29	8.06	2.37

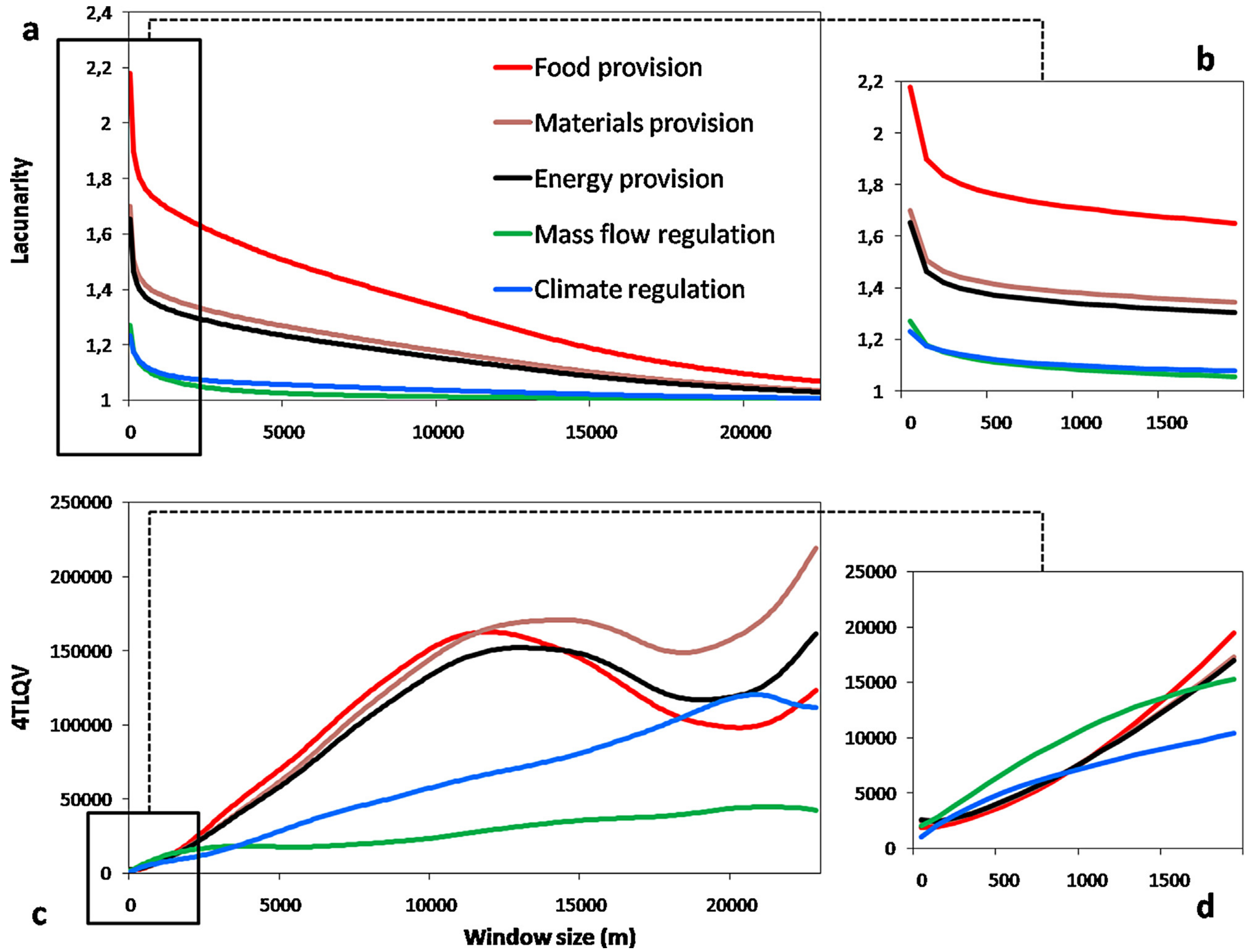


Fig. 5. Lacunarity curves (a and b) and 4TLQV (c and d) for the five ecosystem services with different ranges of windows size: 0–23,000 m (a and c) and 0–2000 m (b and d).

(>26%). Both regulating services (mass flow and climate regulation) that showed a small area of no supply in their patterns – 8.06 and 2.37% of study area – had the two lowest lacunarity values (maximum values of 1.2707 and 1.2327 and mean values of 1.0217 and 1.0394, respectively) and they were more widely scattered throughout the study area.

Despite the differences in lacunarity statistics and curves, the position of the breakpoints (i.e., window size values recording abrupt changes in slope of the lacunarity curves) was similar for all ecosystem services. Thus, the five curves showed a characteristic spatial scale of gaps around window sizes of 2400 and 3300 m, which are relatively small in comparison with the range tested (100–23,000 m). This means that lacunarity metric, and therefore the gap distribution is more scale-dependent for window sizes smaller than those breakpoints. For larger window sizes, the lacunarity values are independent of the scale, and the ES gaps are more homogeneously distributed.

The results of the 4TLQV for the five ecosystem services assessed are shown in Table 2 and Fig. 5. In general, the 4TLQV values increased more or less homogeneously from minimal levels in the smallest window sizes and then followed different patterns as the window size increased, depending on the particular ES considered. In any case, the curves for the provisioning services tended to be similar. The values reached a maximum of 162,553, 170,903 and 151,774 for food, materials and energy, respectively, for window sizes in the interval between 12,000 and 14,400 m. From these values onward, the curves tended to decrease although new relative increments and peaks appeared for the largest window size (23,000 m). The mass flow regulation service was associated with the lowest 4TLQV values and the flattest curve. In fact, the maximum value is three times lower than the maximum value of the other ecosystem services and corresponds to a relatively large window size (21,300 m). Finally, the curve for the climate regulation service showed intermediate values between the provisioning and mass flow regulation services, with a smoother and more gradual increase and a maximum value (1,20,430) for the relatively large window size of 20,900 m.

4. Discussion

The approach used in the present study was based on the use of the ΣNDVI indicator as a spatially explicit continuous variable to construct spatially explicit models of supply of five ecosystem services. Although similar approaches have not been widely used (see Konarska et al., 2002; Petrosillo et al., 2013), they are potentially useful (Ayanu et al., 2012; Burkhard et al., 2013) for avoiding the drawbacks involved and discussed in the use of LULC maps as ES proxies (Eigenbrod et al., 2010a,b; Frank et al., 2012; Koschke et al., 2012; Crossman et al., 2013; Hou et al., 2013; Kandziora et al., 2013), in relation to the effects on their spatial and thematic resolution by production processes (i.e., standardization, generalization or interpolation of data). The combination of the ΣNDVI with other variables influencing ES supply (i.e., population density, relief, protected areas) and filtering of the data on biomass spatial distribution yielded five maps showing important differences in ES supply.

The application of two methods of spatial analysis (lacunarity and 4TLQV) enabled recognition of different spatial patterns for the five ecosystem services analyzed. The maps obtained were highly heterogeneous from the spatial point of view, which enabled discrimination of the most important areas of ecosystem services supply. This reinforces the idea that the ecosystem service supply is not homogeneous across different landscapes and should not be considered as a static phenomenon (Fisher et al., 2009). Discrimination between supply and non-supply areas, at a particular scale for each ecosystem service, is a necessary condition for correct definition of ES flows (Syrbe and Walz, 2012). Specifically, in the present study, we found significant differences between the provisioning and the regulating services. Although breakpoints in the lacunarity curves can be found in a similar range of values (between 2400 and 3300 m), the lacunarity results showed higher mean and maximum values for food, materials and energy provision in comparison with mass flow and climate regulation (Fig. 5). The shape and slope of the curves also differ depending on the group of ecosystem services analyzed, and they therefore indicate different spatial distribution of supply. Thus, for the regulating services, a fine scaled, "self-similar" pattern can be detected in areas larger than the 2400–3300 m window. Self-similarity is identified in fractal geometry as the independence of scale in spatial data, so that one part of the object under study provides the same information as any other part (Iannaccone and Khokha, 1996). As the tendency for lacunarity values become saturated implies self-similarity, gap density patterns are reproduced similarly, regardless of window size, and consequently, of the scale. For both mass flow and climate regulation services, the highest lacunarity values correspond to fine local variations in spatial pattern, indicating that supply is not ensured at the finest scales (Fig. 5). However, once the breakpoints are reached, lacunarity tends to become saturated asymptotically (i.e., the pattern inside the considered window will be similar regardless of scale), while adopting low values (i.e., gaps do not compromise the connection of ES supply areas). Therefore, this can be interpreted as a guarantee of the spatial supply of the ecosystem service from the scales defined by the breakpoints onwards. For provisioning services, the trends in the lacunarity values are, nevertheless, different. Even when changes at the breakpoints indicated changes in the scale domains, the steep slope of the curves towards larger windows (i.e., scales), showing variations from 1.4 or 1.8 to almost 1.0, hardly reflect a self-similar pattern. Our previous findings enable these effects to be related to non-self-similar, coarse-grained irregular patterns in moving-windows analysis methods (Diaz-Varela et al., 2009).

Differences in the supply of provisioning services can be predicted from the compositional (i.e., unrelated to the spatial configuration) point of view, by considering the relative proportion of the supply areas. Maps of provisioning services show larger non-supply areas (>26%) than the regulating services (<8.1%). According to Plotnick et al. (1993), there is a relationship between the relative weight of the analyzed areas and the lacunarity results obtained. These results indicate high clustering in areas of provisioning services, consistent with the results of a similar approach developed by Roces-Díaz et al. (2014), in which the supply of the ecosystem services was analyzed by lacunarity and a set of landscape metrics.

The 4TLQV results provided a better understanding of the scale effects beyond the lacunarity breakpoints, and the spatial configuration of the ES supply. Thus, the spatial distribution of the quadrats captured the aforementioned clustered pattern for the provisioning services at its corresponding scale. The maximum 4TLQV values reached as the quadrats approach the spatial domain of the respective supply/non-supply clusters in food (quadrat size of approx 12,000 m), energy (approx. 14,000 m) and materials are shown in Fig. 5 (approx. 14,400 m; in Fig. 4, see also how supply vs. non-supply areas are spatially distributed). However, for the regulating services, the interpretation is different for both cases and also in relation to the provisioning services. Thus, mass flow regulation services reached a local maximum of around 3000 m (thus, corresponding to the fine-scale trend detected by the lacunarity analysis), and the absolute maximum close to the largest quadrat sizes. This may reflect the self-similar pattern previously revealed by the lacunarity analysis. In the case of the climate regulation service, a different pattern is shown, with a steady increase in 4TLQV values until the absolute maximum (120,430 at a window size of approx. 21,300 m), which is significantly lower than those obtained from the provisioning services. This may indicate the influence of the protected areas in the spatial configuration of ecosystem services, which occurs in the lower-right quarter of the image, thus making the data variance more evident in larger quadrats. These results are also consistent with previous findings in forest ecosystems in SE Spain, i.e., the concentration of provisioning services in specific zones and a more clustered pattern than regulating services, which were provided at larger-than-local scales (García-Nieto et al., 2013).

Nevertheless, one of the main limitations of the approach used is that those ES not related to biomass were not able to be analyzed. For example, cultural services (such as traditional knowledge, tourism, etc.) would need to be measured by integrating other types of variables not directly related to physical parameters, but to social ones, such as public opinions, viewpoints and feelings. For these variables, alternative ways of expressing the spatial explicitness and/or scales would be needed to make them comparable to other ES and supply schemes.

Another important element that places our findings in context is the consideration of spatial distribution of demand as a key issue for appropriate mapping of provisioning services (Burkhard et al., 2012). Thus, the lower spatial heterogeneity of regulating services may be related to their independence from the demand: they are provided directly from the ecological functioning of ecosystems and they do not depend on the needs of society. On the contrary, provisioning services are clustered in suitable areas for harvesting different products, such as food and timber, and they show large gaps in unfavorable areas. In our data, the provisioning services (food, materials and energy) were considered to depend on population distribution, and therefore, supply of these ecosystem services was higher around settled areas. In a similar way, we considered that the supply of ES also depends on terrain variables (slope) and on the presence of protected areas (related to the actual resources use) as potential constraints to or enhancements of the final ES supply value.

Some factors that are not related to the potential production of biomass – such as land use planning and integration in protected areas – may have a large influence on the effective supply of some ES, especially the provisioning services. Some parts of the study area are characterized by high levels of biomass (i.e., inside the Natural Park of Fuentes del Narcea, Degaña e Ibias), and therefore, forest harvest and plantations of exotic species such as *Eucalyptus* spp. are very limited. Thus, although our approach did not specifically analyze the demand, the combination of population density, terrain slope and protected areas provided information that complements the assessment of ES supply and plays an important role in the spatial analysis of ecosystem services and in practice as a proxy or surrogate for such demands. In fact, the demands for ecosystem services can be characterized by similar approaches, such as population data, preferences of society and distance to resources (Schägner et al., 2013).

Finally, and taking into account that the selection of suitable scale is a key issue in ecosystem services assessments from a spatial point of view (Hauck et al., 2013), the five ES studied showed important variance peaks within the spatial range used for the analysis (below 23,000 m). This suggests that the ideal study area for the analysis of ecosystem services supply at a regional scale should be of side larger than at least 20–25 km to maximize capture of any possible variance.

5. Conclusions

The method developed in this study, which is a quantitative approach based on the use of remotely sensed (RS) data, proved useful for the detection of the supply of five ecosystem services related to biomass production: food provision, materials provision, energy provision, mass flow regulation and climate regulation. Specific models for each ES were developed by integrating ΣNDVI spatial data (i.e., an index derived from RS that acts as a useful indicator of the amount of biomass) with terrain slope, human population density and protected areas. The method yielded spatial models representing supply scenarios for five different ecosystem services, while avoiding possible uncertainties, such as those inherent in Land Use/Land Cover data (i.e., generalization of ecosystem types in the study area and the assumption of invariance across spatial scales).

The use of lacunarity and 4TLQV for spatial analysis of the models enabled us to establish differences between these five models by the detection of characteristic spatial patterns as well as scales. Specifically, lacunarity analysis was useful for detecting scale thresholds at the local level and for indicating whether the scale domains imply self-similarity in the supply pattern. However, 4TLQV was more sensitive to scale thresholds at larger spatial levels. The results obtained for each ES would be useful for determining the capacity of a region to supply the ecosystem service at specific locations and scales. For instance, provisioning services were variable in their supply, probably because of the relationship between their spatial distribution and human activities, making it difficult to guarantee their provision at multiple local sites. Conversely, regulating services, related to ecosystems affected by different degrees of anthropogenic influence, are represented by fine-scaled patterns.

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Use of forest data to analyze the potential supply of forest ecosystem services and their spatial relationships in NW Spain.

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Corresponding Author: Mr. JOSE VALENTIN ROCES-DIAZ,
Corresponding Author's Institution: University of Oviedo.
First Author: JOSE VALENTIN ROCES-DIAZ.
Order of Authors: JOSE VALENTIN ROCES-DIAZ; Benjamin Burkhard; Marion Kruse; Felix Müller; Emilio R. Díaz-Varela; Pedro Álvarez-Álvarez.

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Use of detailed forest data to analyze the potential supply of forest ecosystem services and their spatial relationships in NW Spain

Jose V. Roces-Díaz[1]*, Benjamin Burkhard[2,3], Marion Kruse[2], Felix Müller[2], Emilio R. Díaz-Varela[4], Pedro Álvarez-Álvarez[1]

1: GIS-Forest Research Group. Department of Organisms and Systems Biology. University of Oviedo. Polytechnic School of Mieres, 33600 Mieres, Spain.
2: Institute for Natural Resource Conservation, University of Kiel, Olshausenstraße 75, 24118 Kiel, Germany.
3: Leibniz Centre for Agricultural Landscape Research ZALF, Eberswalder Straße 84, 15374 Müncheberg, Germany.
4. Department of Agriculture and Forestry Engineering. University of Santiago de Compostela. Campus Universitario, s/n 27002 Lugo, Spain.

(* Corresponding Author: e-mail: jvroces@gmail.com. GIS-Forest Research Group. Department of Organisms and Systems Biology. Polytechnic School of Mieres. 33600. Mieres. Asturias. Spain).

Highlights

- We analyzed the potential supply of six ecosystem services associated with forests.
- We used a high detailed forest database to analyze the potential supply of ecosystem services.
- We performed a multi-scale spatial analysis of the potential supply of ecosystem services.
- We studied the spatial relationships between services and the presence of hotspots.

