Integrating species distribution models at forest planning level to develop indicators for fast-growing plantations. A case study of *Eucalyptus globulus* Labill. in Galicia (NW Spain)

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Abstract

Planting eucalypt stands in the Iberian Peninsula is controversial. In Galicia (NW Spain) the area covered by eucalypts and the intensity of eucalypt timber harvesting are among the highest in Europe. In this region, management plans for forest resources are intended for relatively homogeneous territorial units, smaller than the province, called forest districts (ForDis). The status of eucalypt plantations in ForDis is usually assumed to be highly variable, although this has not yet been quantified. Within this framework, the present study aimed to integrate an existing *Eucalyptus globulus* distribution model for current conditions and two different climate change scenarios with current forest cover (including eucalypt plantations) to provide quantitative and spatially-explicit information for identifying ForDis where eucalypt plantations may become problematic. Four parameters (suitability, importance, potential expansion and fragmentation) comprising 13 related indicators were calculated for eucalypt plantations in each of the 19 ForDis in the region. The findings show that more than 44% of the afforested area is covered by eucalypts in the province of A Coruña and in forest districts VI and XVIII (in Lugo and Pontevedra, respectively). A huge continuous patch of eucalypt, of more than 35000 ha, was detected across two ForDis (I and VI). The potentially high ecological and financial risks associated with this vast area of monoculture would negatively affect the sustainability and multifunctionality of these forest ecosystems. Analysis of the expected suitability of areas for *E. globulus* in forthcoming climate change scenarios identified four inland ForDis (IX, X in Lugo, XVI in Pontevedra and XI in Ourense) where an important increase in cover by this species may occur if no action is taken. Moreover, these areas overlap with the large ongoing expansion already observed for the more productive and frost-resistant *E. nitens*. The findings also revealed edge-dominated native broadleaved forest patches in the habitat suitable for *E. globulus* in the provinces of A Coruña and Lugo. Although the current level of occupancy of eucalypt within natural protected areas (NPAs) is moderate, the suitability of these areas for eucalypt plantations will increase in the predicted climate change scenario,

possibly leading to aggravation of potential conflicts in these biodiversity hotspots. Regional forest agencies should therefore increase monitoring efforts to prevent further impacts on native forest and natural protected areas.

The proposed quantitative indicators and methodology used are intended to be useful for forest planners and policy decision-makers in other regions where current and future conflicts related to exotic tree plantations are expected.

Keywords

Tasmanian blue gum, forest planning, forest plantations, natural protected areas, species distribution models, climate change.

1. Introduction

Forests are increasingly recognized to be important for tackling many of the current great challenges as they provide many goods and services demanded by society (Freer-Smith et al., 2019). Although the global forest area decreased by 4.2% in the period 1990-2020, planted forest increased by around 72.4% in the same period (FAO, 2020). The increment is explained by the response to the need to satisfy the increasing demand for timber resources, which has mainly been supported by establishing plantations of fast-growing species belonging to genus such as *Pinus*, *Eucalyptus*, *Populus*, *Acacia* and *Tectona* (FAO, 2010). These plantations also play a dual role in helping to mitigate climate change (Freer-Smith et al., 2019) by *i*) acting as efficient CO_2 sinks and *ii*) providing the raw material for producing thermal and electrical energy from forest biomass. Consequently, fast growing forest plantations will make an important contribution to the inevitable transition of fossil-fuel-based economies to economies based on clean energy with a low carbon footprint.

Fast-growing plantations are often based on exotic species grown as monocultures with short rotations, and greater control and planning efforts are thus required to guarantee sustainable management and to preserve ecological processes and forest ecosystem biodiversity (Freer-Smith et al., 2019). Species distribution models (SDMs), which can be used to quantify potentially suitable habitat for particular species (Guisan and Zimmermann, 2000), are powerful tools for use in conservation planning, despite some limitations or weakness (McShea, 2014). These models are particularly important when dealing with planted species for which the current or future potential suitable habitat may already be covered by native forests or fall within natural protected areas (NPAs) (López-Sánchez et al., 2021).

Within the framework of forest planning, SDMs can be used to predict future landscape scenarios on the basis of projected climatic variables under different climate change scenarios. This makes it possible to develop useful indicators that can be directly integrated in forest planning documents enabling direct links with policy- and decision-making process (McShea, 2014). Such indicators can be direct or surrogate estimates of key features of forest ecosystems (such as integrity and resilience) and also enable assessment of temporal and spatial changes (Ćosović et al., 2020). Overall, this type of information will be also useful for stakeholders, and the integration of SDMs-derived outputs at forest planning scale should therefore contribute to mitigating the so-called "assessment-planning gap". This gap refers to the difficulty in constructing reliable conservation planning strategies due to non-applicable scientific findings and the lack of true involvement of relevant stakeholders in the planning process (Villero et al., 2017).

The study area (Galicia) is an autonomous region in NW Spain with very suitable environmental conditions for growing trees. The region is considered one of most productive forest areas in Europe (García-Villabrille et al., 2014) and it is by far the most important timber-producing region in Spain (Gómez-García, 2020). For more than a thousand years, until almost the middle of the 20th century, a non-wooded forest landscape, with alternating shrubland, extensive pastures and agricultural crops, clearly dominated in the region (Xunta de Galicia, 2018b). Nevertheless, the increasing demand for timber for industrial purposes, together with the suitable environmental conditions, led to wide scale afforestation from the middle of the 19th century onwards, mainly with three highly productive species: *Pinus pinaster* Aiton, *Pinus radiata* D. Don and *Eucalyptus globulus* Labill. In the last two decades, *Eucalyptus nitens* (Deane and Maiden) Maiden has also been added to this group of highly productive species. Plantations of these species, together with the abandonment of traditional agricultural activities, act as the main drivers of the great forest landscape transformation in the last century in the region (Marey-Pérez and Rodríguez-Vicente, 2009; Corbelle-Rico et al., 2015). Galicia was thus transformed into an eminently forest region where 67.7% of the territory is currently categorised as forest and almost a half as wooded land (Xunta de Galicia, 2018b). Plantations of the above-mentioned major four species currently cover 57.46% of the total wooded area (MAPA, 2019a) and play a key role in the Galician forestry sector, representing 92.27% of the average timber volume harvested in the period 2005-2016 in the region (7669591 m^3) and almost a half of the same (48.66%) in the whole of Spain (MAPA, 2019b). Moreover, the existence of these plantations led to Galicia being one of the regions in Europe with the highest intensity of forest harvesting in the period 2000-2010 (Levers et al., 2014).

At landscape scale, the conversion of native forest or highly biodiverse natural vegetation into forest plantations may have important consequences for native ecosystems, including habitat loss and fragmentation, thus decreasing the size of remaining habitat patches and increasing their isolation (Hanski, 1999). As a result, the probability of successful dispersal and establishment of individuals and the persistence of populations in smaller and more isolated habitat patches will be reduced, with negative impacts on local and regional species richness (Harrison and Bruna, 1999; Teixido et al., 2010; Lomba et al, 2011). However, forest plantations established on former agricultural or otherwise degraded land may provide important opportunities for biodiversity conservation (Parrotta et al., 1997). Thus, the impact of forest plantations on biodiversity will depend on the type of land use they replace (Pawson et al., 2013) and also on the percentage of landscape covered. Analysis of landscape configuration or spatial patterns is therefore very important in any study seeking to guarantee ecosystem goods and services and particularly biodiversity conservation. This type of analysis is usually carried out using a wide array of metrics describing the size, shape and isolation of forest patches (e.g. McGarigal and Marks, 1994; Hargis et al., 1998).

The greatest expansion of eucalypt plantations occurred from the middle of the 20th century and was mediated by two major events: *i*) the beginning of the industrial production of pulp from eucalypt in Portugal in the 1950s (Bermudez et al., 2002) and *ii*) the installation of pulp mills in Galicia and in the nearby region of Asturias during the 1960s and 1970s (Riesco, 2004). Most of the plantations are of *E. globulus*, but since 1992, commercial plantations of *E. nitens* have also been established (Pérez-Cruzado, 2011). Both eucalypt species currently occupy an area of 345326 ha (MAPA, 2019a), which in the period 2005-2016 provided an annual average timber harvest of 3787104 m^3, representing 49.38% of the total volume harvested in the region and 26.05% in the whole Spain (MAPA, 2019b). The rapid expansion of eucalypt species was mainly due to afforestation of non-wooded land (shrubland and abandoned agricultural land). Nevertheless, the high profitability of commercial eucalypt plantations has led some forest owners to clear-cut patches of native forest for reforestation with *E. globulus* and *E. nitens*. Moreover, some plantations were established in natural protected areas, aimed at protecting biological diversity and the habitats that sustain the diversity. In these areas, uncontrolled proliferation of exotic eucalypt plantations may jeopardise conservation goals.

The overall objective of this research was to provide indicators of the current and foreseeable future situation of eucalypt plantations in Galicia for use in formulating or revising forest planning documents (PORFs) at the forest district (ForDis) level. With this goal, we integrated an existing species distribution model (SDM) for *E. globulus* with spatial information about forest cover, current species distribution and timber harvesting rates. The case study focused on eucalypts plantations in Galicia due to the importance of these trees in Southern Europe.

2. Materials and methods

2.1. Study area

The study was carried out in Galicia (NW Iberian Peninsula) (Figure 1). The region occupies an area of 29575 km^2 and has a marked variation in elevation, ranging from 0-2127 m above sea level, with a correspondingly variable climate. The region has a mild oceanic climate, with an average annual temperature of 10–14 ºC and average annual rainfall of 800–1500 mm, with the lowest precipitation rates occurring during the summer months. The coastal area is characterized by mild temperatures and abundant, uniformly distributed rainfall. The more continental inland area experiences more seasonally extreme temperatures. The predominant soils are developed on granitic rock and acid schist, have a loam or sandy loam texture and are well drained.

Insert here Figure 1

2.2. Forest land planning framework

In Spain, responsibility for forest management was transferred from the Spanish government to the autonomous governments in the middle of the 1980s. As a result, the autonomous governments are currently almost the exclusive authorities in the forestry sector (MMA, 2002). In the autonomous community of Galicia, the Galician Forest Plan (PFG) is the main forest policy document and has been in force since 1992. The PFG provides the overall direction and guidance for the entire afforested area in the medium and long term, in order to satisfy the demand for resources by society and also to guarantee biodiversity conservation. The forest planning documents, which develop PFG prescriptions, are generally known as “forest resource management plans” (PORFs) and are intended for the territorial units designated as forest districts (ForDis). The 19 existing ForDis in Galicia cover large areas, although smaller than the province, and are characterized by homogeneous geographic, socioeconomic, ecological and cultural features (Marey Pérez et al., 2006; Xunta de Galicia, 2018a).

One of the major characteristics of the Galician forest sector is the type of forest ownership and size. Thus, private forests comprise 97.3% of Galician forest land, of which 64.2% of plots of mean size of 1.7 hectares are individually owned. This land is often divided into up to ten non-contiguous parcels, yielding a mean surface area of only 0.26 ha. Around 33.1% of private forests are owned by communities and occupy an average area of 223 ha (Xunta de Galicia, 2018b). This scattered and very small private ownership is one of the primary hindrances to further development of the sector (Robak et al., 2012), although great efforts have been made during the last few decades to overcome this structural problem through land consolidation and the creation of forest societies.

2.3. Sources of data

Four different sources of data were considered in this study: *i*) a map of the current distribution of eucalypt plantations; *ii*) a raster-based SDM of suitable habitat for *E. globulus*; *iii*) a map of types of forest cover; and *iv*) the average amount of timber harvested in 2018 and 2019 in each ForDis.

The current eucalypt distribution and area involved ($EU_{SNFI4.5}$) were obtained from the 2018 update of the Fourth Spanish National Forest Inventory for the most productive forest species in northern Spain (hereinafter SNFI4.5) and its associated vectorial forest-cover map (scale 1:25000) (MAPA, 2019a). This map provides an accurate delineation of eucalypt-dominated forests, with a minimum patch area of 2.5 ha (Alberdi et al., 2017).

In order to estimate the current and future suitable habitat for *E. globulus*, we used the raster-based SDM developed for northern Spain by López-Sánchez et al., (2021). Three spatially continuous maps were obtained by applying the model developed to a list of current environmental variables (current suitable habitat) and to future climate variables reflecting two climate change scenarios, i.e. moderate (RCP 4.5) and pessimistic (RCP 8.5) for the 2050 time horizon (future suitable habitats).

To assess the distribution among ForDis of the types of forest cover that could be affected by a hypothetical expansion of eucalypt in its suitable habitat, we used the 2018 version of the CORINE Land Cover database (CLC2018). This database provides the land-related data at 20 m spatial resolution and considering a minimum mapping unit of 25 hectares (EEA, 2019). The nomenclature of the vector data has 3 hierarchical levels. The classes in the first level are artificial surfaces, agricultural areas, forests and semi-natural areas, wetlands and water bodies. The second level has 15 classes and the third level, 44 subclasses. Although the more detailed classes do not discriminate tree species, use of this database enabled us to differentiate different types of forest cover (coniferous, broadleaved and mixed forest) and other types of land use.
Statistics on timber harvested in 2018 and 2019 in each ForDis were recorded by the regional government and are freely available online (Xunta de Galicia, 2020).

2.4. Data analysis

Data from the four sources of information were combined to produce metrics at two spatial forest planning levels (ForDis and natural protected areas, NPAs) and for three time horizons (current situation and two future scenarios under climate change projections) (Figure 2).