Keywords

Forest ecosystem services; European Atlantic Region; Spatial analysis; Multi-scale analysis; Hotspots; Coldspots

Abstract

Forests are extremely important terrestrial ecosystems regarding their capacity to provide goods and services to society. Nevertheless, this potential strongly depends on the type of forest and on the management applied. In this study, we used a high detailed forest map to assess some ecosystem services (ES) closely associated with forest ecosystems in the northwestern Iberian Peninsula. The following ES were considered: i) provision of food (basically fruits); ii) provision of materials (mainly timber and pulp); iii) provision of biomass for energy (firewood); iv) climate regulation (carbon storage by aboveground forest biomass); v) erosion regulation (protection against erosion by forest cover); and vi) cultural (recreational use and nature tourism). By combining information on tree species and cover (Spanish National Forest Map) with forest harvest data and other statistics (National Forest Inventory), we established representative models for the six ES. For this purpose, spatial grids of 25x25 m of resolution representing different categories of potential supply of each ES were established. The six models of ES provision were analyzed by spatial statistics (Moran's I and Getis-Ord Gi*), thus enabling detection of hotspots and coldspots and the characteristic spatial scales for ES supply. The combined use of highly detailed map data, non-spatial databases and spatial analysis yielded accurate ES supply data and constitutes a highly promising approach for spatial planning and forest management.

1. Introduction

During recent years, the concept of ecosystem services (ES) has become of increasing importance in different fields of landscape ecology, environmental management and land use planning. These topics have been addressed in many articles and research projects (e.g. MEA, 2005; EME, 2011; Seppelt et al., 2011; Schägner et al., 2013). ES studies are performed at multiple spatial and temporal scales and involve different ecological zones and ecosystem types. Forests are terrestrial ecosystems of particular importance for ES supply because of the large surface area that they cover, the high biodiversity they incorporate and the multiple ES they supply. Their importance as ES providers has been highlighted by different authors (e.g. Turner et al., 2007; Patterson and Coelho, 2009; Harrison et al., 2010). Among the wide range of forest ecosystem services (FES) identified, those associated with habitat maintenance, provision of materials and energy, regulation of climate, erosion, flood and biological cycles and also with cultural services, such as recreation, aesthetic values and traditional knowledge, are of particular importance (Naidoo et al., 2008; Dunker et al., 2012; Gamfeldt et al., 2013; García-Nieto et al., 2013). For quantification and assessment of ES, it is important to differentiate between potential ES supply (the capacity of a spatial unit to provide a specific ES in a certain time period) and ES flow (the actual amount of a specific ES used; Burkhard et al., 2014). In order to integrate ES assessment with land use planning and management tools, several authors have focused on spatial analysis of ES. This has led to the development of applied conceptual frameworks that have improved methods of ES mapping, modelling and spatial analysis (i.e. Maes et al., 2012; Crossman et al., 2013; Mouchet et al., 2014). Spatial aspects such synergy and trade-offs between different types of ES, e.g. between provisioning services and regulating or cultural services (García-Nieto et al., 2013; Martín-López et al., 2014), and their relationships with biodiversity and landscape heterogeneity (Turner et al., 2013; Anderson et al., 2014) should be considered in land use planning. Identification of areas with high or low ES supply (hotspots or coldspots) is key to developing ES-based land use policies and related environmental management policies (Egoh et al., 2008).

ES mapping studies have focused on the spatial scale of the analyses and the types of data used as relevant elements (Hauck et al., 2013). Land Use/Land Cover (LULC) data are often used to map and analyze ES supply. However, there are some uncertainties associated with ES mapping approaches based only on LULC data (Hou et al., 2013). For example, the transfer of sampled point data to larger spatial units such as LULC types leads to generalizations for the whole study area. In reality, ES supply does not take place homogeneously within a LULC type or across different spatial scales (Eigenbrod et al., 2010). However, some authors have suggested that different ES display characteristic supply patterns on different spatial scales (Martin-López et al., 2009; Roces-Díaz et al. 2014a) because they depend on specific ecological processes.

In addition to LULC or ecological processes on large spatial scales, some ES are associated with structural landscape elements such as corridors and habitat patches. Such elements normally cover small areas or are fragmented in small patches. Therefore, the spatial resolution of the geographic database used for ES assessment should enable identification of these (Kandziora et al., 2013). The thematic resolution of the spatial database (e.g. the number of LULC types or soil types) may also affect the results, especially when the number of attributes does not sufficiently reflect the spatial peculiarities of the study area. This is also important for landscape pattern analysis (Bailey et al., 2007). Some LULC data, such as the European CORINE Land Cover[1] (CLC), include different ecosystem types within one class. This is the case

[1] http://www.eea.europa.eu/data-and-maps/figures/corine-land-cover-types-2006

for the CLC type *3.1.1. Broadleaved forest,* which includes different types of forest ecosystems with distinct species composition and spatial structure such as forest native woodlands and plantations of exotic broadleaved species, which also provide different ES (Rodriguez-Loinaz et al., 2013).

We identified similar issues in the study area, i.e. the Northwest Iberian Peninsula. From the point of view of climate, there is a high potential productivity in the area, especially in low-altitude areas (Benavides et al., 2009). Although the area spans less than 10% of the total surface area of Spain, it provides 60% of the annual Spanish timber harvest volume (MAGRAMA, 2013a). This is basically provided by plantations of *Eucalyptus* spp. and *Pinus* spp. These plantations have increased in importance since the second half of the 20th century (Teixido et al., 2010) and have significantly altered the configuration of the traditional agroforestry landscape in the area (Saura and Carballal, 2004). These forest ecosystems are based on an intensive management system aimed at the provision of selected forest products such as timber and pulp for paper production. Consequently, the ES supply is very different from that supplied by native forests in the area, such as *Quercus* spp. and *Fagus sylvatica* L. (Onaindia et al., 2013; Rodriguez-Loinaz et al., 2013).

Accurate information and data are needed to identify and quantify FES supplied by different systems. In this study, we used the Spanish National Forest Map 1:25,000 (MAGRAMA, 2013b), which provides information such as the species and cover for each spatial unit of the database. Sustainable forest planning, forest resource management and biodiversity conservation are based on the integration of various spatial and thematic ecosystem aspects (García-Nieto et al., 2013; Onaindia et al., 2013). By analyzing these aspects in different forest ecosystems, synergy and trade-offs between different FES can be identified, quantified and assessed in relation to the type of management applied (Dunker et al., 2012).

Thus, the objectives of this study were as follows:

i) to test the potential of a detailed spatial forest dataset with high spatial resolution and including detailed information about tree species composition and tree cover, to quantify the potential supply of six forest ecosystem services; and

ii) to analyze the spatial distribution of FES supply and detect major hotspots and coldspots at different scales.

2. Materials and Methods

Figure 1 shows a conceptual diagram of the workflow involved in this study, including data collection, ES selection and assessment, data analysis and map production. The ES potential supply was assessed by a combination of expert assessment, forest statistics and literature sources.

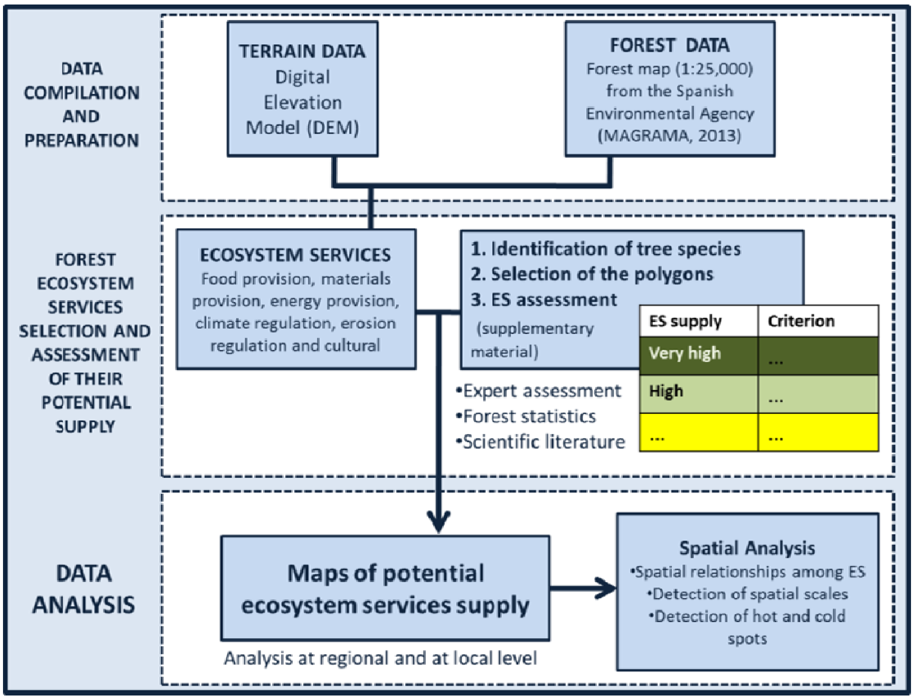

Figure 1. Conceptual diagram of the workflow, data sources, selected ES and analysis involved in this study.

2.1. Study area

The study was carried out in NW Spain, in the Autonomous Communities of Asturias and Galicia, which are located in the European Atlantic Region (EEA 2011). These Autonomous Communities comprise 63% of the Atlantic Region in the Iberian Peninsula (Figure 2). The study region covers an area of 40,200 km^2, of which approximately 40% comprises forest land. The elevation ranges between 0 to more than 2500 m and the terrain is rugged, especially in the eastern zone. The climate is oceanic throughout most of the area, and the mean precipitation exceeds 1000 mm/year (Ninyerola et al., 2005). Although the amount of precipitation is decreasing in summer, physiological drought only occurs in an area of approximately 5,000 km^2 in the SW part of the study area, which is within the Mediterranean climate region. This zone is one of the most densely forested regions in Spain (MAGRAMA 2013a). During the last century, human activities have greatly transformed the most easily accessible areas at low and medium elevations (< 1000 m). Much of the low-lying land is used to produce fast growing species such as *Eucalyptus* spp. and *Pinus* spp. for timber production. Remnants of natural forests with *Fagus sylvatica*, *Betula* spp. and *Quercus* spp. as the main species can still be found in this area (Roces-Díaz et al, 2014b). However, these forests are more abundant in the mountainous zones than in low-lying areas (García et al., 2005). These forest ecosystems are often scattered within habitats associated with livestock use, such as meadows and heathlands. The timberline is represented by deciduous forest and rarely exceeds an elevation of 1700 m (Díaz and Fernandez-Prieto 1987).

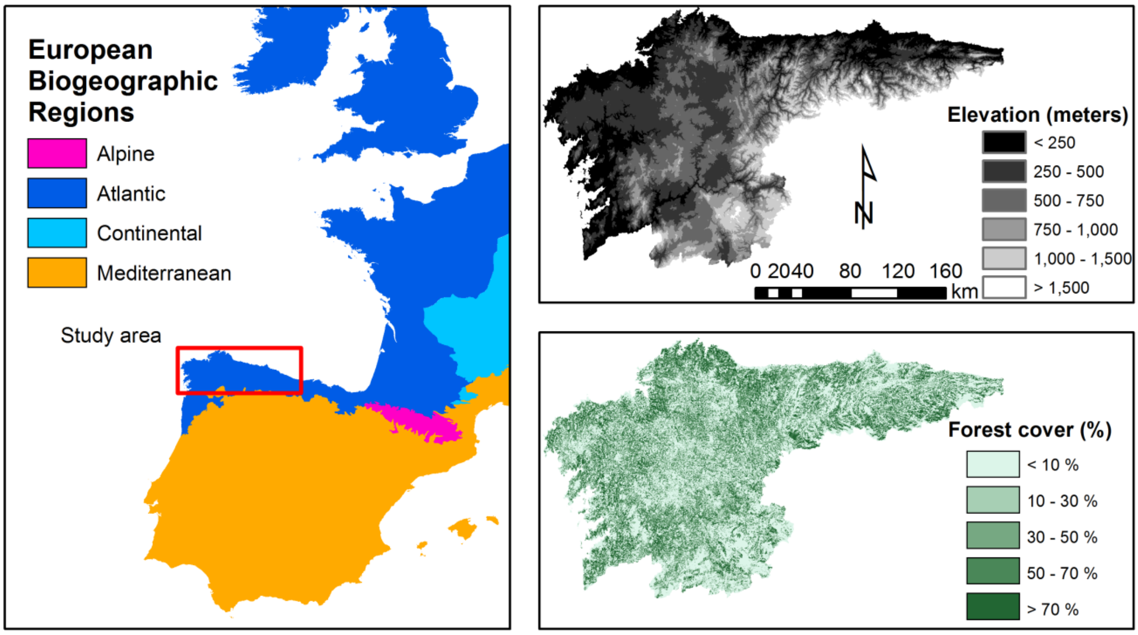

Figure 2: Location and biogeographical classification of the study area (left; based on EEA, 2011). Digital elevation model (top right; take from IGN, 2013) and forest cover (below right; based on the Spanish National Forest Map (MAGRAMA, 2013b).

2.2. Data sources

2.2.1. Forest database

The main data source used in this study was the Spanish National Forest Map (1:25,000), constructed and provided by the Spanish Environmental Agency (MAGRAMA, 2013b). The map is based on data collected over a period of six years (2007-2012) and work including the digitizing of ortho-photographs of the study area. Homogeneously-occurring spatial features were digitized by focusing on forest features and with a minimum mapping unit of 1 ha for forest areas. After digital definition of these features, different forest characteristics (including the identification of species and their coverage) were assigned and confirmed by field sampling.

The spatial databases of five zones (the provinces of A Coruña, Asturias, Lugo, Ourense and Pontevedra) of the forest map were merged in an ArcGIS shape file that finally contained 129,556 individual polygon features. Information about the three main forest species (SP_i code), their cover (% of the total area within the polygon) and the sum of different plant cover in the patch (% of total patch area) was attributed to each polygon.

2.2.2. Selection of ecosystem services

The potential supply of six forest ecosystem services (FES) was analyzed. The FES were selected from the most extensive types of ES classification (i.e. MEA, 2005; Haines-Young and Potschin, 2013), considering their representativeness and specific importance to the study area. The following six FES were considered: i) provision of food (basically fruits from forest species); ii) provision of materials (mainly timber and pulp); iii) provision of biomass for energy (firewood for domestic use); iv) climate regulation (carbon storage by aboveground forest biomass); v) erosion regulation (protection against erosion by forest cover); and vi) cultural (including aspects such as recreational use and nature tourism).

2.2.3. Assessment of potential ES supply

For each FES, the individual potential supply was assessed on the basis of three data sources: i) forest statistics for the study region, ii) scientific literature, and iii) expert criterion. The expert criterion was used to complement the assessment of some ES, for which data were otherwise difficult to obtain. Basically, we identified which of the species from the whole database have the potential to supply each FES in each patch (polygon). On the basis of the three above-mentioned data sources, the selected polygons were classified in six categories of potential FES supply: no (relevant) supply, very low, low, intermediate, high and very high FES supply. The method and the assignment of classes ("matrix method") have previously been described (Burkhard et al., 2009; 2012). For example, for food provision, the forest tree species that could provide fruits for human consumption (i.e. 11 tree species) were first identified. Patches where these specific tree species were present were then identified and classified according to their spatial cover (%) within the six potential ES supply classes. For provision of materials, species that have often been harvested during the last 25 years were identified using forest statistics for the area. The polygons covered by these species were then assigned to the 6 potential FES supply classes. Specific information about the classification of potential supply capacities of each of the six selected FES, the different criteria and data used are provided in the Supplementary material (Appendix A).

2.3. Analytical methods

For each FES, a map of the potential supply was created. Each of the six maps were then analyzed at 1) regional and 2) local spatial levels.

2.3.1. Analysis at regional level

The spatial relationships between the different FES were analyzed by using a sample of 12,000 points that were randomly distributed over the whole study area. The spatial autocorrelation of each FES was analyzed using Moran´s I coefficient (Eq.1; Moran, 1948; ESRI, 2013a).

$$I = \frac{n}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{i,j}} \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{i,j} z_i z_j}{\sum_{i=1}^{n} z_i^2} \qquad \text{Eq.1.}$$

where n is the number of features (points); $w_{i,j}$ is the distance between the features i and j; z_i is the deviation of the attribute (here the potential supply of each FES) from feature *i* from the mean value.