Insert here Figure 2

2.4.1. Integrating current and potential suitable eucalypt areas with types of forest land cover

We first calculated metrics for different forest cover types from the following five layers: *i*) current and future suitable habitat for eucalypt obtained from the available SDM model (López-Sánchez et al., 2021); *ii*) current cover by broadleaved forest (code 311 of CLC2018); *iii*) current cover by coniferous and mixed forest (codes 312 and 313 of CLC2018); *iv*) current cover by other types of forest and semi-natural land (codes 321, 322, 323, 324, 333 and 334 of CLC2018); and *v*) current *E. globulus* ($EUGL_{SNFI4.5}$) and *E. nitens* ($EUNI_{SNFI4.5}$) cover, obtained from the SNFI4.5 (MAPA, 2019a).

For the current situation, the land occupied by several forest cover categories was determined at two different spatial levels (ForDis and NPAs). For the spatial definition of the NPAs, we used the official, freely available vectorial mapping for these areas (MITECO, 2019). As result of this procedure, we determined the following four forest cover categories for each ForDis:

- Current area occupied by eucalypt plantations ($EU_{SNFI4.5}$), by summing $EUGL_{SNFI4.5}$ plus $EUNI_{SNFI4.5}$.
- Current area occupied by native broadleaved forest (S_{NBF}) and the area included within the current eucalypt suitable habitat (SH_{NBF}). These were obtained on the basis of the difference between the current area of broadleaved forest (code 311 of CLC2018) and the current area occupied by eucalypt ($EU_{SNFI4.5}$) and acacia stands. This assumption appears valid, as the recent SNFI4.5 only inventoried 1217.6 ha of exotic broadleaved forest (*Acacia* sp.) within the current *E. globulus* suitable habitat in the whole study area.
- Current area occupied by coniferous and mixed forest (S_{CMF}) and the area included within the current eucalypt suitable habitat (SH_{CMF}). These were obtained by including the current area of conifer and mixed forest (codes 312 and 313 of CLC2018, respectively).
- Current area occupied by other natural and semi-natural land (S_{FSA}) and the area included in the current eucalypt suitable habitat (SH_{FSA}). These were obtained by considering the following CLC2018 codes: 321 (natural grassland), 322 (moor and heathland), 323 (sclerophyllous vegetation), 324 (transitional woodland-shrub), 333 (sparsely vegetated areas) and 334 (burnt areas).

In addition, the areas occupied by the same forest cover categories were calculated by considering the future suitable habitat for *E. globulus*. For this purpose, the SDM developed for the species by López-Sánchez et al. (2021) was implemented for two different climate change scenarios predicted for 2050: moderate (RCP4.5) and pessimistic (RCP8.5). The "moderate scenario" (RCP 4.5) assumes a CO_2 concentration of 650 ppm and a temperature increase of 1.0–2.6 °C by 2100, whereas the "pessimistic scenario" (RCP 8.5) considers a CO_2 concentration of 1350 ppm and a temperature increase of 2.6–4.8°C by 2100.

2.4.2. Features analysed and indicators

Several issues concerning fast-growing forest plantations must be addressed in order to understand current and potential expansion and landscape configuration. These concerns are very important for guaranteeing ecosystem goods and services, and particularly biodiversity conservation. Within this framework, analysis of four factors in each ForDis was proposed in relation to the current and foreseeable future situation of eucalypt plantations: *i*) suitability, *ii*) importance, *iii*) potential expansion and i*v*) fragmentation (see Table 1 for a complete description of each).

We used the degree of suitability (DS) indicator to assess the suitability of the habitat for *E. globulus*. The current importance of eucalypt was assessed by both the degree of occupancy (DO) and the economic relevance (ER). In order to calculate these indicators, we considered the area occupied by both *E. globulus* and *E. nitens*, as timber harvesting data do not discriminate between these two species.

The potential for expansion of the species was assessed by considering the different forest cover types currently existing within the suitable habitat for *E. globulus*. Thus, three different potential expansion indicators were calculated: *i*) potential for replacement (PR), which evaluates the potential replacement of native broadleaved forests by the exotic species *E. globulus*; *ii*) potential for substitution (PS), which evaluates the potential substitution of other non-native species (mainly *Pinus* spp. in the study area) by *E. globulus*; and *iii*) potential for afforestation (PF), which evaluates the potential for establishment of new *E. globulus* forest in natural and semi-natural non-wooded areas.

In addition, we used the FRAGSTATS 4.2 spatial analysis program (McGarigal *et al.,* 2016) to quantify the degree of habitat fragmentation for eucalypt and native broadleaved cover. We only analyzed these two types of forest cover as we wanted to compare the status of eucalypt plantations with the less altered native forests, which are of greater interest in term of biodiversity and other ecosystem services (Calviño-Cancela et al., 2012). We used several fragmentation indices related to patch size, core area and aggregation (Table 1). A 30 m-edge influence was applied for calculating the core area metrics (Laurance, 2000; Midha and Mathur, 2010).

Insert Table 1 here

3. Results

In this section we present the values of the thirteen indicators used for the two levels of spatial analysis (ForDis and NPAs) for the current situation and the 2050 time horizon under two climate change scenarios. Results of landscape fragmentation analysis for both ForDis and NPAs are also included.

3.1. Assessing the current situation within ForDis and NPAs

3.1.1. Eucalypt suitability and importance

The results obtained for DS, DO and ER indicators are shown in Table 3. According to these results, a high proportion of the land in the province of A Coruña (94%) is suitable for growing *E. globulus*, followed by Pontevedra (82%), Lugo (21%) and Ourense (with only 4%). These results are consistent with the area currently occupied by the species in A Coruña, already more than 200000 ha (Table 2), which is equivalent to 54% of degree of occupancy (DO) at province level. At forest district level, the DO exceeded 45% in all ForDis and reached 65% in one of them (ForDis I-Ferrol). The economic relevance (ER) indicates that eucalypt harvesting accounts for more than 60% of the total volume harvesting in all the ForDis of the province, reaching 88% in ForDis I-Ferrol (Table 3, Figure 3).

Insert Table 2 here

As a consequence of the very high suitability of the land for growing eucalypts, a total of 67% (3285 ha) of the whole area of eucalypt plantations included in NPAs in Galicia (4962 ha) is in the province of A Coruña. This area is mainly concentrated in ForDis I-Ferrol (Table 2). In A Coruña, the degree of suitability (DS) of NPAs for eucalypts is slightly lower (10% lower), than in the rest of the province, and the degree of occupancy (DO) is much lower (53.7% for the whole province compared with 29.5% for NPAs). The maximum DO value again corresponds to ForDis I-Ferrol (32.1%).

Eucalypt is globally moderately important in the province of Lugo according to the current suitability and occupancy of the species (21% for both indicators). However, the highest occupancy by eucalypt (DO) in the whole Galicia occurs in one seaboard forest district (ForDis VI-A Mariña Lucense), with a DS of 90%, with 70% of the wooded surface occupied by eucalypt (64000 ha) (Tables 2 and 3). Only one other ForDis in the province of Lugo has significant suitability or occupancy of the species, the ForDis X-Terra Chá, which is close to the coast. A quarter of the forest area in this ForDis is suitable for *E. globulus* and at present 21% of the wooded land is covered by eucalypt (Figure 3). Two ForDis (VII-A Fonsagrada-Os Ancares and IX-Lugo-Sarria) with low eucalypt occupancy (DO of 1.6 and 7.1%) and suitability (DS of 0.0 and 3.3%) have, however, higher ER values (19% and 22%, respectively) than expected a priori. Globally, the presence of the species in NPAs in the province of Lugo is very low (DO = 3%) and the suitability of the NPAs is 7% (Table 3). Nevertheless, DS values of 58% and 19% and DO values of 31% and 7% were obtained for respectively the seaboard ForDis VI-A Mariña Lucense and the neighbouring ForDis X-Terra Chá.

The province of Pontevedra is the third most important according to current area occupied by eucalypt, with 52540 ha (Table 2). However, according to the suitability (82%) and degree of occupancy (27%) at province level, the province ranks second. One ForDis (XIX-Caldas-O Salnés) stands out, with 44% of its wooded area covered by eucalypt and an ER of 70%. The DO values are between 10-30% and the ER between 32-45% for the remaining ForDis (Table 3, Figure 3). ForDis XVI- Deza-Tabeirós is similar to ForDis VII and IX in Lugo, with a low presence of eucalypt (DO = 10%) but a relatively high economic relevance (ER = 32%). Regarding the NPAs in this province, with the exception of ForDis XVI, with DS of 39%, the DS is greater than 95% in the three remaining ForDis, although the DO is always lower than 10%. However, the indicators of potential expansion are always greater than 60% (Table 3).

Ourense is the only inland province of Galicia and this is the main reason why the suitability is relatively high (DS = 24%) in only one ForDis (XI-O Ribeiro-Arenteiro), although the DO is currently only 1%. In contrast to expectations considering the values of these indicators, and similar to what is observed in ForDis VII, IX and XVI, the ER is 18% (Table 3, Figure 3). There is no relevant presence of eucalypt in the NPAs in the province of Ourense (Table 3).

Insert Table 3, Figure 3 here

3.1.2. Potential expansion of eucalypt

As a result of the almost total suitability of the land in the province of A Coruña for eucalypt, the values of all of the potential expansion indicators are very high. The potential for replacement (PR) values are higher than 90% for all ForDis, indicating that more than 90% of the native forest is growing in suitable habitat for *E. globulus*. Similar values were obtained for the potential for substitution (PS), indicating that most coniferous or mixed forest could also be substituted by eucalypt. The percentage of natural and semi-natural non-wooded areas included in the suitable habitat for *E. globulus* (potential for afforestation, PF) is high and greater than 75% in all ForDis. Analysis of the potential expansion indicators at the spatial level in NPAs produced similar results, with average PR, PS and PF of 80-90% for the whole province and values between 50-100% for the different ForDis (Table 3, Figure 3).

As for suitability and abundance, in the province of Lugo the potential for expansion was only relevant in the ForDis VI-A Mariña Lucense, with PR = 95%, PS = 75% and PF = 71% (Table 3). PR values of 65% and 19% and PS and PF values between 19 and 51% were obtained for the NPAs in the above-mentioned ForDis and its neighbouring ForDis X-Terra Chá.

Overall for the province of Pontevedra, the values of the indicators were 83% for PR, 90% for PS and 68% for PF; these values are very similar to those obtained for A Coruña. The potential rates of replacement, substitution and afforestation with eucalypt were also very high in the NPAs in the province of Pontevedra. In the inland province of Ourense only the ForDis XI-O Ribeiro-Arenterio displayed a significant potential for *E. globulus* expansion, with values of

19-32% for the expansion-related indicators (Table 3, Figure 3). Correspondingly, a significant potential for replacement was only observed in this ForDis, with a value of 14%.

3.1.3. Landscape fragmentation

In the province of A Coruña, the mean patch size (MPS) is between three and fifteen times greater for eucalypts than for native broadleaved forest. The greatest differences (15 and 8 times greater) occur in ForDis I-Ferrol and ForDis II-Bergantiños-Mariñas Coruñesas, respectively (Table 4, Figure 3). The MPS of the native broadleaved forest is almost constant throughout the province, with values of between 3 and 5 ha, whereas the values for eucalypt ranged from 15-38 ha. The largest patch index (LPI) indicates a huge continuous area occupied by eucalypt in ForDis I, with a value of 26%, equivalent to almost 35000 ha of continuous eucalypt cover. Remarkably, the largest area of native broadleaved forest patch (LPI = 1.6%), with 2150 ha of continuous native forests, also occurs in this ForDis. Regarding the core area, the total core area (TCA) of eucalypt plantations is 2-4 times greater than in native forest. The most surprising finding was that the mean core area (MCA) is 3-19 times greater in eucalypt plantations. Indeed, the highest values for eucalypts (35.8 and 17.2) and the lowest values for native forest (1.9 and 1.7) were observed in the above-mentioned ForDis, I and II respectively (Table 4). The aggregation metrics indicate that in the whole province patch density (PD) is on average two times greater in native forest than in eucalypt forest, but it is six times higher in ForDis I. The nearest neighbor distance (ENN), as a consequence of greater fragmentation, is lower in native forest (85 m) than in eucalypt plantations (120 m). The situation is more encouraging regarding the fragmentation analysis of NPAs included within the eucalypt suitable habitat in the province of A Coruña. Thus, MPS of native forest patches is 1-5 times greater than that of eucalypt patches, although the maximum value of MPS in the five ForDis in the province does not exceed 9 hectares. The mean shape index (MSI) values are greater than in eucalypt patches, indicating greater irregularity. Additionally, the total core area (TCA) and mean core area (MCA) are higher in native forest patches than in eucalypt plantations patches, although the values of the latter indicator are below 7 ha (Table 4).

In the province of Lugo, the worst scenario in terms of fragmentation of native forest in the whole Galicia occurs in ForDis VI-A Mariña Lucense. In this ForDis, eucalypt MPS is twenty-five times greater than native forest (75 ha *vs*. 3 ha) with a huge LPI of 40%, which implies the existence of continuous area occupied by eucalypt of more than 50000 ha (Figure 4). The MCA in this ForDis is 62 ha for eucalypt and 2 ha for native broadleaved forest, which indicates that most native forest patches are edge habitats (Figure 5). Within NPAs, similar MPS values were found for eucalypt and native forest (around 3-4 ha), showing that the area occupied by eucalypts is more fragmented but is still abundant, as indicated by the higher TCA of eucalypt (1.5 times) than of native forest (Table 4). The MPS values in the other ForDis in the province of Lugo are lower than 7.3 ha and are always lower than MPS values for native forest (up to 7.4 ha), and the situation in NPAs is similar. The TCA is also much higher in native forest than eucalypt and the LPI comprised between 0.1 and 0.7% of the forest area, which implies maximum areas of continuous occupation by eucalypt of up to 217 ha.