The coefficient indicates the variation in values of one variable, in this case the potential supply of each ES, based on the distance between the elements (here the points of ES supply) of a landscape inside the study area. As a result, Moran´s I enables classification of the spatial patterns of the points on the basis of the degree of clustering or dispersion that the values of potential supply of the ES show. This index can vary from -1 (highly negative spatial autocorrelation) to +1 (highly positive autocorrelation). In the next step, the Spearman correlation coefficients between these points were calculated for the six ES. In order to explore the characteristic spatial scales of each ES supply pattern, the incremental spatial autocorrelation (ISA) for the 12,000 points sample was calculated. The ISA runs the Moran´s I for a series of increasing windows sizes, measuring the intensity of spatial clustering for each size. It thus measures autocorrelations for a range of distances. The Z-scores for Moran´s I reflect the intensity of the spatial clustering for each value of the range of scales used (between 5,000 and 150,000 m, Eq.2).

$$Z_I = \frac{I - E[I]}{\sqrt{E[I^2] - E[I]^2}} \qquad \text{Eq.2}$$

where *I* is the Moran´s coefficient and *E[I]* is (Eq.3):

$$E[I] = \frac{-1}{n-1} \qquad \text{Eq. 3}$$

where n is the number of features.

The curve for the Z_I-scores (vertical axis) and the window sizes (horizontal axis) shows peaks that indicate distances where the spatial processes of clustering are most pronounced: this enables detection of the spatial scales at which the clustering based on Moran’s I took place.

In order to identify areas of high and low FES supply (respectively hotspots and coldspots) in each FES map, the Getis-Ord Gi* statistic (Getis and Ord, 1992; Ord and Getis, 1995; ESRI, 2013b) was calculated (Eq.4).

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \left[\frac{\sum_{j=1}^{n} x_j}{n}\right] \sum_{j=1}^{n} w_{i,j}}{S \sqrt{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}}} \qquad \text{Eq.4}$$

where n is the number of features; $w_{i,j}$ is the distance between the features i and j; x_j is the value of potential supply of the ES, and S is calculated as follows (Eq.5):

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - \left[\frac{\sum_{j=1}^{n} x_j}{n}\right]^2} \qquad \text{Eq.5}$$

For a given dataset, the Getis-Ord Gi* statistic identifies those clusters of spatial features with values (of potential FES supply) higher (or lower) of those expected to be found by random chance (ESRI, 2013b). The output of the Gi* is a Z-score for each feature that represents the statistical significance of clustering for a specified distance. Higher Z-scores indicate higher intensity of feature value (FES supply) clustering and hotspots of FES supply. Negative Z-scores indicate clusters with low FES supply values (coldspots). The analyses were performed using ArcGIS 10.1 spatial statistic tools.

2.3.2. Analysis at local level

Finally, the six FES were analyzed at local level for the 393 municipalities in the study area. Administrative units are often used as spatial references in official statistics and play an important role in planning and decision-making processes. It was therefore important to analyze how the spatial distribution of FES supply is represented at the basic levels of spatial administration. For this purpose, each cell was assigned a value between 0 (no (relevant) potential supply) and 5 (very high potential supply). The values of the cells for each municipality were summed to produce a map with the classification of potential FES supply within the municipal spatial limits of the area. The Getis-Ord Gi* statistic was calculated (as described above) for each FES to detect clusters of municipalities with high (hotspots) or low (coldspots) levels of potential FES supply.

3. Results

3.1. Maps of potential supply of forest ecosystem services

The maps in Figure 3 show the potential supply of the six selected FES. The maps show the spatial supply pattern of each FES in the study area compiled at a comparably high spatial resolution of 1:25,000. The differences in the no (relevant) potential supply areas for each FES were noteworthy. These zones are larger for some FES, such as food provision and cultural FES, and smaller for others, especially for erosion regulation. Most of the areas supplying food are in the central and eastern parts of the study area. The zones with no (relevant) potential supply of food provision cover 88.8% of the study area, while such zones cover between 0.1 and 4.5% for the five remaining classes (see Figure 3). The zones with a high and very high potential supply of materials provision services comprise 20.6% of the study area and they are mainly located on areas close to the coast, especially in central and western areas. The energy provision and climate regulation services show a similar pattern, with smaller areas of no (relevant) supply (53.5% for both FES) and a broader distribution over the study area. For these two FES, the zones with medium, high and very high potential FES supply make up more than 25% of the whole area. Erosion regulation shows a quite different pattern from the other FES. No (relevant) supply areas are found in only 9.6% of the area, mainly in the western part. More than 75% of the area was covered by the intermediate, high and very high potential erosion regulation FES supply areas. Finally, cultural FES included large zones of no (relevant) supply (67.3% of the study area). Zones of intermediate, high and very high cultural FES supply together comprise 28.6% of the area and are mainly located in mountainous areas away from coastal zones

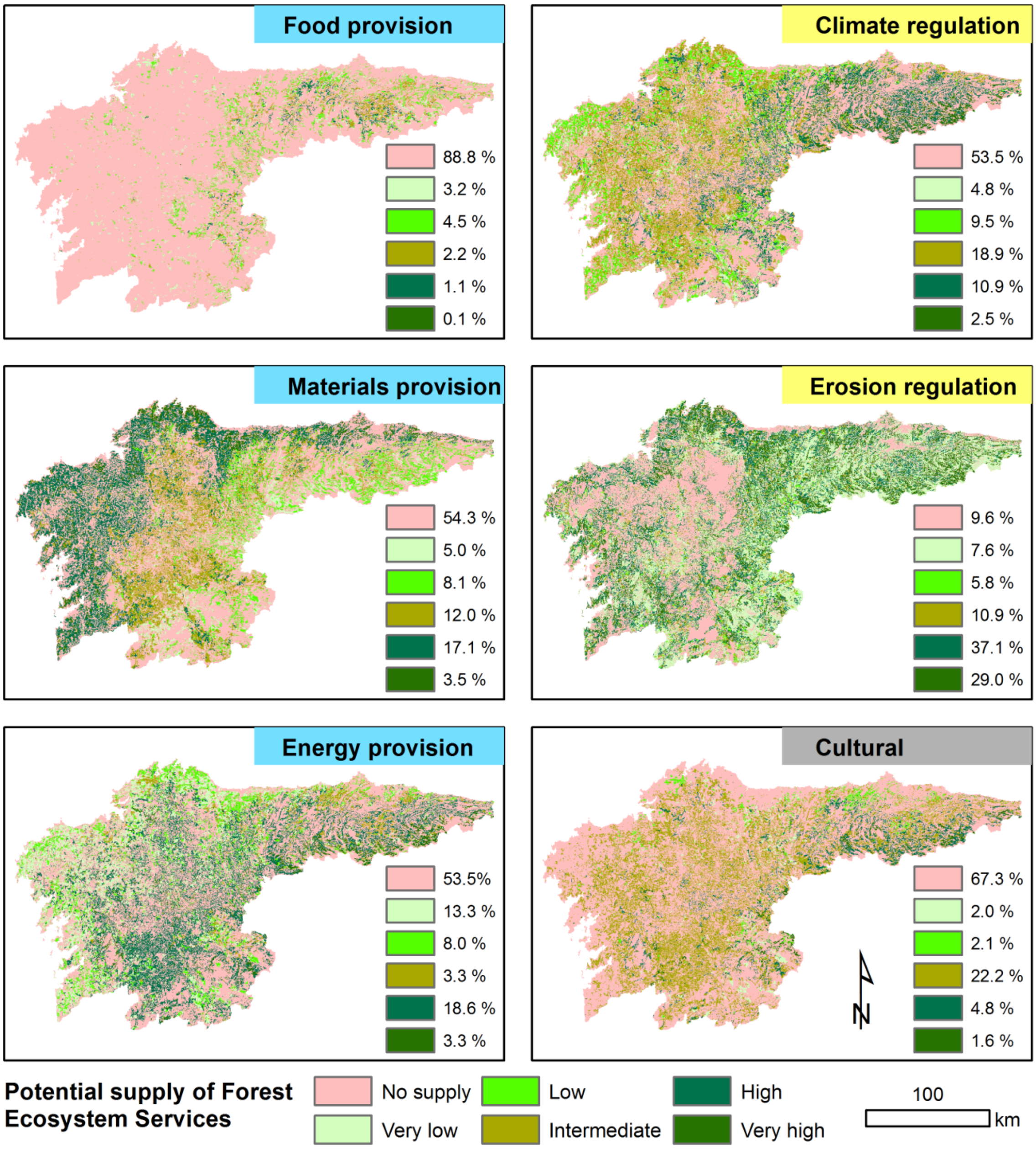

Figure 3. Maps of potential supply of forest ecosystem services. The values represent the percentage of the total study area covered by each potential FES supply class.

3.2. Regional analysis

Spatial autocorrelation analysis with the Moran´s I coefficient shows comparable results for the six FES. All display a clustered pattern and positive spatial autocorrelation (Table 1). This indicates that the supply of these FES is not randomly distributed and that it may correspond to specific spatial processes, both natural (elevation, hydrologic pattern) and anthropogenic (land management). The potential supply of each polygon seems to be more closely related to the values of the nearby polygons than to the values of the remaining features. All FES show Moran´s Index values between 0.08 and 0.18, with Z-scores higher than 39 and a p value of 0.

Table 1. Values of Spatial autocorrelation analysis with Moran´s I coefficient.

Ecosystem Service	Moran´s Index	Z-score	P value	Type of pattern
Food provision	0.18	86.85	0.00	Clustered
Materials provision	0.17	80.94	0.00	Clustered
Energy provision	0.08	39.39	0.00	Clustered
Climate regulation	0.08	40.26	0.00	Clustered
Erosion regulation	0.12	61.06	0.00	Clustered
Cultural	0.10	50.97	0.00	Clustered

Table 2 shows the Spearman correlation coefficients between the supply values for the sample. All FES are positively and significantly correlated (at $P< 0.01$). The correlation values varied from 0.27 (food vs. materials provision) to 0.96 (energy provision vs. climate regulation). For example, correlations for food provision were lower than 0.56 for the remaining five FES. Materials provision was highly correlated with energy provision (0.82) and climate regulation (0.85). Energy provision was closely correlated with materials provision (0.82), climate regulation (0.96) and cultural FES (0.86). Finally, cultural services were highly correlated only with energy provision (0.86) and climate regulation (0.84).

Table 2. Correlation coefficients for the potential supply of the six FES (data of the 12,000 points sample).

FES	Materials provision	Energy provision	Climate regulation	Erosion regulation	Cultural
Food provision	0.27	0.46	0.56	0.31	0.50
Materials provision	-	**0.82**	**0.85**	0.42	0.55
Energy provision	-	-	**0.96**	0.48	**0.86**
Climate regulation	-	-	-	0.50	**0.84**
Erosion regulation	-	-	-	-	0.40

The results of the incremental spatial autocorrelation method enabled identification of different spatial patterns and characteristic scales of FES supply. Figure 4 shows the values of the Z_I-score (vertical axis) of the Moran´s I coefficient for different window sizes, which delimit a spatial domain definable as the characteristic scale at which the FES is provided (horizontal axis, from 5,000 to 150,000 m). None of the curves shows a clear peak on the range of distances analyzed. The food and materials provision services show similar curves until a spatial domain defined by a window of 20.000 m. From this window size onwards, food provision has higher values and does not show a clear peak, while materials provision has a small peak at 95,000 m. The curves for the remaining FES have lower values, with a small increase for the smallest windows and a flat shape for larger sizes. Thus, the curves for cultural services and erosion regulation are of similar shape for sizes smaller than 35,000 m, while the curves for energy provision and climate regulation have similar shapes up to 75,000 m.

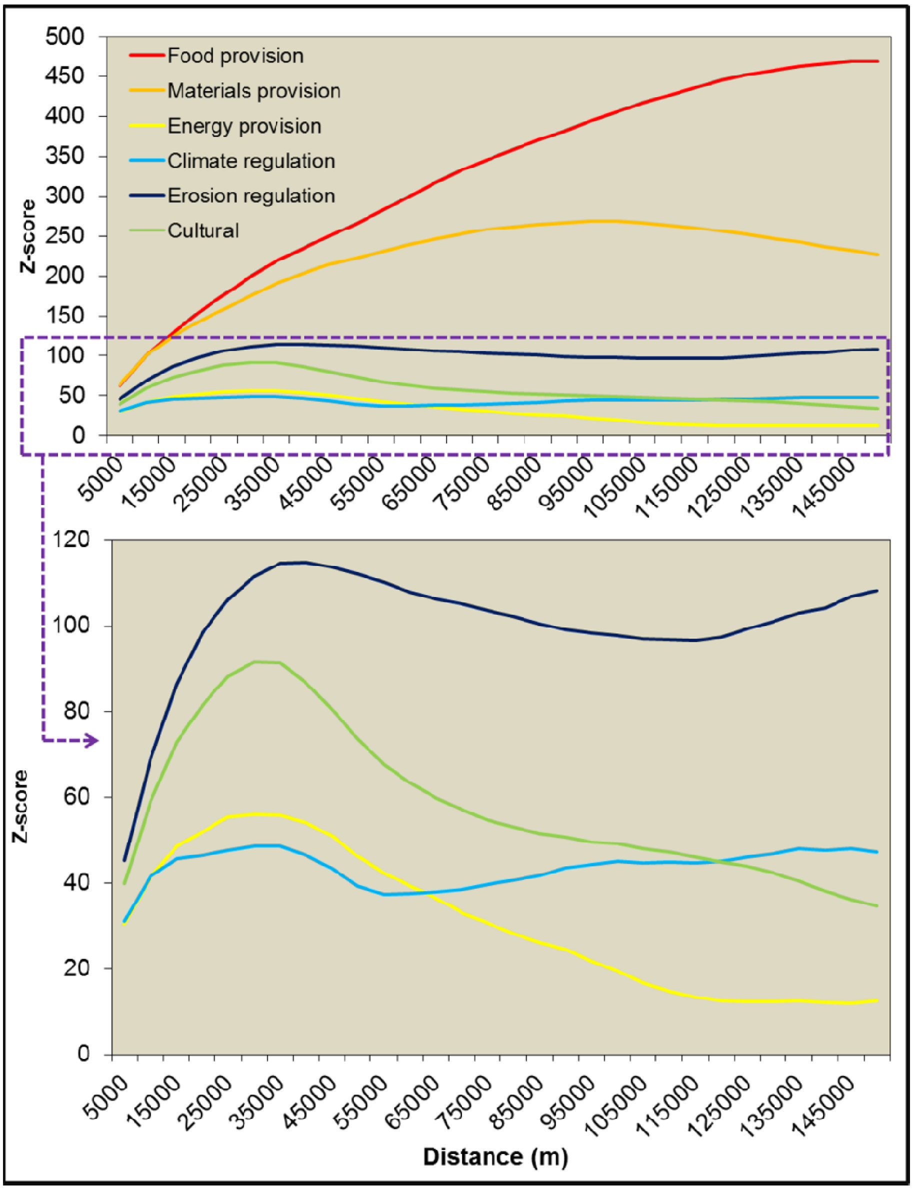

Figure 4. Curves of incremental spatial autocorrelation analysis for the potential supply of the six ES (data representing the sample of 12,000 points).

Finally, calculation of the Getis-Ord Gi* statistic enabled identification of hot and coldspots of the potential supply of each FES (Figure 5). Hot/coldspots are zones with spatial clustering of features with high/low values of FES supply. They show different spatial distributions for the six ES. For example, hotspots of food provision are clustered in the central and eastern zone, whereas there is a very large coldspot area in almost the whole western part of the study area. Materials provision hotspots appear on the coast of the central and western zone. Energy provision, climate regulation and cultural services show similar distributions, and finally, the erosion regulation service shows hotspots in the eastern part of the study area, distributed following the direction of the Cantabrian Mountains.