The inland province of Ourense does not have large areas of continuous cover by eucalypts and only ForDis XI and XII have LPI values of 0.1%, which implies maximum continuous cover by eucalypt of up to 25 ha. In Pontevedra, ForDis XVIII and XIX present highest LPI (2-2.2%) which implies largest continuous patches of 1900-2400 ha and MPS reaches 20-25 ha with 7.9-6 ha for native forest, respectively. The MCA is 14.5-18.6 ha for eucalypt and 5.8-4.0 ha for native forest and the PD is 0.47-0.9 in eucalypt and 1.7-2.9 in native forest indicating a high degree of fragmentation of native forest. The remaining ForDis have the largest continuous patches of eucalypt, of between 452-1080 ha, with greater LPI for native forest than eucalypt (2.9-5.5 *vs*. 1.1-0.8).

Insert Table 4, Figure 4 here

3.2. Forecasting indicators in climate change scenarios

Projected indicator values for foreseeable climate change scenarios do not show important changes for the province of A Coruña, as almost the whole province is already suitable for *E. globulus*. However, some important changes are expected for two ForDis in each of the remaining three provinces. In Lugo, for the 2050 time horizon, the degree of suitability is expected to increase by between 35 and 52% and the potential expansion indicators by between 33 and 62% for the non-mountainous inland ForDis (IX-Lugo-Sarria and X-Terra Chá) (Table 5). Globally, this province will increase the suitability for *E. globulus* by between 12 and 15% for 2050 under moderate and pessimistic climate change scenarios, respectively. Future projections also show two ForDis of the Ourense province with an important increase in suitability for *E. globulus* (XI-O Ribeiro-Arenteiro and XII-Miño-Arnoia), which will increase by between 57-70% and 30-60% for 2050 under moderate and pessimistic climate change scenarios, respectively, with a similar increase in the expansion indicators (Table 5). In Pontevedra, ForDis XVI- Deza-Tabeirós and ForDis XVII-O Condado-Paradanta are expected to suffer increases in DS of 27-31% and 13-15% under the respective climate change scenarios. The increases will also apply to the NPAs within each of the ForDis, so that a similar pattern to that corresponding to the rest of the territory is expected for these natural areas (see Table 5).

Insert Table 5 here

4. Discussion

4.1. Eucalypt suitability and importance

A wide range of suitability and importance of current eucalypt plantations is observed across the autonomous region of Galicia. The higher suitability for eucalypt in the seaboard provinces without very mountainous areas (A Coruña and Pontevedra) and in ForDis VI-A Mariña Lucense (in the coastal area of the province of Lugo) highlight the preference of the species in Galicia for a temperate climate (López-Sánchez et al., 2021). The high suitability in the province of A Coruña is also accompanied by the importance of the species in this area, reaching the highest percentage of the total wooded surface occupied by eucalypt in Northern Spain and representing 75% of the mean annual volume harvested in the province. In the province of Pontevedra, both the suitability (between 63 and 95%, depending on ForDis) and economic relevance (an average of 49%) indicators are slightly lower than in A Coruña. This can be attributed to the fact that the degree of occupancy of pine plantations and mixed forest in the province of Pontevedra is almost twice that in the province of A Coruña (MAPA, 2019a). The province of Lugo includes the ForDis in Galicia with the highest percentage of eucalypt cover over its wooded surface (ForDis VI- A Mariña Lucense). The environmental conditions in the inland province of Ourense, with large mountain areas and important influence of Mediterranean climate, are not very suitable for the species (López-Sánchez et al., 2021), and therefore the values for the three indicators are very low.

Some surprising findings were obtained for the indicators in Four ForDis (VII-A Fonsagrada-Os Ancares, IX-Lugo-Sarria, X-O Riberiro-Arenteiro and XVI-Deza-Tabeirós). Thus, although the values for suitability and occupancy are very low in these areas, eucalypts account for between one fifth and one third of the total volume harvested, i.e. the economic relevance of eucalypt in those districts is rather high. There are two possible reasons for this finding: *i*) the very high productivity of *E. nitens* and *ii*) the “hidden” area occupied by eucalypt in these ForDis. During at least the past two decades, *E. nitens* has been planted by landowners in these inland areas of Galicia (Pérez-Cruzado, 2011; González-García et al., 2015). The owners often choose this species because it is more frost resistant than *E. globulus* (Prado and Barros, 1989). Many of these plantations occupy very small areas (often less than 1 hectare) as a consequence of the extremely high fragmentation of forest property in Galicia (Ónega-López et al., 2008). These very small patches are not considered in the current forest cover maps because their spatial resolution is lower than the patch size. Therefore, the economic importance indicator in these ForDis becomes a suitable proxy for the existence of the "hidden" area occupied by eucalypt. Moreover, due to the greater tolerance of *E. nitens* to lower temperatures, this species is spreading through these ForDis towards inland Galicia.

In Galicia, a review of the PFG is currently ongoing, and once approved it will establish the main guidelines for the Galician forestry sector for the next twenty years (Xunta de Galicia, 2018a). Forecasts for this time horizon in the PFG establish a maximum of 268000 ha for *E. globulus* and 70000 ha for *E. nitens* (Xunta de Galicia, 2018b). Our results show that the current area occupied by *E. globulus* exceeds this amount, and the target area forecast for *E. nitens* have probably already been reached. These findings suggest that measures should be taken to reduce the abundance of eucalypts, although this does not necessarily imply a reduction in the economic relevance of the species. A reduction in the area occupied can be accompanied by increasing plantation productivity through the application of adequate silvicultural practices by selecting more productive forest land for establishing new plantations and/or applying the results of genetic improvement programs (Binkley et al., 2017). These measures can be also complemented by the conversion of mixed eucalypt stands to pure pine or native broadleaved forest, as already encouraged by the forest authorities through financial aids (DOG, 2019) and even by forbidding replacement of current pine stands by eucalypt plantations.

Although eucalypt is not very common in NPAs, reduction of its presence in these areas is desirable (Teixido et al., 2010). Regional regulations forbid the establishment of new eucalypt plantations in sites included into the Natura 2000 network (DOG, 2014). Nevertheless, plantations established prior to 2014 can continue to be managed in successive rotations (DOG, 2014). Most of the plantations were already present in most of the Natura 2000 sites whole the Iberian Peninsula when these were designated as protected areas, as pointed out by Deus et al. (2018).

4.2. Potential expansion of eucalypt

Forest districts within provinces where the suitability for *E. globulus* is currently high (A Coruña and Pontevedra) also have high values for potential expansion (replacement, substitution and afforestation). The large increase in suitability of this species under climate change scenarios also indicates large increases in potential expansion in the future in six ForDis: IX and X (Lugo), XI and XII (Ourense) and XVI and XVII (Pontevedra). Moreover, the eucalypt-suitable habitat in the study area has already increased due to the introduction and expansion of *E. nitens* (González-García et al., 2015). This species, which grows adequately in the current *E. globulus* suitable habitat, has several features that make it preferred by forest owners: *i*) it is frost tolerant (it tolerates temperatures as low as -10 ºC; Prado and Barros, 1989); *ii*) it shows a greater energy potential in the various tree biomass components compared to *E. globulus* when forest waste is used for biomass production (Pérez et al., 2006); and *iii*) it exhibits high growth rates (MAI in total volume with bark up to 46 m^3/ha/year in the best sites; Diéguez-Aranda et al. (2012), even greater than *E. globulus* (32–36 m^3/ha/year); García-Villabrille, 2015; Viera et al., 2016).

In general, in Galicia, eucalypt plantations can be planted in former agricultural land and in shrublands (i.e. afforestation), or in former pine plantations (i.e. substitution). Nevertheless, plantations in former native forest (i.e. replacement) are forbidden by existing forest law (DOG, 2012). Nevertheless, this law is inadequately monitored and replacements do occur in certain areas.

Substitution of previous maritime and radiata pine plantations by eucalypts has occurred for more than one decade, mainly in inland areas in the provinces of A Coruña and Lugo (González-

García et al., 2015). The species most commonly used is *E. nitens* (López-Sánchez et al., 2021), which is even substituting previous *E. globulus* plantations in areas affected by *Gonipterus platensis* (> 350 m.a.s.l and shallow soils) as it is less affected by this pest (Martín Gil et al., 2018; Gonçalves et al., 2019). A similar substitution process for conifer species has occurred in Portugal (Mendes, 2007; Vaz et al., 2019).

As the forest authorities generally have insufficient resources for monitoring forestland, some forest owners have replaced clear-cut native forest with new eucalypt plantations. To protect and enhance native forests, the regional government has recently established an official database of native broadleaved forest covering areas greater than 15 ha, so that owners will be eligible for tax benefits and will be given priority for receiving public grants for sustainable management and conservation (DOG, 2020). Nevertheless, this measure may be insufficient in view of the high potential of replacement of *E. globulus* in forest districts in coastal provinces and *E. nitens* in inland areas, which could lead to aggravation of the potential conflicts concerning the natural forests. In particular, greater effort must be made to monitor eucalypt expansion in some mountainous inland areas with large areas of native forest and where the economic relevance of eucalyptus reveals a significant presence of *E. nitens* in very small plots (i.e. VII- A Fonsagrada-Os Ancares).

In summary, four major challenges arise concerning eucalypt expansion: *i*) high future values of potential expansion indicators for *E. globulus*; *ii*) current strong expansion of *E. nitens* (González-García et al., 2015); *iii*) increasing demand for raw material for energy production (e.g. a new biomass power plant consuming around 500000 Mg of forest biomass has recently been installed in Galicia (Rico, 2018)); and *iv*) foreseeable demand for raw material for new bioproducts, such as fibre for the textile industry (e.g. Xu et al., 2017; Yañez-S et al., 2018).

Indeed, eucalypt plantations represent one of the best ways for forest owners in Galicia to obtain profits from their small, highly scattered plots (Díaz-Balteiro et al., 2009; Arenas et al., 2019). Nonetheless, in view of the major challenges mentioned above, regulations for establishing new eucalypt plantations are recommended. Specifically, decision-makers should be urged to control substitution of previous coniferous plantations and to increase efforts involved in monitoring native broadleaved forests to prevent their replacement.

4.3. Landscape fragmentation

The largest patch index (LPI) values indicated huge continuous areas of eucalypt in ForDis I-Ferrol and VI-A Mariña Lucense, of respectively 35000 and 50000 ha. Large LPI values were also observed in other ForDis within the province of A Coruña (range from 1470 to 10179 ha) and in the ForDis in Pontevedra (range from 429 ha to 2435 ha).

Very large areas of continuous eucalypt plantations should be avoided due to high biotic, abiotic and financial risks (Freer-Smith et al., 2019) and also because this can exacerbate the negative impacts of the species (Montero de Burgos, 1990; Veiras and Soto, 2011). Moreover, the biotic and abiotic risks do not act independently, and the impacts may accumulate (Jactel et al., 2019). From the point of view of forest land planning, encouraging owners to establish new plantations with complementary tree species at stand level, in order to achieve mosaics of different forest types at landscape level in the ForDis with such large LPI is strongly recommended (Freer-Smith et al., 2019).

Fragmentation analysis also revealed extreme fragmentation of native broadleaved forest in the provinces of Lugo and A Coruña with very small mean patch size (4.1 ha, as average) and mean core area (2.6 ha). Extreme fragmentation of native broadleaved forest and the above-mentioned formations of large and continuous eucalypt plantations both occur as a direct result of the rapid expansion of eucalypt throughout the territory and the replacement of patches of native forest during the last few decades.

Replacement of native forest patches by eucalypt has led to the removal of stands that are much more diverse than eucalypt plantations (e.g. Bas López et al., 2018; Calviño-Cancela et al., 2012) and that can act as corridors connecting areas of high diversity. As a consequence of the small patch to small patch species replacement (consequence of the very small and highly fragmented private forestland), remaining native broadleaved forests in seaboard areas under strong pressure from eucalypt plantations are gradually reduced to form smaller and more fragmented and scattered patches (micro-patches). Patches with interior habitat are scarce and almost all patches become edge habitat (mean core area 1.7-1.9 ha) thus greatly influencing the forest matrix and strongly limiting the presence of sensitive-to-edge species (Harper et al. 2005; Echeverría et al. 2007). Thus, different fragmentation studies in temperate forest have established a threshold area of 2-5 ha for the initiation of interior forest (e.g. Levenson, 1981; Ranney et al. 1981; Palik and Murphy 1990). The high level of fragmentation of native forest is an important threat to biodiversity (SCBD, 2005) as it decreases landscape connectivity, and patches become more isolated and increasingly affected by edge effects (Murcia, 1995). Furthermore, these impacts also reduce the biotic integrity of ecosystems (Kroner et al., 2016) and their ability to recover from disturbances (resilience) (Bregman et al., 2014). Moreover, in the medium term, the changes in patterns of habitat fragmentation and connection will probably have at least as large an impact on forest ecosystems as that caused by climate change (e.g. Sinclair et al., 2010).