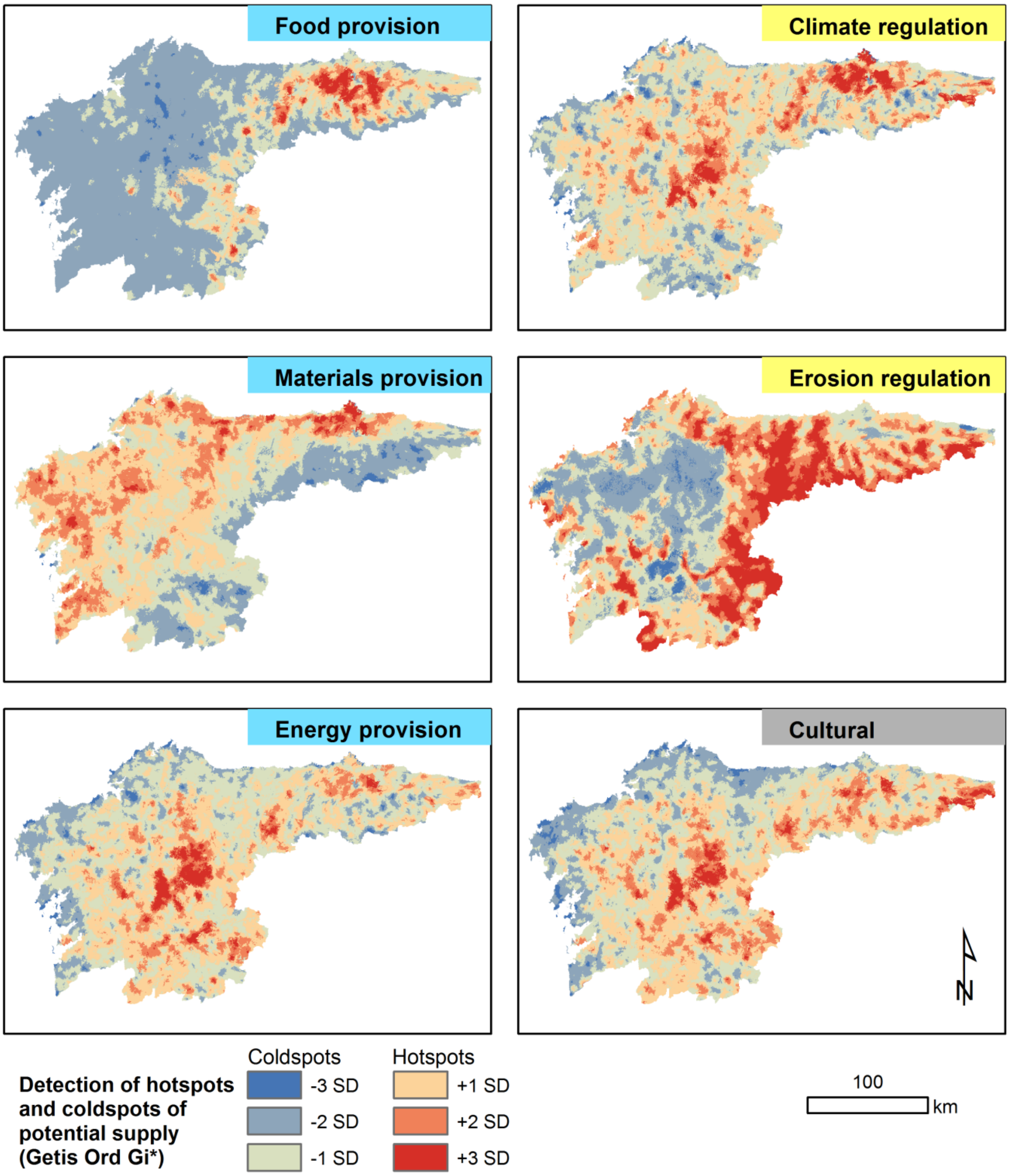

Figure 5. Maps of hotspots (red color; +1, +2 and +3) and coldspots (blue color; -1, -2 and -3) of potential FES supply based on standard deviation of Getis-Ord Gi* statstic.

3.3. Local analysis

Analysis of the potential supply of the six forest ecosystem services in the 393 municipalities in the study area yielded different results from those obtained at regional level. The local level analysis shows the differences in the spatial distribution of the FES. Nevertheless, it is apparent that the extent of the administrative units influences the results, with higher values obtained in the largest municipalities (Figure 6). For food provision, the municipalities with highest values are located in the eastern areas, where respective hotspots are also located. The western zones comprise a large coldspot.

The highest values for materials provision (and corresponding hotspots) occur in zones close to the coast. The remaining four FES show a similar pattern, and the municipalities with highest values of FES supply occur in inland zones of the eastern half and the hotspots are basically located in the zone comprising the Cantabrian Mountains.

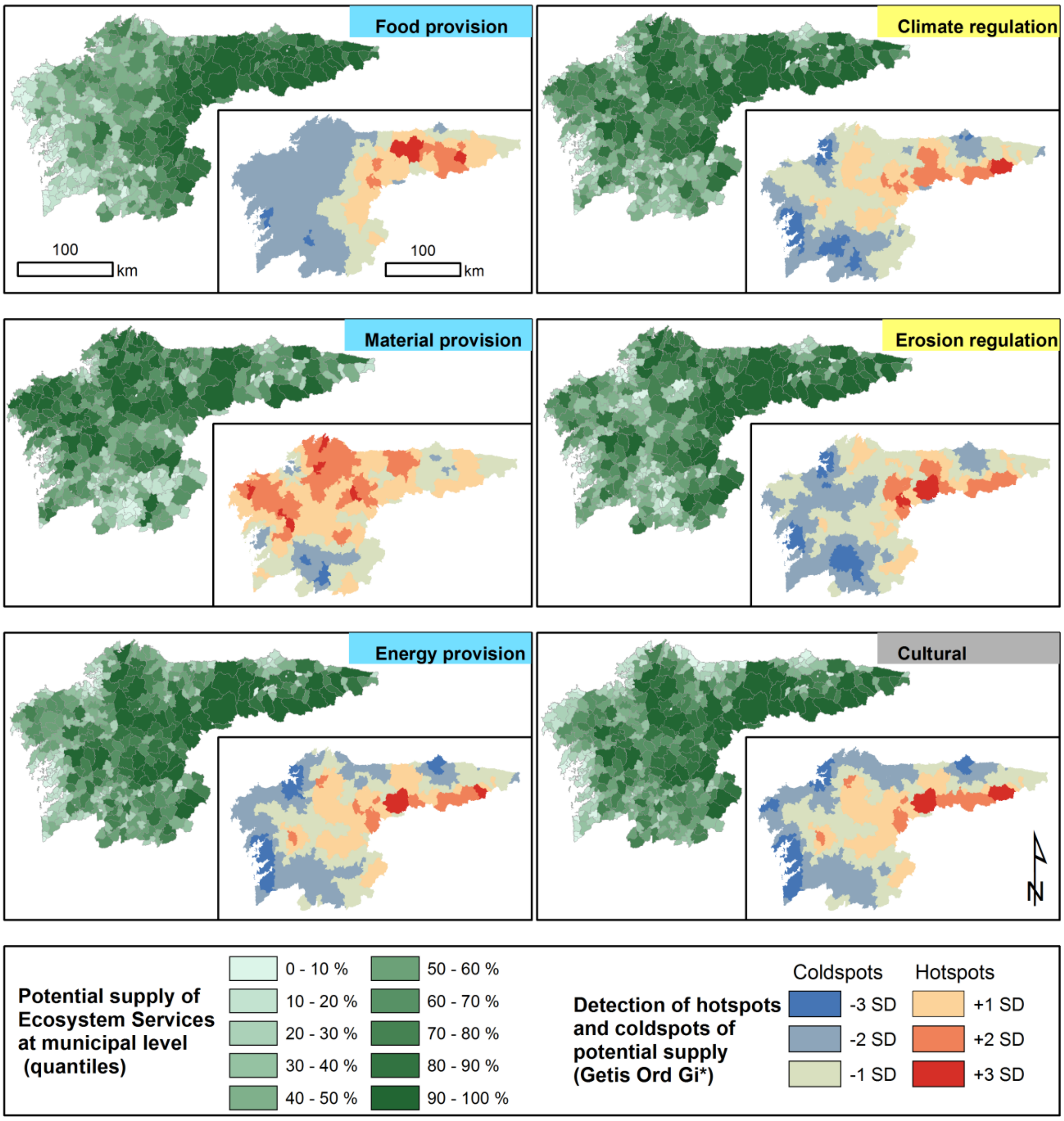

Figure 6. Maps of sum of potential supply of forest ecosystem services by municipalities (different shades of green) and detection of hotspots (different shades of red; +1, +2 and +3) and coldspots (different shades of blue; -1, -2 and -3) of potential FES supply based on standard deviation of the Getis-Ord Gi* statistic.

4. Discussion

Highly detailed cartographic information about forest ecosystems in the northwest of the Iberian Peninsula was used in this study to estimate the potential supply and spatial distribution of six FES. The characteristics of the data were essential for ensuring the quality of the results obtained. The data include precise information about the structural characteristics of forest features. In addition to the type of forest, each map polygon contains information about the tree species composition and cover. This information enhances the data analysis and interpretation compared with ES mapping based solely on land cover data. In addition to the higher thematic resolution, the spatial resolution is also high. The data were mapped at a scale of 1:25.000, with a minimum mapping unit of 1 ha for forest areas. When using these forest data as a basis for the identification of ecosystems and their services, both of these factors allowed i) removal of some of the bias derived from the use of over generalized and simplified Land Use Land Cover (LULC) proxies in ES assessments (Eigenbrod et al., 2010), and ii) reduction of the uncertainties of this type of analysis (Hou et al., 2013). Higher resolution cartographic data are therefore useful for the characterization of ES supply if they provide ecosystem characteristics at a sufficient level of detail (Kandziora et al., 2013).

The results show differences between the spatial patterns of the six FES analyzed. Food supply and cultural services have larger areas of no (relevant) potential supply and more clustered patterns of areas with high supply than the other FES. Regulating services show larger potential supply areas, which are distributed throughout the study area. Comparable results were found in studies focusing on the spatial characterization of ES patterns, in areas both close to (Garcia-Nieto et al., 2013; Roces-Diaz et al., 2015) and distant from (Qiu and Turner, 2013) the study area. The statistical analysis with Moran´s I values revealed that all ES are clustered and show high spatial autocorrelation. The autocorrelations for each FES follow specific patterns: food and materials provision display high levels of autocorrelation; energy provision and climate regulation show lower levels with identical values, erosion regulation and cultural services show intermediate autocorrelation values. However, the information used was not exhaustive, as only forest ecosystem types were addressed, and therefore high levels of spatial autocorrelation are expected. Nonetheless, the Incremental Spatial Autocorrelation (ISA) analysis enabled identification of spatial clustering and specific spatial scales of FES supply. The relevance of spatial scales in ES assessments has been highlighted in different studies (i.e. Martin-Lopez et al., 2009; Roces-Díaz et al., 2014a; Castro et al., 2014; Geijzendorffer et al., 2015).

Ecological processes operate at different spatial and temporal scales (Hein et al., 2006), generating different ES at each scale.

Each FES showed scale-specific behavior. Thus, food FES showed very definite areas of supply and were clearly concentrated in eastern parts of the area. The ISA results show a curve of increasing values, higher than for the other FES and without any peak or inflexion point. This can be interpreted as spatial clustering of the areas of supply, which would transcend the limits of the geographical area under study. Thus, two domains of scale may be taken into consideration: one higher than the study area and another, only identifiable within the definite areas previously described, and which may require partition of the study area in two smaller areas (eastern and western). The ISA results for materials provision show a peak corresponding to a window size of 95,000 m and with higher values than for the other FES, except food provision. This peak could define the spatial scale at which the provision of materials is manifested in the area.

The spatial heterogeneity and Z-scores of these two FES are higher than for the other FES. The Moran's I index values are also much higher for food and materials provision than for the other FES. Two main trends can be detected for energy provision and cultural services, both of which show an initially increasing trend, peaking at respectively 30,000 and 35,000 m, and then decreasingly sharply and finally adopting a more moderate but decreasing trend. Such peaks can be interpreted as the extension at which the maximum spatial variability of the Z-scored is verified and can be identified as a characteristic scale for supply of the service. Beyond these peaks, the variability decreases as the size of the area increases. Consequently, any increase in the size of the area defined by the peaks would not yield relevant changes in the spatial pattern (i.e. the spatial pattern shows a high degree of scale-independence). Erosion and climate regulation initially show a similar trend with the peaks defining similar spatial domains. However, instead of a continuous decrease after the peak, the curve tends to increase towards the end. This may reveal a possible second spatial domain, identifying clustering at a new spatial level beyond the study region. In summary, the analysis identified four different spatial scale conditions: supra-regional clustering (food); clustering at intermediate sub-regional levels (materials); clustering at low subregional levels (energy and cultural); and two-level clustering (climate and erosion). The method used and the results obtained have some points in common with other techniques that have been successfully applied in recent research for the detection of spatial patterns ES supply such as the lacunarity analysis (Roces-Diaz et al., 2014a) and four term local quadrat variance (4LTQV; Roces-Diaz et al., 2015).

The results were supported by the correlation analysis, which enabled identification of different levels of positive correlation between the different FES. Correlation analysis is an usual method of exploring the occurrence of ES trade-offs and bundles (Egoh et al., 2008; Mouchet et al., 2014). Thus, regulating (climate and erosion), materials provision and cultural services were generally more closely correlated with each other than with food provision. This may be based on the wood density criterion that was selected for the classification. Wood density is strongly correlated with the amount of aboveground carbon stored in the ecosystem, which is usually high in native forest ecosystems such as *Quercus* spp. and *Fagus sylvatica* forests. These forests are also important for the supply of cultural and erosion regulation services. Although fast growing plantations with *Pinus* spp. and *Eucalyptus* spp., which are common on the study area, have a high potential supply of materials provision services, their potential to supply other FES is comparably low. Native deciduous forests have lower growth rates, but have a higher potential supply of FES such as climate regulation and cultural services (i.e. Rodriguez-Loinaz et al., 2013; Onaindia et al., 2013; Palacios-Agundez et al., 2014). Such differences in FES supply indicate the importance of ES-based forest (Fürst et al., 2013; Frank et al., 2015) and landscape planning (Castro et al., 2014). Sustainable planning approaches should take into account ES to integrate multifunctional and multiple ES considerations. Our results are consistent with comparable ES correlations analyses. For example, Wu et al. (2013) and Raudsepp-Hearne et al. (2010) found that the two large groups of regulating and cultural services show clear trade-offs with provisioning ES. Regulating and cultural services are often correlated in spatial ES analyses and their occurrence is often higher in areas that are important for biodiversity conservation (Gimona and Van der Horst, 2007; Egoh et al., 2008; 2009).

Spatial analysis of hotspots and coldspots of ES supply are common (e.g. Egoh et al., 2009; Bai et al., 2011; García-Nieto et al., 2013; Schulp et al., 2014; Franko et al., 2015). However, few studies (e.g. Timilsina et al., 2013; Homolova et al., 2014) have used the Getis Ord Gi* statistic to analyze ES hotspots and coldspots. Hotspots and coldspots can be interpreted as areas (grid cells) with very high/very low values of one variable used for the assessment of ES supply. In this study, the Getis Ord Gi* method was used to identify features i) with a high/low value of potential FES supply, and ii) that are surrounded by other features with high/low- values. This means that the detection of hotspots and coldspots depends on the spatial configuration of the study area. The patterns of FES hotspots and coldspots clarify the general spatial distribution of FES supply. They also help to explain the differences in clustering from the ISA analysis, as explained above.

Finally, the analysis based on municipal borders yielded a different spatial pattern than analysis based on the use of the 25x25 m grid of the whole study area. The results obtained show a strong influence of the area of the administrative unit when this is used to obtain the relative values (i.e. level of provision by surface unit), which can induce misleading interpretations. Administrative units corresponding to different European NUTS levels are often used in ES assessments at different scales (Haines-Young et al., 2012) or regional municipalities (Rodriguez-Loinaz et al., 2015). However, using higher spatial and thematic resolutions for ES analyses is of interest in order to detect spatial patterns and local variations such as hotspots and coldspots, which the municipal scale did not show.

5. Conclusions

Detailed data from thematic forest cartography were used in this study to analyze the potential supply of six Forest Ecosystem Services (FES). Compared to common land use/land cover-based approaches, the additional information in the database about forest species structure and composition enabled more accurate spatial ES assessment, although only in relation to forest ecosystems.

The results indicated differences between FES supply patterns. Moran´s I statistics showed high levels of clustering with variations between the six analyzed FES, which were further clarified by the Incremental Spatial Autocorrelation analysis. Thus, four different patterns of spatial clustering and scale were identified: supraregional (food), intermediate sub-regional (materials), low subregional (energy and cultural), and two-level (climate and erosion). These patterns are explicitly shown in the spatial representation of hotspots, which were calculated using the Getis Ord Gi* statistic. The interrelationships were revealed by Spearman correlation analysis, which identified synergy between cultural and regulating services.

We conclude that a method combining spatial and non-spatial statistics with highly detailed ecosystem data may be highly suitable for application in spatial planning and forest management and could be used to implement the ES framework on forest planning at a regional scale

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Appendix A. Supplementary data

Appendix A provides additional information about the ES assessment used in the study.

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Supplementary material

Appendix A. Classification of potential supply of ecosystem services

Food provision. This basically concerns the supply of fruits by tree species. Other resources (e.g. mushrooms and hunting) are not included because there was no information available at the same spatial scale as the forest map. From the forest tree species included in the Spanish National Forest Map (scale 1:25,000), 172 species present in the study area and with fruits that are used as food were selected (Table A1). The patches where these species are included were denominated Forest Fruit Tree Species (FFTS). These were classified based on the six ES supply levels in relation to their cover (%).

Table A1. Forest tree species with fruits used for human consumption.