5. Conclusions

The so-called "management plans for forest resources" (PORFs) are used to develop the regional forestry plan (PFG) in Galicia. To accurately design and implement future policies regarding the allocation of forest use at forest district level, policy-makers (i.e. politicians and land or forest planners) need indicators at this spatial operational level. The study findings provide quantitative and spatially explicit information identifying where eucalypt plantations are becoming problematic and could be used to correct and prevent future uncontrolled expansion of the species. Thus, the threshold value of 45% for the current degree of occupancy (DO) has already been exceeded in all ForDis in the province of A Coruña and ForDis VI and XIX in Lugo and Pontevedra, respectively. Considering the expected suitability of *E. globulus* in forthcoming climate change scenarios, we identified four inland ForDis (IX, X in Lugo, XVI in Pontevedra and XI in Ourense) where important future increments are forecast. Moreover, those areas overlap with the ongoing expansion already observed for *E. nitens*, and they are therefore key ForDis for monitoring and controlling eucalypt expansion towards inland Galicia. The huge continuous patches of eucalypt in seaboard ForDis in Galicia are subject to high ecological and financial risks, which may negatively impact forest ecosystem sustainability and multifunctionality. The study findings also identified edge-dominated native broadleaved forest patches in the *E. globulus* suitable habitat in the provinces of A Coruña and Lugo. The current degree of occupancy of eucalypt within NPAs is moderate and lower than outside of these areas. Nevertheless, the suitability of habitat for eucalypt plantations will increase in the foreseeable climate change scenario, which may lead to aggravation of the potential conflicts concerning those highly biodiversity areas. It must also be noted that other considerations such as regulations to control the species, socioeconomic and market demands changes and foreseeable future increases in forests threats (including the appearance of new pests and diseases) will probably play a very important role in limiting, reversing or even encouraging expansion of the species. Thus, monitoring efforts by regional forest administrations should be increased to prevent further impacts on native forest and natural protected areas.

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8. Tables

Table 1. Metrics used to characterize eucalypt plantations and native broadleaved forest.

Feature		Metric	Symbol	Units	Description
Suitability[1]		Degree of suitability	DS	%	Ratio between the area of suitable *E. globulus* habitat included in the ForDis and the whole forest area in ForDis
Importance[2]		Degree of occupancy	DO	%	Ratio between area covered by eucalypt in the ForDis and the total wooded area
		Economic relevance	ER	%	Ratio between mean annual volume of eucalypt harvested and the mean total volume harvested in the ForDis
Potential[1] expansion		Potential for replacement	PR	%	Ratio between the current area of native broadleaved forest included in the *E. globulus* suitable habitat in the ForDis (SH_{NBF}) and the total area in the whole ForDis (S_{NBF})
		Potential for substitution	PS	%	Ratio between the current area of coniferous or mixed forest included in *E. globulus* suitable habitat in the ForDis (SH_{CMF}) and the total area in the whole ForDis (S_{CMF})
		Potential for afforestation	PF	%	Ratio between the area of natural and semi-natural non-wooded areas included in the *E. globulus* suitable habitat in the ForDis (SH_{FNA}) and the total area in the whole ForDis (S_{FNA})
Fragmentation[1]	Area	Largest patch index	LPI	%	Proportion of the landscape encompassed by the largest patch
		Mean Patch Size	MPS	ha	Average size of the patches of a forest type category
		Mean Shape Index	MSI	-	Average shape index of patches of corresponding forest type category, adjusted by a constant for a square standard
	Core	Total core area	TCA	ha	Sum of core areas of all patches corresponding to a forest type category
		Mean core area	MCA	ha	Average core areas of the patches of the corresponding forest type category
	Aggregation	Patch density	PD	patches/100 ha	Number of patches in a category divided by total area and multiplied by 100
		Euclidean nearest neighbour distance	ENN	m	Average distance between patches of corresponding forest type category, based on the edge-to-edge distance

[1] Feature analysed for *E. globulus* suitable habitat. [2] Feature analysed for whole ForDis.

Table 2.- Area (ha) of forest cover categories at different levels of analysis.

		Area in the whole ForDis												Area included in suitable habitat							
		Total area								Only areas included in NPAs				Total area				Only areas included in NPAs			
Province	**ForDis**	**Sf**	**Sw**	**$EUGL_{SNF4.5}$**	**$EUNI_{SNF4.5}$**	**$EU_{SNF4.5}$**	**S_{NBF}**	**S_{CMF}**	**S_{FSA}**	**$EU_{SNF4.5}$**	**S_{NBF}**	**S_{CMF}**	**S_{FSA}**	**$EU_{SNF4.5}$**	**SH_{NBF}**	**SH_{CMF}**	**SH_{FSA}**	**$EU_{SNF4.5}$**	**SH_{NBF}**	**SH_{CMF}**	**SH_{FSA}**
A Coruña	I	112252	85743	54419	1576	55995	23056	6692	26510	2745	4745	1070	6061	53866	21035	5886	19909	2633	4197	901	4936
	II	113163	92919	43761	6533	50295	17442	25182	20245	148	365	267	605	49604	17008	23956	15599	146	365	258	563
	III	127766	104603	33046	18405	51451	28543	24609	23164	383	436	586	3191	50788	27969	24055	19432	333	429	467	1588
	IV	66517	47008	16474	5100	21573	9747	15688	19509	59	149	169	276	21244	9593	14716	18580	58	149	164	268
	V	81921	49348	22209	2185	24394	7513	17441	32573	117	94	522	3244	23917	7340	15873	29493	115	90	496	3210
	Subtotal	501620	**379620**	**169908**	**33800**	**203708**	**86301**	**89611**	**122001**	3452	5790	2614	13379	199419	**82945**	**84485**	**103013**	3285	5231	2287	10565
Lugo	VI	110492	91505	60689	3018	63707	19253	8545	18988	1598	1839	1702	5660	62045	17421	6415	13440	1468	1196	729	2908
	VII	142269	83605	251	1127	1378	64190	18037	58663	75	26682	4397	26280	0	0	0	0	0	0	0	0
	VIII	133205	73990	94	71	165	42606	31219	59214	0	11295	4540	20277	1	68	12	68	0	25	12	39
	IX	137443	99639	941	6123	7064	59030	33545	37805	8	5330	430	5157	584	1074	986	1849	4	42	84	359
	X	123801	77978	3861	12224	16085	35345	26548	45823	328	3356	1025	10385	4651	10199	4619	11912	53	640	199	1999
	Subtotal	647209	**426714**	**65835**	**22563**	**88398**	**220423**	**117893**	**220494**	2010	48503	12094	67759	67281	**28763**	**12032**	**27268**	1524	1903	1023	5305
Ourense	XI	78712	44907	359	55	414	22405	22088	33805	0	545	408	4044	197	7140	5264	6404	0	80	17	396
	XII	108657	57430	43	0	43	36552	20835	51227	0	1160	29	4698	3	514	655	806	0	0	0	28
	XIII	133651	39124	0	6	6	32279	6839	94527	0	9487	1345	31325	0	0	0	0	0	0	0	0
	XIV	136074	38393	50	10	60	18699	19634	97681	0	3605	2418	25075	0	4	7	34	0	0	0	0
	XV	89929	26127	128	30	157	19242	6728	63802	8	2027	875	20162	0	20	4	424	0	16	1	384
	Subtotal	547023	**205981**	**580**	**100**	**680**	**129177**	**76124**	**341042**	8	16824	5075	85304	200	**7679**	**5930**	**7667**	0	96	17	807
Pontevedra	XVI	94435	58363	5368	472	5839	30820	21704	36071	50	2785	983	8509	5521	19893	18080	16237	37	1619	699	2440
	XVII	51407	31373	6213	956	7169	14976	9228	20034	25	215	26	22	6660	13646	7715	14099	25	215	26	22
	XVIII	58024	41289	11889	38	11927	11858	17504	16735	11	522	853	92	11576	11532	17123	14937	9	519	849	92
	XIX	86390	62282	27376	228	27605	21581	13096	24108	84	838	187	2800	26698	20962	12265	20362	82	818	179	2713
	Subtotal	290255	**193307**	**50847**	**1693**	**52540**	**79235**	**61532**	**96948**	170	4360	2049	11423	50455	**66034**	**55183**	**65635**	152	3170	1753	5267
	Total	1986106	**1205622**	**287170**	**58156**	**345326**	**515136**	**345160**	**780484**	5640	75477	21832	177864	317356	**185420**	**157630**	**203584**	4962	10401	5080	21944