Forest Fruit Tree Species (FFTS)		
Castanea sativa Mill.	*Prunus* spp.	*Prunus avium* L.
Corylus avellana L.	*Pinus pinea* L.	*Juglans regia* L.
Laurus nobilis L.	*Arbutus unedo* L.	*Ficus carica* L.
Malus spp.		

Table A2 shows the final potential classification of this ES.

Table A2. Classes of potential supply of food provision.

Potential supply class	**Criterion**
Very high	Cover by one of the FFTS is >= 70%
High	Cover by one of the FFTS is >= 50% and <70%
Intermediate	Cover by one of the FFTS is >= 30% and <50%
Low	Cover by one of the FFTS is >= 10% and <30%
Very low	Cover by one of the FFTS is > 0% and <10%
No (relevant) supply	Other polygons.

Materials provision. This ES concerns products provided by forests such as timber destined for construction or pulp for paper production. It does not include ES used for food or energy. The data used for the ES classification are forest harvest statistics (Consejería de Agroganadería y Recursos Autóctonos, 2014) for the study area in the period 1990-2013 (Table A3). The maximum value of potential supply was awarded to those species with the highest harvest in this area during the last 25 years.

Table A3. Statistics of forest harvests in the Autonomous Community of Asturias during 1990-2013. Source: Consejería de Agroganadería y Recursos Autóctonos (2014).

Type of forest (species)	**Total harvest 1990-2013 (cubic metres)**	**Total harvest 1990-2013 (percentage)**
Eucalyptus spp.	9,898,585	63.4
Pinus pinaster Ait.	1,827,249	11.7
Pinus radiata D.Don	1,829,394	11.7
Pinus sylvestris L.	192,638	1.2
C. sativa	1,336,600	8.6
Quercus spp.	195,651	1.3
Fagus sylvatica L.	30,870	0.2
Betula spp.	72,640	0.5
Alnus glutinosa (L.) Gaertn	90,421	0.6
Populus spp.	41,011	0.3
Others	101,441	0.6

Table A4 shows the final classification.

Table A4. Classes of potential supply of materials provision.

Potential supply class	Criterion
Very high	Polygons in which the cover by *Eucalyptus* spp. >=50%
High	Polygons in which the cover by *P. radiata* or *P. pinaster* is >=50%. Polygons in which the cover by *Eucalyptus* spp. is >0% and <50%
Intermediate	Polygons in which the cover by *C. sativa* is >=50% Polygons in which the cover by *P. radiata* or *P. pinaster* is >0% and <50%
Low	Polygons in which the cover by *P. sylvestris*, *Quercus robur* L., *Quercus petraea* (Matt.) Liebl., *F. sylvatic*a, *A. glutinosa*, *Populus* sp. and *Betula* spp. is >=50%. Polygons in which the cover by *C. sativa* is > 0% and <50%
Very low	Polygons in which the cover by *P. sylvestris*, *Q. robur*, *Q. petraea*, *F. sylvatica, A. glutinosa*, *Populus* sp. or *Betula* sp. is > 0 and < 50%
No (relevant) supply	Other polygons.

Energy provision. The classification of this ES was based on forest statistics (Consejería de Agroganadería y Recursos Autóctonos, 2014) and data on the physical properties of the wood, mainly wood density (Table A5; Serrada et al, 2008) related to the calorific value. Although *Eucalyptus* spp. show the highest value of wood density, this is not the main species for firewood use in the region (MAGRAMA, 2013). Other tree species such as *Quercus* spp. are often harvested for home energy production. For this reason, *Eucalyptus* spp. plantations do not account for the maximum value of potential supply of this ES.

Table A5. Value of wood density of the main forest tree species in the study area. Source: Serrada et al. (2008).

Forest species	Wood density (kg/m^3)	Forest species	Wood density (kg/m^3)
Eucalyptus spp.	785	*Q. robur*	710
P. pinaster	540	*Q. petraea*	710
P. radiata	500	*Quercus pyrenaica* Willd.	740
P. sylvestris	520	*F. sylvatica*	720
Fraxinus spp.	715	*C. sativa*	590
Betula spp.	660	*A. glutinosa*	525
Populus spp.	440		

Table A6 shows the final classification.

Table A6. Classes of potential supply of energy provision.

Potential supply classes	Criterion
Very high	Polygons in which the cover by *Quercus* spp. or *F. sylvatica* is >= 50%
High	Polygons in which cover by *C. sativa* or *Fraxinus spp.* is >=50%. Polygons in which cover by *Quercus* spp. or *F. sylvatica* is >0 and <50%.
Intermediate	Polygons in which cover by *Betula* spp. or *A. glutinosa* is>=50%. Polygons in which cover by *C. sativa*, *Fraxinus spp.* is > 0 and <50%
Low	Polygons in which cover by *Eucalyptus* spp. or *Pinus* spp. or *Populus* spp. is >=50%. Polygons in which cover by *Betula* spp. or *A. glutinosa* is > 0 and <50%
Very low	Other polygons with forest cover >0%
No (relevant) supply	Other polygons.

Climate regulation. For the classification of this ES, data related to the amount of biomass and carbon storage in the forest of this area was used (Table A7; MMA, 2006a; Castaño-Santamaría et al., 2013). Although a large part of the carbon content is contained in the below-ground biomass and in the soil, we did not include this information because no data was available at the same spatial resolution of the forest data used in this study. Therefore, we only focused on the potential carbon storage in the above-ground forest biomass.

Table A7. Estimation of above-ground biomass and carbon content of forest in the area. Source: Castaño-Santamaría et al. (2013) and MMA (2006a),

Type of forest (species)	**Number of plots**	**Mean value of Above-ground biomass (Mg dry biomass/ha)**	**Mean value of carbon content (Mg/ha)**
Eucalyptus spp.	1,201	89.36	40.52
P. pinaster	1,499	75.63	36.22
P. radiata	237	84.12	43.06
P. sylvestris	189	83.86	42.68
C. sativa	229	156.04	74.99
Q. robur	351	97.45	47.30
Q. petraea	42	95.81	46.99
Q. pyrenaica	172	79.33	38.16
F. sylvatica	115	211.93	102.56
Betula spp.	57	72.12	25.53

Other forest species in the study area that were not included by Castaño-Santamaría et al. (2013) were classified here according to a second criterion: the Biomass Expanding Factor (BEF). BEF values were as follows: 0.83 for *Fraxinus* spp. (similar to *Q. robur* or *Q. petraea*); 0.62 for *Populus* spp. and *A. glutinosa*; 0.80 for *Arbutus unedo* and *Sorbus* spp. (Gil et al., 2011; MMA, 2006b). Table A8 shows the final classification.

Table A8. Classes of potential supply of Climate regulation.

Potential supply class	Criterion
Very high	Polygons in which the cover by *F. sylvatica or C. sativa* is >=50%
High	Polygons in which the cover by *F. sylvatica* or *C. sativa* is >0% and <50%. Polygons in which the cover by *Q. robur*, *Q*. *petraea*, *Fraxinus*, spp., *A. unedo* or *Sorbus* spp. is >=50%
Medium	Polygons in which the cover by *P. radiata*, *P*. *sylvestris*, *Eucalyptus* spp. or *A. glutinosa* is >=50 %. Polygons in which the cover by *Q. robur*, *Q. petraea*, *Fraxinus*, spp., *A. unedo* and *Sorbus* spp. is >0% and <50%.
Low	Polygons in which the cover by *Q. pyrenaica*, *P. pinaster* or *Betula* spp. is >=50%. Other polygons with forest cover >=50%.
Very low	Other polygons with forest cover >0 and <50%
No (relevant) supply	Other polygons

Erosion regulation. Factors similar to those included in the Revised Universal Soil Loss Equation (RUSLE) method (Renard et al., 1991) were used to classify erosion regulation ES. Areas with no potential risk for soil erosion were first identified according to their slope. For this, a grid of the L (length of the slope) and S (inclination of the slope) factors was established using a Digital Elevation Model of resolution 25 m (IGN, 2014). In this GRID, areas with no erosion risk (flat areas and similar zones) were defined by selecting cells in which the LS value was lower than 2 times the Standard Deviation. These cells have no erosion risk and thus, the ES is neither demanded nor supplied here (null potential supply). Secondly, the remaining cells were considered to have a potential erosion risk and were thus classified according to the five ES classes considering the percentage plant cover in each cell (Table A9). Thus, three of the factors of the RUSLE methodology were used for this proxy.

Table A9. Classes of potential supply of erosion regulation.

Potential supply class	CRITERION
Very high	Cells with potential risk of soil erosion (LS factor value higher than -2 SD) and plant cover >=75%
High	Cells with potential risk of soil erosion and plant cover >=50% and <75%
Intermediate	Cells with potential risk of soil erosion and plant cover >=25% and <50%
Low	Cells with potential risk of soil erosion and plant cover >=5% and <25%
Very low	Cells with potential risk of soil erosion and plant cover <5%
No (relevant) supply	Cells without risk of soil erosion (where the value of LS was <2 SD)

Cultural ecosystem services This ES was classified following different criteria, all of which are related to the social value of the forests, including aspects such as the potential recreational use, the value from the perspective of traditional use, etc. Forests with a high protection level composed of endangered species (i.e. *Taxus baccata* L., *Ilex aquifolium* L., *Quercus suber* L., *Quercus ilex* L., *Quercus faginea* Lam. or *Olea Europea* L.pet) or those classified as priority habitats by the European Habitats Directive (EC, 1992) were included in the highest supply class (=5). Forests of *Q. robur*, *Q. petraea*, *Q. pyrenaica* and *F. sylvatica,* which are included as Habitats of Interest by the same directive, were classified as having high supply. Other forests including species that produce fruits used for human consumption were classified as medium supply level, because we considered that the collection is often associated with recreational use for urban populations. Other native forest, such as *Betula* spp., were classified as having low supply levels. *Pinus sylvestris* plantations, which do not have a high cultural use value level, were classified as having very low supply levels. The final classification is shown in Table A10.

Table A10. Classes of potential supply of cultural services.

Potential supply class	Criterion
Very high	Polygons in which cover by *I. aquifolium*, *T. baccata*, *O. europea*, *Q. faginea*, *Q. ilex* or *Q. suber* is > 0%. Polygons in which cover *by A. glutinosa*, *Fraxinus* spp., *Tilia* spp. and *Acer* spp. is >=50%
High	Polygons in which cover by *Q. robur*, *Q. petraea*, *Q. pyrenaica* or *F. sylvatica*>= 50%. Polygons in which cover *by A. glutinosa*, *Fraxinus* spp., *Tilia* spp. or *Acer* spp. is > 0%
Medium	Polygons in which cover by *C. sativa, A. unedo*, *F. carica*, *P. avium*, *P. pinea*, *Malus* spp., *C. avellana, J. regia* or *L. nobilis* is >= 50%. Polygons in which cover by *Q. robur*, *Q. petraea*, *Q. pyrenaica* or *F. sylvatica* is > 0%.
Low	Polygons in which cover by *Betula* spp. or *Sorbus* spp.is >=50%. Polygons in which cover by *C. sativa, A. unedo*, *F. carica*, *P. avium*, *P. pinea*, *Malus* spp., *C. avellana, J. regia* or *L. nobilis* is > 0%.
Very low	Polygons in which cover by *P. sylvestris* is >= 50%. Polygons in which cover by *Betula* spp. or *Sorbus* spp. is > 0%.
No (relevant) supply	Other polygons

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Report of the impact factor of the publications

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Environmental niche and distribution of six deciduous tree species in the Spanish Atlantic region

Jose V Roces-Díaz [(1)], Borja Jiménez-Alfaro [(2)], Pedro Álvarez-Álvarez [(1)], Miguel A Álvarez-García [(3)]

(1) GIS-Forest Group, Department of Organisms and Systems Biology, University of Oviedo, E-33993 Mieres (Spain); (2) Department of Botany and Zoology, Masaryk University, CZ-61137 Brno (Czech Republic); (3) INDUROT, Department of Organisms and Systems Biology, University of Oviedo , E-33993 Mieres (Spain)

@ Jose V Roces-Díaz (jvroces@gmail.com)

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Understanding the influence of environmental factors on the distribution of tree species is essential for developing management actions at regional level. We developed species distribution models for six European tree species to determine their potential niche in the Spanish Atlantic region, where deciduous forests are relatively well preserved. Data from the national Forest Inventory and topo-climatic and soil variables were used to construct distribution models by using Generalized Linear Models. The main factor accounting for the current geografic distribution of the selected species were minimum winter temperature and mineral fertility of soils. Suitable habitats for *Quercus petraea* and *F. sylvatica* were mainly high-altitude areas with low minimum temperatures. In contrast, *Q. robur* and *C. sativa* were restricted to low altitudes and warmer conditions. *Betula pubescens* was not influenced by the elevation, probably because its adaptation to Atlantic conditions, though its distribution was associated with low fertility soils. Although the submediterranean *Q. pyrenaica* was positively influenced by the slope, model performance was poor for this species, possibly because of the truncated environmental range of the species in the study area. The findings suggest that temperature rather than moisture is shaping the distribution of deciduous trees at the southern limit of the Atlantic biogeographic region. Strong elevational difference between the warm coast and the cold mountains may determine the geographical disjunction between *Q. robur* and *Q. petraea* in southern Europe.

Keywords: Species Distribution Models, Topo-climatic Variables, *Quercus* species, *Fagus sylvatica*, *Castanea sativa*, *Betula pubescens*, Iberian Peninsula, Deciduous Forests

Introduction

The temperate mid-latitude ecozone of the northern hemisphere is mainly distributed in the Atlantic regions of North America and Europe and also in central Europe (Schultz 2005). The climax vegetation of this ecozone consists of temperate deciduous forests, which dominate from sea level to the subalpine zone. These ecosystems comprise some of the main components of European landscapes (Meeus 1995) and provide the society with important flow of services (MA 2005, Harrison et al. 2010). The main ecosystem services provided by forests are regulation processes, such as soil protection, climate, etc., although provision of cultural services is also important.

The distribution of tree species in Europe is mainly determined by climatic factors (Svenning & Skov 2004, 2007), despite the effect of historical factors such as the presence of glacial refuges (Muñoz Sobrino et al. 2006, Willner et al. 2009) and naturalization of species beyond their former range. The dominant forest tree species in the temperate mid-latitude ecozone are taxonomically related, most belonging to the *Fagaceae* family. These species require a minimum of 120 days per year with an average temperature above 10 °C, and most of them grow in areas where winter is shorter than 4 months (Walter 1979) and frost damage is a secondary factor. Although it has been suggested that minimum temperature is one of the main determinants for the growth and development of native trees (Sykes et al. 1996), other climatic variables and soil factors are also expected to shape the distribution of tree species (Ashcroft et al. 2011).

Several attempts have been made to characterize the ecological niche and spatial distribution of forest tree species in Europe (Sykes et al. 1996, Brus et al. 2011, Casalegno et al. 2011). However, biogeographical regions differ in terms of historical and climatic factors. A better understanding of species-environment relationships requires data sources spanning over large areas with high spatial resolution (*e.g.*, National Forest Inventories - NFI), to be used for the development of climatic models, with the aim of analyzing particular areas and assessing the influence of environmental conditions. Computing species distribution models (SDMs - Guisan & Thuiller 2005, Elith & Leathwick 2009) applied on such data may be especially useful for defining the environmental niche of tree species and for assessing their potential distribution at regional scales.

In this study, we applied SDMs on species occurrence data from the Spanish NFI to compare the climatic niche of six European tree species in the Atlantic region, at the southern distribution limit of temperate deciduous forests in Europe. The studied region is characterized by an oceanic and relatively warm climate and representing a unique environmental zone in Europe (the *Lusitanian* zone, according to Metzger et al. 2005). The study area was the Autonomous Community of Asturias, one of the most densely forested areas of the Iberian peninsula, where deciduous forests are relatively well preserved. Asturias is characterized by an elevational gradient ranging from the sea level to altitudes often higher than 2000 m a.s.l., by far the strongest altitudinal gradient found across the entire European Atlantic region. According to local vegetation surveys, the distribution of tree species is determined by strong climatic gradients and soil conditions (Díaz & Fernández-Prieto 1994), although it is unknown whether local environmental gradients affect the ecological niche of forest trees. Thus, Asturias provides a good study system for investigating the environmental niche of European tree species in oceanic temperate climates with high topographic heterogeneity.

Understanding the ecological determinants that affect the distribution of forest tree species in this region is important for planning appropriate management actions aimed at preventing the potential impacts of climate

Publication 2

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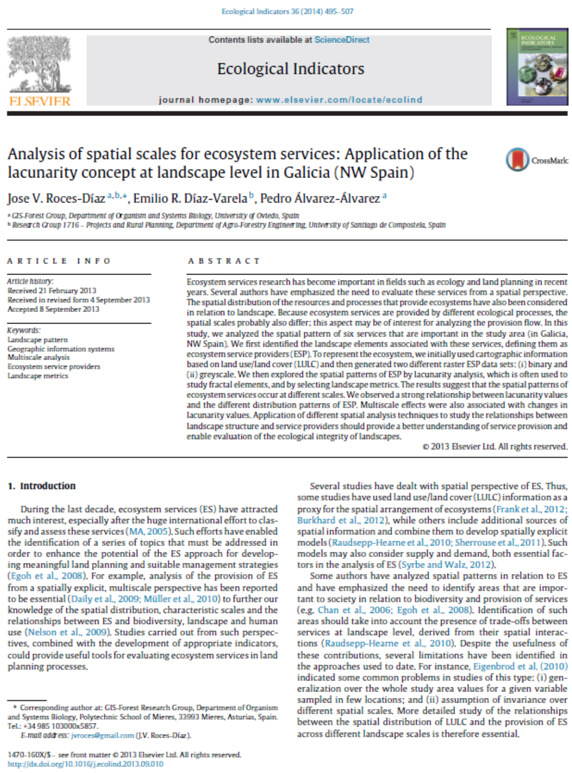

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Analysis of spatial scales for ecosystem services: Application of the lacunarity concept at landscape level in Galicia (NW Spain)

Jose V. Roces-Díaz [a,b,*], Emilio R. Díaz-Varela [b], Pedro Álvarez-Álvarez [a]

[a] GIS-Forest Group, Department of Organism and Systems Biology, University of Oviedo, Spain
[b] Research Group 1716 – Projects and Rural Planning, Department of Agro-Forestry Engineering, University of Santiago de Compostela, Spain

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ABSTRACT

Ecosystem services research has become important in fields such as ecology and land planning in recent years. Several authors have emphasized the need to evaluate these services from a spatial perspective. The spatial distribution of the resources and processes that provide ecosystems have also been considered in relation to landscape. Because ecosystem services are provided by different ecological processes, the spatial scales probably also differ; this aspect may be of interest for analyzing the provision flow. In this study, we analyzed the spatial pattern of six services that are important in the study area (in Galicia, NW Spain). We first identified the landscape elements associated with these services, defining them as ecosystem service providers (ESP). To represent the ecosystem, we initially used cartographic information based on land use/land cover (LULC) and then generated two different raster ESP data sets: (i) binary and (ii) greyscale. We then explored the spatial patterns of ESP by lacunarity analysis, which is often used to study fractal elements, and by selecting landscape metrics. The results suggest that the spatial patterns of ecosystem services occur at different scales. We observed a strong relationship between lacunarity values and the different distribution patterns of ESP. Multiscale effects were also associated with changes in lacunarity values. Application of different spatial analysis techniques to study the relationships between landscape structure and service providers should provide a better understanding of service provision and enable evaluation of the ecological integrity of landscapes.

1. Introduction

During the last decade, ecosystem services (ES) have attracted much interest, especially after the huge international effort to classify and assess these services (MA, 2005). Such efforts have enabled the identification of a series of topics that must be addressed in order to enhance the potential of the ES approach for developing meaningful land planning and suitable management strategies (Egoh et al., 2008). For example, analysis of the provision of ES from a spatially explicit, multiscale perspective has been reported to be essential (Daily et al., 2009; Müller et al., 2010) to further our knowledge of the spatial distribution, characteristic scales and the relationships between ES and biodiversity, landscape and human use (Nelson et al., 2009). Studies carried out from such perspectives, combined with the development of appropriate indicators, could provide useful tools for evaluating ecosystem services in land planning processes.

Several studies have dealt with spatial perspective of ES. Thus, some studies have used land use/land cover (LULC) information as a proxy for the spatial arrangement of ecosystems (Frank et al., 2012; Burkhard et al., 2012), while others include additional sources of spatial information and combine them to develop spatially explicit models (Raudsepp-Hearne et al., 2010; Sherrouse et al., 2011). Such models may also consider supply and demand, both essential factors in the analysis of ES (Syrbe and Walz, 2012).

Some authors have analyzed spatial patterns in relation to ES and have emphasized the need to identify areas that are important to society in relation to biodiversity and provision of services (e.g. Chan et al., 2006; Egoh et al., 2008). Identification of such areas should take into account the presence of trade-offs between services at landscape level, derived from their spatial interactions (Raudsepp-Hearne et al., 2010). Despite the usefulness of these contributions, several limitations have been identified in the approaches used to date. For instance, Eigenbrod et al. (2010) indicated some common problems in studies of this type: (i) generalization over the whole study area values for a given variable sampled in few locations; and (ii) assumption of invariance over different spatial scales. More detailed study of the relationships between the spatial distribution of LULC and the provision of ES across different landscape scales is therefore essential.

* Corresponding author at: GIS-Forest Research Group, Department of Organism and Systems Biology, Polytechnic School of Mieres, 33993 Mieres, Asturias, Spain. Tel.: +34 985 103000x5857.
E-mail address: jvroces@gmail.com (J.V. Roces-Díaz).

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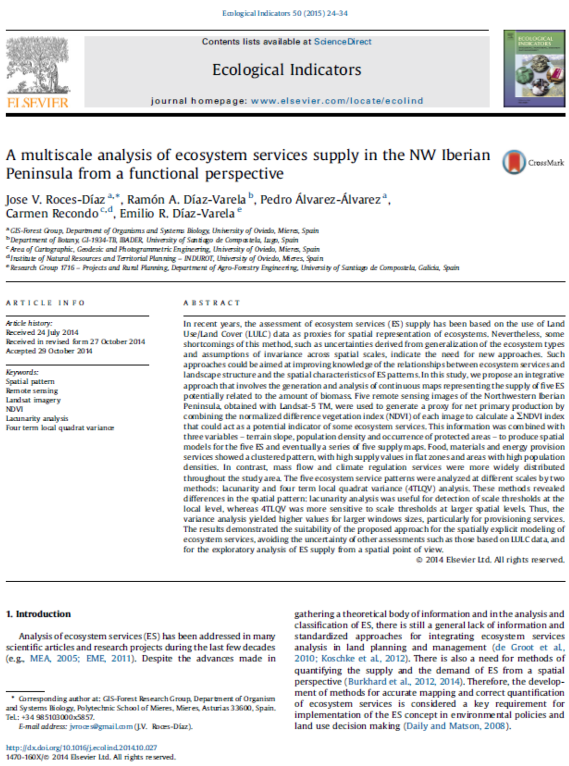
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A multiscale analysis of ecosystem services supply in the NW Iberian Peninsula from a functional perspective

Jose V. Roces-Díaz [a,*], Ramón A. Díaz-Varela [b], Pedro Álvarez-Álvarez [a], Carmen Recondo [c,d], Emilio R. Díaz-Varela [e]

[a] GIS-Forest Group, Department of Organisms and Systems Biology, University of Oviedo, Mieres, Spain
[b] Department of Botany, GI-1934-TB, IBADER, University of Santiago de Compostela, Lugo, Spain
[c] Area of Cartographic, Geodesic and Photogrammetric Engineering, University of Oviedo, Mieres, Spain
[d] Institute of Natural Resources and Territorial Planning – INDUROT, University of Oviedo, Mieres, Spain
[e] Research Group 1716 – Projects and Rural Planning, Department of Agro-Forestry Engineering, University of Santiago de Compostela, Galicia, Spain

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Four term local quadrat variance

ABSTRACT

In recent years, the assessment of ecosystem services (ES) supply has been based on the use of Land Use/Land Cover (LULC) data as proxies for spatial representation of ecosystems. Nevertheless, some shortcomings of this method, such as uncertainties derived from generalization of the ecosystem types and assumptions of invariance across spatial scales, indicate the need for new approaches. Such approaches could be aimed at improving knowledge of the relationships between ecosystem services and landscape structure and the spatial characteristics of ES patterns. In this study, we propose an integrative approach that involves the generation and analysis of continuous maps representing the supply of five ES potentially related to the amount of biomass. Five remote sensing images of the Northwestern Iberian Peninsula, obtained with Landsat-5 TM, were used to generate a proxy for net primary production by combining the normalized difference vegetation index (NDVI) of each image to calculate a ΣNDVI index that could act as a potential indicator of some ecosystem services. This information was combined with three variables – terrain slope, population density and occurrence of protected areas – to produce spatial models for the five ES and eventually a series of five supply maps. Food, materials and energy provision services showed a clustered pattern, with high supply values in flat zones and areas with high population densities. In contrast, mass flow and climate regulation services were more widely distributed throughout the study area. The five ecosystem service patterns were analyzed at different scales by two methods: lacunarity and four term local quadrat variance (4TLQV) analysis. These methods revealed differences in the spatial pattern: lacunarity analysis was useful for detection of scale thresholds at the local level, whereas 4TLQV was more sensitive to scale thresholds at larger spatial levels. Thus, the variance analysis yielded higher values for larger windows sizes, particularly for provisioning services. The results demonstrated the suitability of the proposed approach for the spatially explicit modeling of ecosystem services, avoiding the uncertainty of other assessments such as those based on LULC data, and for the exploratory analysis of ES supply from a spatial point of view.

1. Introduction

Analysis of ecosystem services (ES) has been addressed in many scientific articles and research projects during the last few decades (e.g., MEA, 2005; EME, 2011). Despite the advances made in gathering a theoretical body of information and in the analysis and classification of ES, there is still a general lack of information and standardized approaches for integrating ecosystem services analysis in land planning and management (de Groot et al., 2010; Koschke et al., 2012). There is also a need for methods of quantifying the supply and the demand of ES from a spatial perspective (Burkhard et al., 2012, 2014). Therefore, the development of methods for accurate mapping and correct quantification of ecosystem services is considered a key requirement for implementation of the ES concept in environmental policies and land use decision making (Daily and Matson, 2008).

* Corresponding author at: GIS-Forest Research Group, Department of Organism and Systems Biology, Polytechnic School of Mieres, Mieres, Asturias 33600, Spain. Tel.: +34 985103000x5857.
E-mail address: jvroces@gmail.com (J.V. Roces-Díaz).

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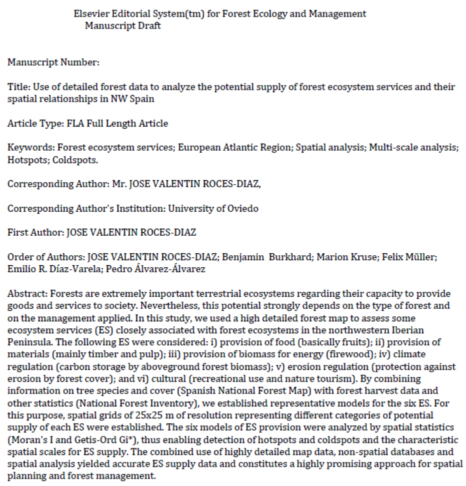

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Corresponding Author: Mr. JOSE VALENTIN ROCES-DIAZ,

Corresponding Author's Institution: University of Oviedo

First Author: JOSE VALENTIN ROCES-DIAZ

Order of Authors: JOSE VALENTIN ROCES-DIAZ; Benjamin Burkhard; Marion Kruse; Felix Müller; Emilio R. Díaz-Varela; Pedro Álvarez-Álvarez

Abstract: Forests are extremely important terrestrial ecosystems regarding their capacity to provide goods and services to society. Nevertheless, this potential strongly depends on the type of forest and on the management applied. In this study, we used a high detailed forest map to assess some ecosystem services (ES) closely associated with forest ecosystems in the northwestern Iberian Peninsula. The following ES were considered: i) provision of food (basically fruits); ii) provision of materials (mainly timber and pulp); iii) provision of biomass for energy (firewood); iv) climate regulation (carbon storage by aboveground forest biomass); v) erosion regulation (protection against erosion by forest cover); and vi) cultural (recreational use and nature tourism). By combining information on tree species and cover (Spanish National Forest Map) with forest harvest data and other statistics (National Forest Inventory), we established representative models for the six ES. For this purpose, spatial grids of 25x25 m of resolution representing different categories of potential supply of each ES were established. The six models of ES provision were analyzed by spatial statistics (Moran's I and Getis-Ord Gi*), thus enabling detection of hotspots and coldspots and the characteristic spatial scales for ES supply. The combined use of highly detailed map data, non-spatial databases and spatial analysis yielded accurate ES supply data and constitutes a highly promising approach for spatial planning and forest management.

Resumen de la Tesis doctoral

Consideración previa

La práctica totalidad de la presente memoria, atendiendo tanto a la normativa existente que regula los estudios de doctorado en la Universidad de Oviedo como a las normas de publicación de las revistas en la que los artículos incluidos fueron publicados, está en lengua inglesa. Por dichos motivos, se ha incluido este apartado, donde se resumen en lengua española los principales contenidos del documento.

Introducción y justificación

En concepto de servicios ecosistémicos (ES) aparece desde mediados de la década de 1990, cada vez con una mayor relevancia y frecuencia, en diferentes campos relacionados con las ciencias medioambientales, tanto en trabajos de tipo científico como técnico. Si bien el origen de dicho concepto se encuentra en artículos científicos de la segunda mitad del Siglo XX, no es hasta la citada década de 1990 cuando comienza a popularizarse, fundamentalmente a partir de trabajos como Costanza et al. (1997) en la revista *Nature* o el libro de G. Daily (1997) "*Nature´s Services*". Aunque numerosos autores han propuesto diferentes definiciones, coloquialmente este concepto puede definirse como los beneficios –directos o indirectos- que el funcionamiento de la naturaleza a diferentes escalas aporta a la sociedad –en sus diferentes niveles de organización, desde local a global-.

A partir de dicha popularización, diferentes organismos internacionales comenzaron a emplear este término en proyectos de diferentes ámbitos. Así, el proyecto de Evaluación de los Ecosistemas del Milenio (MA, *Millennium Assessment*) surgió como una forma de analizar el estado de los ecosistemas y de la biodiversidad que albergan a escala global, relacionado estrechamente con uno de los Objetivos del Milenio formulados en el año 2000 por la Organización de las Naciones Unidas. En dicho proyecto intervinieron más de 1,300 investigadores de todo el mundo, y el principal objetivo fue: "analizar las consecuencias para el bienestar humano de los procesos de cambios existentes en los ecosistemas y sentar las bases científicas para desarrollar acciones de mejores en la conservación y gestión sostenible de dichos sistemas."

Numerosos autores han centrado sus esfuerzos en definir tipologías de ES que engloben todos los beneficios obtenidos a partir del funcionamiento medioambiental (p.ej. De Groot et al. 2002; Wallace, 2007; Costanza, 2007; Fisher and Turner, 2008; Fisher et al., 2009; Haines-Young and Potschin, 2013). De forma general se acepta la clasificación en tres grandes tipologías: servicios de provisión, de regulación y culturales. Igualmente, y teniendo en cuenta que la diversidad biológica es el principal componente que regula el funcionamiento de los ecosistemas, esta generalmente aceptada la estrecha relación de este concepto con los ES. Por ello, diferentes autores han analizado esta relación, tratando de identificar los elementos de la misma que juegan papeles claves en el suministro de los ES. Por ejemplo Kremen (2005) acuñó el término Proveedores de Servicios Ecosistémicos (ESP) para denominar a dichos elementos.

A nivel de paisaje, se suele determinar cuál es el tipo (o tipos) de ecosistema que suministra un ES determinado. Así, los ES que aparecen están en un paisaje estarán estrechamente relacionados con los tipos de ecosistemas presentes en el mismo (la composición), pero también la disposición espacial que tienen estos elementos condicionará el suministro de los ES (Frank et al., 2011; 2013; Syrbe and Walz, 2012). Por ello, el análisis de ES desde un punto de vista de paisaje, considerando las interacciones entre los elementos que lo forman y cómo la estructura del mismo (el tipo de elementos y su disposición espacial) se relacionan con estos servicios ha sido desarrollado de forma intensa en los últimos años. Para ello una de las claves ha sido el empleo de fuentes de información que representan amplias zonas (como cartografías de usos y coberturas del suelo), así como metodologías que permiten el análisis desde un punto de vista espacial (como los Sistemas de Información Geográfica).

Numerosos autores han destacado la necesidad de que se desarrollen modelos espacialmente explícitos que representen aspectos de los ES como su suministro (p.ej. Daily et al., 2009; Müller et al. 2011) de cara a integrar este concepto en la planificación territorial. No obstante, es necesario que estos modelos representen de una forma adecuada los tipos de ecosistemas y la disposición espacial de los mismos, de cara a minimizar alguno de los errores o fuentes de incertidumbre que los tipos de datos empleados pueden llevar asociados (Eigenbrod et al., 2010; Hou et al., 2013). Este tipo de errores, se vinculan muy frecuentemente a una excesiva simplificación de los ecosistemas o del paisaje donde se integran, pudiendo omitirse ecosistemas de pequeña extensión o escasa representación pero que, presentan una gran relevancia en el contexto de suministro de ES.

Por dichas razones en esta tesis doctoral, se han empleado diferentes tipos de información para analizar y caracterizar, desde un punto de vista espacial, el suministro de diferentes ES y de alguno de los tipos de ecosistemas más relacionados con dicho suministro. Las fuentes empleadas han sido, por un lado información sobre parcelas de inventario forestal, así como datos climáticos y ambientales de cara a caracterizar las zonas óptimas de los principales ecosistemas forestales de la zona de estudio. Por otro lado, se ha empleado información sobre tipos de coberturas del suelo, imágenes procedentes de sensores remotos y una cartografía temática de tipo forestal, de cara a obtener modelos espaciales de varios ES de la máxima precisión posible.

Dichos análisis se han centrado en paisajes agrarios y forestales del noroeste de la Península Ibérica. La zona general de estudio engloba una superficie total de unos 40,000 km^2 (las Comunidades Autónomas de Asturias y Galicia), si bien los diferentes trabajos han empleado en su mayoría áreas de menor extensión dentro de la misma. Es una zona con una precipitación elevada, que supera en su práctica totalidad los 1,000 mm/año (Ninyerola et al., 2005) dentro de la Región Biogeográfica Atlántica (EEA, 2011), en la que los ecosistemas de tipo forestal –tanto nativos, como los dominados por *Quercus* spp., *F. sylvatica* o *C. sativa* como plantaciones de *Pinus* spp. o *Eucalyptus* spp.- ocupan un gran porcentaje respecto al total y que por tanto, son clave dentro del paisaje, en el que se mezclan con otros elementos relacionados con el uso agroganadero del medio.

Objetivos

El objetivo general de este trabajo es desarrollar un análisis de la distribución del suministro de ES desde un punto de vista multi-escalar, empleando para ello datos procedentes de diferentes tipos de fuentes, como mapas categóricos o imágenes de sensores remotos, centrándonos en paisajes agrícolas y forestales del noroeste de la Península Ibérica.

Los objetivos específicos de este trabajo son:

- Identificar los factores ambientales que condicionan la distribución espacial de los principales tipos de ecosistemas forestales autóctonos y definir las zonas con un mayor potencial para la presencia de estos ecosistemas en el área de estudio;
- Usando bases de datos disponibles, con una elevada resolución espacial y basadas en la descripción de tipos de coberturas del territorio, analizar el patrón espacial de una serie de suministradores de servicios ecosistémicos. Para ello se empleará una métrica multi-escalar basada en geometría fractal llamada *lacunarity*, que proporciona una estimación de la regularidad en la distribución de los huecos de provisión de los ES;
- Empleando imágenes procedentes de sensores remotos (Landsat) de diferentes estaciones dentro de un año fisiológico, combinadas con otra

información relativa a variables socio-ambientales, desarrollar una aproximación al suministro de una serie de ES, analizando sus patrones espaciales por medio de dos métricas de tipo multi-escalar: *lacunarity* y *four term local quadrat variance*;

- Por medio de un mapa temático de tipo forestal, con una elevada resolución espacial, caracterizar el suministro potencial de varios ES ligados a ecosistemas forestales, y posteriormente, analizar su patrón espacial, poniendo especial interés en la identificación de *hotspots* y en la caracterización de las relaciones espaciales entre dichos ES.

Resultados

Los principales resultados obtenidos en este trabajo han sido los siguientes:

Caracterización y modelado de la distribución de los principales tipos de ecosistemas forestales en Asturias (NO de España)

Usando datos de presencia/ausencia de las seis principales especies arbóreas forestales autóctonas de Asturias, se realizaron modelos lineales generalizados (GLM) de regresión logística para determinar que variables ambientales, relacionadas con la topografía del terreno o las condiciones climáticas, determinaban su distribución. Este trabajo buscó por tanto, definir de una forma espacialmente explícita el nicho ecológico de dichas especies. Los datos empleados partieron la de red de 1877 parcelas del Tercer Inventario Forestal Nacional para el territorio de Asturias. Las especies analizadas fueron: *Q. robur, Q. petraea, Q. pyrenaica, F. sylvatica, C. sativa* y *B. pubescens.* Las variables empleadas fueron: i) la media de las temperaturas mínimas diarias del mes más frio (ºC; TMIN); ii) la pendiente del terreno (%, SLOPE); iii) la radiación acumulada durante un año (kJ m^{-2} $year^{-1}$; RADI); iv) la precipitación anual acumulada (mm; PRECI); y v) la fertilidad del terreno (a través de una variable semi-cuantitativa entre 1 y 4; FERTI).

Los GLM obtenidos presentaron diferentes niveles de ajuste. Los valores más elevados del indicador usado (el área bajo la curva ROC) fueron para *F. sylvatica* (0.861) *Q. robur* (0.760), *C. sativa* (0.758) y *Q. petraea* (0.753). Por su parte los modelos de las especies restantes mostraron valores más bajos (*B. pubescens* 0.627 y *Q. pyrenaica* 0.569). La variable TMIN fue la que ha aparecido con mayor frecuencia en dichos modelos. *Q. robur*, y *C. sativa* mostraron su preferencia por zonas donde sus valores fueran elevados, mientras que otras especies –*Q. petraea*, *F. sylvatica*-

mostraron una mayor afinidad por zonas con valores bajos. De igual forma, la variable FERTI, relativa a la fertilidad mineral del sustrato, mostró una relación positiva con la presencia de *F. sylvatica* y negativa con *Q. robur* y *B. pubescens*.

A partir de los modelos generados, se realizaron mapas que representan la idoneidad potencial de hábitat para cada una de las especies. Dichos mapas tienen una resolución espacial de 200 m (el tamaño de las capas asociadas a las variables ambientales empleadas en los análisis), y las diferentes especies muestran una distribución claramente diferenciada de sus áreas óptimas. Así, *Q. robur* y *C. sativa* presentan una preferencia por zonas de baja altitud, encontrándose el mayor porcentaje de sus áreas favorables a altitudes por debajo de 500 m. Por el contrario, otras especies aparecieron asociadas a estaciones más frías *como F. sylvatica* y *Q. petraea* y son las que tienen una mayor presencia de zonas óptimas por encima de los 1000 m de altitud, más ligadas a estaciones en la Cordillera Cantábrica.

A su vez, cabe señalar que estas pautas de asociación entre los hábitats más favorables paras las especies se analizaron mediante un análisis de correlación. Así las especies con una mayor afinidad por las zonas de montaña –*Q. petraea* y *F. sylvatica*- mostraron entre si valores elevados (0.87) y valores bajos respecto a las especies asociadas a zonas de menores altitudes (*F. sylvatica* -0.876 con *Q. robur* y -0.834 con *C. sativa; Q. petraea* -0.938 con *C. sativa* y -0.839 con *Q. robur*). Las dos especies restantes, que presentaron modelos con peores resultados (*B. pubescens* 0.627 y *Q. pyrenaica*) mostraron valores de correlación intermedios.

Análisis espacial de servicios ecosistémicos y sus escalas a partir de datos sobre usos y coberturas del suelo en el noroeste de la Península Ibérica

Posteriormente se empleó una base de datos con información sobre usos y coberturas del suelo procedente del Sistema de Información Sobre Uso del Suelo en España (SIOSE), que tiene una escala 1:25,0000 para una zona de unos 2,000 km^2. Al contrario de otras aproximaciones tradicionales basadas en mapas de usos y coberturas del suelo (LULC), esta base de datos no clasifica los elementos espaciales en categorías cerradas, si no que aporta información sobre los tipos de cobertura que hay en las mismas y permite que el usuario realice una clasificación acorde a sus necesidades. De este modo, se realizó una clasificación detallada de los diferentes tipos de usos que englobó 38 clases diferentes.

Una vez definido el modelo de representación de los ecosistemas, se identificaron, empleando un procedimiento de criterio de experto, qué las clases funcionaban como suministradoras de seis ES diferentes (ESP): provisión de alimentos, de materiales y de energía, regulación de flujos (erosión) y abiótica (climática) y servicios culturales. Dicha identificación se realizó de dos formas diferentes: i) binaria, donde simplemente se clasificaron las clases en ESP o NO ESP; y ii) cualitativa, donde se clasificaron las clases en cinco categorías según su capacidad de provisión. Los mapas se representaron por medio de patrones de colores blanco/negro para la clasificación binaria (donde los blancos, es decir, los huecos, eran las zonas de NO ESP) y de escala de grises para la clasificación cualitativa (donde los blancos eran igualmente las zonas de NO ESP). El patrón espacial de las ESP de los fue analizado con una métrica multi-escalar denominada *lacunarity*, que es un índice que estima la regularidad del patrón de los huecos (las zonas de NO ESP) a medida que incrementamos la escala de observación (el tamaño de la ventana de análisis).

En los mapas binarios, hubo diferencias entre la superficie englobada dentro de NO ESP para los servicios de provisión (alimentos 79.3%; materiales 84.7%; energía 60.7%) frente a los de regulación y culturales (flujos 25.5%; abiótica 20.2%; culturales 37.9%). Así, los valores de *lacunarity* produjeron en el rango de escalas estudiado (100-3,500 m) grupos de curvas diferenciados entre ellos desde un punto de vista estadístico. De otra forma, en los mapas de tipo escala de grises, las zonas de NO ESP tienen un rango de variación mucho más reducido (entre 19.7% y 31.4% para todos los ES excepto para provisión de materiales 54.8%). En estos patrones, las seis curvas presentaron unos valores prácticamente idénticos y no mostraron diferencias significativas.

Por último, la forma de las curvas de *lacunarity* sirvió para identificar las escalas espaciales características asociadas a los ES. Dicho proceso se llevó a analizando la posición de los puntos de cambio brusco de las pendientes en dichas curvas. En los datos de tipo binario, el patrón de estos puntos mostró diferencias entre los ES, puesto que las correspondientes a los servicios de provisión presentaron dichos puntos a una escala similar (entre 800 y 900 m) mientras que los correspondientes a las curvas restantes presentaron dichos puntos en un rango de valores entre 400 y 800 m. Por otro lado, las seis curvas de los mapas de tipo escala de grises mostraron estos puntos a una escala similar (500-700 m).

Análisis espacial de servicios ecosistémicos y sus escalas a partir de una aproximación de tipo funcional basa en imágenes de sensores remotos en el noroeste de la Península Ibérica

Se analizó el suministro de varios ES empleando como fuente principal de información una serie de imágenes satelitales de una zona de 2,134 km^2 en el nororeste de la Península Ibérica. Se seleccionaron cinco imágenes -relativas a diferentes momentos estacionales dentro de un mismo año - del sensor Landsat 5-TM (resolución espacial 30 m). De cada una de estas imágenes, se calculó el índice de vegetación normalizado (NDVI), y los modelos resultantes del mismo se combinaron por medio de álgebra de mapas para obtener una estimación del potencial de productividad de la vegetación en cada celda durante un ciclo de 365 días, obteniendo así una nueva variable que se denominó ∑NDVI. Dicha variable fue combinada con otras tres: pendiente del terreno, densidad de población y existencia de espacios naturales protegidos de cara a obtener un modelo espacial de cinco ES: provisión de alimentos, de materiales y de energía, regulación de flujos (erosión) y climática.

Los mapas relativos a los servicios de provisión mostraron patrones más agrupados que los de regulación. Las áreas con una mayor capacidad de suministro de estos servicios de provisión aparecieron en los extremos oriental y occidental de la zona de estudio, donde hay unas menores pendientes del terreno y aparecen mayores densidades de población. Por el contrario los servicios de regulación, mostraron patrones más dispersos, distribuidos de forma más regular por todo el área de estudio.

Posteriormente, estos modelos espaciales fueron analizados por medio de dos metodologías multi-escala diferentes: *lacunarity* y *four term local quadrat variance* (4TLQV). El análisis de *lacunarity* proporcionó una evaluación complementaria a la interpretación inicial de los patrones espaciales de los ES. Así, la forma de las 5 curvas es similar, con valores más elevados para el menor tamaño de ventana de análisis empleado (100 m) y una disminución marcada a media que aumentan los tamaños de ventana. En este trabajo, los patrones relativos a los servicios de provisión mostraron en general valores de *lacunarity* más elevados que los de los servicios de regulación. A pesar de estas diferencias en los valores del parámetro y en las curvas, la posición de los puntos de cambio de pendiente de las curvas –y la posición de las escalas características del índice asociado a los mismos- fueron similares para los cinco servicios analizados. Así, las cinco curvas mostraron escalas características con tamaños de ventana entre 2400 y 3300 m, valores pequeños en comparación con el rango analizado (hasta 23,000 m). Esto implica que los valores de *lacunarity*, y por tanto la distribución de los huecos (zonas de no suministro) es más dependiente de la escala para niveles de análisis de tamaño reducido (micro-escala), mientras que para ventanas de análisis mayores, estos huecos están más homogéneamente distribuidos y condicionarán en menor medida el suministro de los ES.

En general, los valores de 4TLQV mostraron un incremento más o menos similar con los menores tamaños de ventana, pero que se fueron diferenciando a medida que aumentaban estos. En cualquier caso, las curvas de los servicios de provisión tuvieron formas parecidas, con máximos de 162,553, 170,903 and 151,774 para alimentos, materiales y energía respectivamente, en un rango de tamaños de ventana similar (12,000-14,400 m). A partir de dichos valores, las curvas decrecieron ligeramente para volver a aumentar a partir de ventanas de 23,000 m. El servicio de regulación de flujos presentó la curva más plana de las cinco producidas, de hecho su valor máximo es tres veces inferior a los máximos del resto de ES y aparece a un nivel de escala mucho mayor (21,300 m). Finalmente, la curva relativa al servicio de regulación climática mostró valores intermedios al de las curvas restantes, con un incremento gradual (pero menos marcado que el de los servicios de provisión) y un máximo a un nivel similar al de la curva de regulación de flujos (pero con un valor de 4TLQV menor al obtenido para los servicios de provisión).

Análisis espacial de servicios ecosistémicos a partir de un mapa temático forestal en el noroeste de la Península Ibérica

Por último se buscó realizar una evaluación del suministro potencial de varios ES empleando como fuente principal de datos información cartográfica relativa a los ecosistemas forestales de la zona de estudio – las Comunidades Autónomas de Asturias y Galicia-. Dicha información empleada fue la última versión del Mapa Forestal Español (MFE), que tiene una escala 1:25,000. Para ello, se seleccionaron varios ES vinculados de forma directa a ecosistemas de tipo forestal: provisión de alimentos, de materiales y de energía, regulación climática y de la erosión y servicios culturales. Posteriormente, empleando información de diferentes fuentes (estadísticas sobre aprovechamientos, artículos científicos, inventarios forestales, etc.) se realizó una clasificación del suministro potencial de dichos servicios para cada una de las teselas del MFE en base a la cobertura de las mismas por las diferentes especies.

Los diferentes ES mostraron diferentes patrones espaciales en lo relativo a la distribución de sus clases de suministro potencial. La provisión de alimentos fue el ES que mostró una mayor superficie de no suministro (88.8%) mientras que por el contrario, regulación de erosión presentó en dicha categoría menos del 10%. Las zonas con una mayor importancia para la provisión de materiales se encontraron en áreas costeras, a baja altitud, mientras que para otros servicios, como provisión de energía, regulación climática o servicios culturales hay que destacar las zonas de interior. Los mapas de suministro potencial de estos ES fueron analizados desde un punto de vista espacial empleando diferentes metodologías. En primer lugar cabe decir que los seis patrones espaciales generados mostraron un elevado nivel de agrupación (a partir del índice *Moran´s I*). Por otro lado, se evaluó el nivel de correlación (para los seis ES; algunos pares de ES mostraron valores elevados entre sí (como provisión de materiales con energía o regulación climática, o provisión de energía con regulación climática y servicios culturales) mientras que otros (como provisión de alimentos con provisión de materiales o regulación de la erosión) presentaron valores muy inferiores. Posteriormente, se realizó un análisis de *Incremental Spatial Autocorrelation* que permitió establecer las escalas características de los patrones de los seis ES mediante la identificación de picos en las curvas que representaron dicho índice. Los servicios de provisión de alimentos y materiales mostraron curvas razonablemente similares aunque la primera alcanzó valores más elevados. Las curvas de los servicios restantes mostraron valores inferiores, con un pequeño ritmo de crecimiento para los menores tamaños de ventana. Las relativas a provisión de energía y regulación climática tienen formas similares hasta una escala de 75,000 m mientras que para distancias superiores la curva de regulación climática se parece más a la servicios culturales. Esta última y la de regulación de erosión tienen una forma similar para escalas pequeñas (hasta 35,000 m).

Por último, se realizó para la detección un análisis de *hotspots* y *coldspots* de los seis ES empleando el índice Getis-Ord Gi* a dos niveles diferentes: i) para toda la zona de estudio (nivel regional) empleando toda la base de datos procedente del MFE; y ii) a nivel de municipio. En lo relativo al análisis a nivel regional los *hotspots* de provisión de alimentos están agrupados en la zona centro-oriental del área de estudio mientras que los de materiales aparecen fundamentalmente en zonas costeras de la mitad occidental. Los relativos a provisión de energía y regulación climática tienen una distribución similar, destacando la elevada densidad de ellos en la zona central, pero aparecen por toda el área de estudio. Mientras que los de regulación de erosión aparecen en zonas de la mitad oriental, siguiendo el eje de la Cordillera Cantábrica. El análisis a nivel municipal muestra resultados que difieren de los anteriores. Así, aunque el patrón general de los *hotspots* se parece al obtenido en el análisis a nivel regional para provisión de alimentos y materiales, la distribución de dichos *hotspots* varia de forma significativa para los ES restantes.

Discusión general

Los resultados de este trabajo están basados en el uso de diferentes fuentes de información para analizar el suministro de ES: mapas categóricos del SIOSE basados en información LULC; mapas derivados de imágenes Landsat 5-TM; datos de inventario forestal y mapas categóricos de tipo forestal basados en el MFE. Estas fuentes de información en combinación con varias metodologías específicas de análisis espacial: *lacunarity*, *four term local quadrat variance* (4TLQV); Modelos Lineales Generalizados; estadístico I de Moran y su derivada *Incremental Spatial Autocorrelation*; y Getis-Ord Gi* fueron usadas para caracterizar el patrón espacial de varios ES, la distribución de alguno de los principales ecosistemas que los proporcionaban y las escalas espaciales características a las que se produce el suministro de los mismos. A pesar de que los análisis de ES fueron desarrollados de forma independiente los unos de los otros (Roces-Díaz et al., 2014; 2015b; 2015c), el grupo de ES analizado fue muy parecido. Así, los ES de provisión de alimentos, materiales y energía, así como los de regulación climática y de la erosión aparecieron en los tres trabajos, y los servicios culturales en dos de ellos.

En primer lugar, los nichos ambientales de las principales especies forestales autóctonas del área de estudio fueron caracterizados y definidos (Roces-Díaz et al., 2015a). Numerosos autores han destacado el papel de los ecosistemas forestales en relación con la diversidad que albergan y el amplio rango de ES que proporcionan (p.ej. Harrison et al., 2010; García-Nieto et al., 2013). Sin embargo, el suministro de ES está estrechamente relacionado con diferentes características de estos ecosistemas o del medio donde se encuentran –como el tipo de gestión, que condiciona la composición de especies o el régimen de cortas y/o perturbaciones-. En nuestro área de estudio los ES proporcionados por plantaciones forestales de especies exóticas (fundamentalmente *Pinus* sp. and *Eucalyptus* sp.) son muy diferentes de aquellos que emanan de bosques autóctonos y que presentan en general menores intensidades de manejo (Rodriguez-Loinaz et al., 2013). Basándonos en esta idea, desarrollamos una definición espacial razonablemente precisa de los nichos ecológicos de las principales especies arbóreas forestales que son autóctonas del área de estudio, y que forman ecosistemas con una gran relevancia en relación a los servicios de regulación y culturales que proporcionan (Roces-Diaz et al., 2015c). Los modelos espacialmente explícitos, ya sean de especies o de hábitats, son herramientas de gran utilidad de cara a la gestión medioambiental (Moran-Ordoñez et al., 2011). A su vez, cabe añadir que este tipo de resultados presenta un gran potencial de cara a analizar los efectos que las estrategias de gestión forestales a escala regional pueden presentar en el suministro de ES (Fürst et al., 2013; Frank et al., 2015).

A su vez, uno de los aspectos que deben considerarse es determinar la influencia que de los diferentes tipos de datos, metodologías o aspectos espaciales pueden tener en el análisis de ES. Por ejemplo, la cuestión de la escala espacial y sus efectos en las evaluaciones de ES ha sido analizada en profundidad en diferentes trabajos (p.ej. Hein et al., 2006; Martín-López et al., 2009; Grêt-Regamey et al., 2014). El suministro así como otras características de los ecosistemas relacionados con la provisión de servicios son fuertemente dependientes de la escala. Así, características internas de los datos, como la resolución espacial Konarska et al., 2002; Grêt-Regamey et al., 2014) o la resolución temática (Kandziora et al., 2013) condicionaran los resultados obtenidos. Otros factores, como el tipo de mapa empleado y las posibles impresiones derivadas del mismo (como por ejemplo una posible sobre-simplificación de los tipos de ecosistemas o del paisaje) también son destacadas por otros investigadores (Eigenbrod et al., 2010). Por estas razones, en este trabajo se exploraron el uso y la influencia que diferentes tipos de fuentes de información presentan en los patrones espaciales de ES.

Así, en Roces-Díaz et al. (2014) empleamos una base de datos con información sobre coberturas del suelo a una elevada resolución espacial (escala cartográfica 1:25,000; unidad mínima de mapeo entre 0.5 y 2 ha, dependiendo del tipo de cobertura). Esta base de datos no establecía una clasificación cerrada de si no que proporcionaba información cuantitativa de los tipos de cobertura que existían en cada uno de los parches del área de estudio, y por tanto es posible realizar una clasificación específica para cada caso. De este modo, los tipos de ecosistemas existentes en la zona estudiada pueden ser caracterizados de un modo preciso, atendiendo a la combinación de coberturas que los forman, y por tanto, pueden minimizarse alguno de los problemas asociados generalmente al empleo de mapas LULC en el análisis de ES (Eigenbrod et al., 2010; Hou et al., 2013). Así, basándonos en una clasificación muy detallada de los tipos de ecosistemas, identificamos las ESP de una serie de ES. Debe destacarse que uno de los errores más frecuentes se relaciona con la presencia de ecosistemas de pequeña extensión o escasa representación que aunque funcionen como ESP, pueden omitirse en mapas LULC de baja resolución, en los que se produce una simplificación de los tipos de ecosistemas y por tanto del paisaje. La elevada resolución espacial de la base de datos empleada también puede resultar de ayuda a la hora de reducir este problema. Mediante la vinculación entre el tipo de ecosistema y el suministro de ES, conseguimos disponer de un patrón de suministro para cada ES. El suministro está estrechamente relacionado con el tipo de ecosistemas presentes (la composición del paisaje), pero también con su distribución espacial (la configuración; Frank et al., 2011; 2013). El empleo del índice *lacunarity* en el análisis de ES fue destacado previamente (Syrbe and Walz, 2012) en relación a la caracterización de las zonas de no suministro. De esta forma, el uso de esta métrica, relacionada con la cantidad total de zonas sin suministro pero también con la regularidad de su distribución a diferentes escalas, resultó útil para establecer relaciones entre el suministro de ES y la composición y configuración del paisaje.

El análisis de *lacunarity* estaba basado en información que describe los elementos del paisaje de acuerdo a las características estructurales que los conforman, por lo que se considera una aproximación de tipo estructural. Por el contrario los resultados de Roces-Díaz et al. (2015b) están basados en el análisis del paisaje empleando datos relacionados con el funcionamiento de sus ecosistemas: una perspectiva denominada estructural. Este tipo de aproximaciones, basadas en información procedente de sensores remotos han sido estudiadas en profundidad por diferentes autores (p.ej. Paruelo et al., 2001; Alcaraz-Segura et al., 2006) para analizar entre otras cosas la heterogeneidad espacial del territorio. En este trabajo hemos empleado información procedente del sensor Landsat 5-TM. Trabajos previos (p.ej. Ayanu et al., 2012; Cabello et al., 2012) han puesto énfasis en el uso de información de sensores remotos para el análisis de ES debido a diferentes características de la misma, como por ejemplo la elevada resolución (espacial, temporal y/o radiométrica), la existencia de datos de tipo continuo, etc. Sin embargo, solamente en los últimos años se ha producido una proliferación de trabajos científicos basados en este tipo de información apara analizar ES (De Araujo-Barbosa et al., 2015). La combinación de un índice que estima la Productividad Primaria Neta de los ecosistemas durante un año fenológico (∑NDVI) con otras variables socio-ambientales permitió obtener modelos espacialmente explícitos del suministro de varios ES. Los patrones de dichos modelos fueron analizados a partir de dos métricas multi-escalares: *lacunarity* y 4TLQV. Basándonos en la idea de que el suministro de ES no es un proceso estático y homogéneo (Fisher et al., 2009), con la metodología empleada pudimos definir aquellas áreas con una mayor relevancia para el suministro de los ES analizados. De este modo los servicios de provisión presentaron patrones más agrupados mientras que los de regulación estuvieron más extendidos por toda el área de estudio. Estos resultados son congruentes con los obtenidos con la aproximación estructural en Roces-Díaz et al. (2014). De forma adicional cabe destacar que mientras que la *lacunarity* fue útil para detectar escalas características a nivel local, 4TLQV fue más sensible a niveles de análisis más amplios.

Dichos niveles de escala fueron analizados en ambos trabajos a partir de la forma de las curvas de *lacunarity* y la posición de los puntos de cambio de pendiente en las mismas. Por un lado, en Roces-Diaz et al. (2014) los patrones asociados a los mapas de tipo binario (solamente diferenciaron ESP y NO ESP) mostraron niveles característicos de escalas para los servicios de provisión con ventanas de 900 m de lado, que fue mayor para los ES restantes. Por otro, los resultados de Roces-Diaz et al. (2015b) presentaron un nivel de escalas superior, con un rango de tamaños de ventanas entre 2,400 y 3,300 m para los cinco ES analizados. Estos valores pueden interpretarse como los tamaños de ventana a partir de los que la distribución de zonas de no suministro comienza a regularizarse, y por lo tanto, el suministro puede considerarse como estable. Por dichas razones podría recomendarse que en el análisis de ES las zonas de estudio que se seleccionasen tengan siempre extensiones superiores a estos rangos de tamaños mencionados.

Además de estas aproximaciones de tipo estructural y funcional para la caracterización de aspectos generales sobre el suministro de ES, datos específicos sobre ecosistemas forestales fueron compilados de cara a analizar el suministro potencial de varios ES forestales. Así, en Roces-Díaz et al. (2015c) empleamos como información básica una cartografía temática de tipo forestal que incluía información de tipo estructural (las especies presentes en cada parche, sus porcentajes de cobertura, etc.) sobre estos ecosistemas. Esta base de datos fue combinada posteriormente con otra información, como estadísticas de aprovechamientos forestales, resultados de otros trabajos científicos, criterio de experto, etc. de cara a conocer el suministro potencial de seis ES relacionados de forma estrecha con ecosistemas forestales. La combinación de información de diferentes fuentes permitió una caracterización más precisa de los ecosistemas forestales de las que permiten otro tipo de fuentes cartográficas. Los modelos de suministro potencial de los ES obtenidos presentaron patrones espaciales muy diferenciados. Por ejemplo la provisión de alimentos y los servicios culturales presentaron un patrón más agrupado mientras que los servicios de regulación estuvieron extendidos de forma más regular por toda el área de estudio. Dichos patrones presentan numerosas similitudes a los obtenidos para estos ES en los otros trabajos mencionados (Roces-Díaz et al. 2014; 2015b). Las relaciones espaciales entre los ES forestales también fueron analizadas, mostrando dos grandes tipos de ecosistemas y patrones espaciales de suministro vinculados: i) plantaciones de crecimiento rápido (fundamentalmente con *Pinus* spp. and *Eucalyptus* spp.) que aparecen mayoritariamente vinculadas a la provisión de materiales, pero presentan valores bajos de otros ES; y ii) bosques autóctonos con menores niveles de crecimiento pero un mayor potencial para suministrar otros ES como regulación climática o servicios culturales. Esta estructura es congruente con los resultados de otros trabajos en los que se analizan los ES forestales en zonas cercanas (p.ej. Rodriguez-Loinaz et al., 2013; Onaindia et al., 2013; Palacios-Agundez et al., 2014). De forma adicional cabe indicar la presencia de zonas con gran relevancia para el suministro de ES (*hotspots*), que fueron identificados usando el estadístico Getis-Ord Gi*. A pesar de que el análisis de *hotspots* y *coldspots* es frecuente en análisis de ES en los últimos años (p.ej. Egoh et al., 2009; García-Nieto et al., 2013), pocos trabajos han empleado esta métrica, y en esos casos ha sido a escala local (Homolova et al., 2014) o a partir de datos de tipo puntual (Timilsina et al., 2013). Este hecho puede relacionarse con la reciente implantación de algoritmos para su cálculo en GIS durante los últimos años. Este estadístico puede ser de gran utilidad de cara a realizar delimitaciones precisas de las zonas más relevantes para el suministro de ES y presenta un gran potencial de cara a identificar aquellas áreas prioritarias para conservación en relación con los ES que proporcionan.

Conclusiones

Las principales conclusiones de este trabajo son:

1. Una vez definidos los nichos ambientales de las principales especies forestales autóctonas del área de estudio, puede concluirse que la variable que condiciona en mayor medida su distribución es la relacionada con las temperaturas mínimas de los meses invernales.
2. La delimitación espacial de estos nichos y de las áreas con una mayor idoneidad de hábitat para estas especies puede ser de utilidad en el análisis de ES. Así, los análisis de suministro potencial de estos ecosistemas o la comparación entre provisión potencial y real puede ser desarrollada en base a este tipo de modelos espaciales.
3. La aplicación del índice multi-escalar *lacunarity* a un mapa de coberturas de elevado nivel de detalle permitió analizar el patrón espacial de suministro de seis ES. Dos tipos de mapas de dichos ES fueron desarrollados basándonos en criterio de experto: mapas binarios y de escala de grises.
4. Los mapas binarios mostraron que los servicios de provisión presentar patrones más agrupados que los servicios de regulación y culturales. Los mapas de escala de grises presentan un patrón similar para los seis ES. La clasificación basada en criterio de experto funcionó aparentemente mejor con las dos categorías de los mapas binarios que con las cinco de los de escala de grises.

5. El empleo del índice *lacunarity* permitió la identificación de escalas funcionales a las que el suministro de dichos ES está teóricamente garantizado. Dichas escalas fueron similares, usando los mapas de tipo binario, para los ES de provisión y mostraron diferencias respecto a los de regulación y culturales. Dichas escalas no mostraron diferencias con los mapas de escala de grises.
6. La combinación de imágenes de sensores remotos y otras variables socio-ambientales en un GIS permitió desarrollar modelos relativos a cinco ES con una elevada resolución espacial que están basando en la productividad primaria neta de los ecosistemas en el área de estudio.
7. Los patrones de dichos ES mostraron diferencias claras a partir del análisis desarrollado mediante dos métricas multi-escalares: *lacunarity* y *four term local quadrat variance* (4TLQV). Los servicios de provisión presentaron patrones más agrupados y una mayor variabilidad para escalas de análisis extensas mientras que los servicios de regulación presentaron un patrón extendido de forma más regular por todo el área de estudio.
8. El análisis de *lacunarity* fue útil para detectar niveles de escala locales y para determinar cuando el dominio de escala implicó auto-similitud en el patrón de suministro. Por otro lado, 4TLQV se mostró más sensible a los niveles de escala que aparecen a extensiones de análisis mayores a las locales.
9. El empleo de un mapa temático de tipo forestal que integra información sobre la estructura y la composición de los ecosistemas permitió desarrollar un análisis de ES ligados a sistemas forestales de elevada precisión, aunque cabe indicar que se centró de forma exclusiva en este tipo de ecosistemas.
10. Se identificaron cuatro patrones diferentes de agregación y escala en los ES forestales: supra-regional (provisión de alimentos), intermedio sub-regional (provisión de materiales), bajo sub-regional (provisión de energía y culturales); y a dos niveles (regulación climática y de la erosión).
11. La identificación de *hotspots* de suministro potencial de estos ES forestales basadas en el estadístico Getis-Ord Gi* permitió una delimitación precisa de las zonas de elevado interés en relación a cada ES. Así las áreas cercanas a la costa, debido a la abundancia de plantaciones forestales, fueron de especial relevancia para el servicio de provisión de materiales. Por el contrario, las zonas con una mayor presencia de ecosistemas forestales

naturales o semi-naturales fueron clave en relación a los servicios de regulación y culturales.

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