Note: Sf: total forest land area; Sw: total wooded area.

Table 3.- Current values of indicators of suitability, importance and potential expansion at ForDis and NPAs spatial levels.

	Total area							**Areas included in NPAs**				
	Feature	**Suitability**	**Abundance**	**Economic relevance**	**Potential expansion**			**Suitability**	**Abundance**	**Potential expansion**		
	Indicator	**DS (%)**	**DO (%)**	**ER (%)**	**PR (%)**	**PS (%)**	**PF (%)**	**DS (%)**	**DO (%)**	**PR (%)**	**PS (%)**	**PF (%)**
	ForDis											
A Coruña	I	89.7	65.3	87.8	91.2	88.0	75.1	86.6	32.1	88.4	84.2	81.4
	II	93.8	54.1	74.9	97.5	95.1	77.1	96.2	18.9	100.0	96.7	93.0
	III	95.7	49.2	68.2	98.0	97.7	83.9	61.3	27.3	98.5	79.7	49.8
	IV	96.4	45.9	62.6	98.4	93.8	95.2	97.9	15.6	100.0	96.9	97.2
	V	93.5	49.4	60.7	97.7	91.0	90.5	98.3	15.9	95.3	95.1	98.9
	Subtotal	**93.7**	**53.7**	**75.0**	**96.1**	**94.3**	**84.4**	84.7	29.1	90.3	87.5	79.0
Lugo	VI	89.9	69.6	83.8	90.5	75.1	70.8	58.3	31.1	65.1	42.8	51.4
	VII	0.0	1.6	19.3	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0
	VIII	0.1	0.2	5.4	0.2	0.0	0.1	0.2	0.0	0.2	0.3	0.2
	XIX	3.3	7.1	22.1	1.8	2.9	4.9	4.5	0.1	0.8	19.5	7.0
	X	25.3	20.6	44.1	28.9	17.4	26.0	19.1	7.0	19.1	19.4	19.2
	Subtotal	**20.9**	**20.7**	**47.4**	**13.0**	**10.2**	**12.4**	7.5	3.2	3.9	8.5	7.8
Ourense	XI	24.1	0.9	18.1	31.9	23.8	18.9	9.9	0.0	14.7	4.1	9.8
	XII	1.8	0.1	4.9	1.4	3.1	1.6	0.5	0.0	0.0	0.0	0.6
	XIII	0.0	0.0	2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	XIV	0.0	0.2	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	XV	0.5	0.6	9.5	0.1	0.1	0.7	1.7	0.3	0.8	0.1	1.9
	Subtotal	**3.9**	**0.3**	**7.9**	**5.9**	**7.8**	**2.2**	0.9	0.0	0.6	0.3	0.9
Pontevedra	XVI	63.3	10.0	31.8	64.5	83.3	45.0	38.9	1.3	58.1	71.0	28.7
	XVII	81.9	22.9	39.3	91.1	83.6	70.4	99.9	9.4	99.9	100.0	100.0
	XVIII	95.1	28.9	45.3	97.3	97.8	89.3	99.4	0.8	99.3	99.6	100.0
	XIX	92.9	44.3	70.4	97.1	93.7	84.5	97.0	7.6	97.6	95.8	96.9
	Subtotal	**81.8**	**27.2**	**49.0**	**83.3**	**89.7**	**67.7**	57.5	2.6	72.7	85.6	46.1
	Total	**43.5**	**28.6**	**58.4**	**36.0**	**45.7**	**26.1**	**15.1**	**5.5**	**13.8**	**23.3**	**12.3**

Table 4. Fragmentation metrics for eucalypt plantations and native broadleaved forest included in the current *E. globulus*-suitable habitat.

	Category	Area												Core								Aggregation							
	Metric	LPI				MPS				MSI				TCA				MCA				PD				ENN			
	Forest type	(1)	(2)	(1) NPA	(2) NPA	(1)	(2)	(1) NPA	(2) NPA	(1)	(2)	(1) NPA	(2) NPA	(1)	(2)	(1) NPA	(2) NPA	(1)	(2)	(1) NPA	(2) NPA	(1)	(2)	(1) NPA	(2) NPA	(1)	(2)	(1) NPA	(2) NPA
A Coruña	I	25.7	1.6	1.2	7.5	44.6	3.0	6.3	9.0	1.8	1.3	1.5	1.5	43452.1	13159.3	1742.3	3145.3	35.8	1.9	4.2	6.7	0.9	5.0	2.9	3.2	116.7	86.4	168.6	116.5
	II	5.8	0.3	0.7	2.8	23.2	3.0	0.7	3.7	1.8	1.4	1.3	1.8	36925.3	9839.3	41.4	171.6	17.2	1.7	0.2	1.7	1.2	3.2	6.8	3.4	120.0	81.8	265.1	84.9
	III	1.0	0.4	2.5	0.7	16.1	5.4	1.7	1.5	1.8	1.5	1.3	1.7	35703.8	18430.3	190.3	137.3	11.2	3.6	1.0	0.5	1.4	2.3	4.4	6.8	122.1	80.8	289.5	134.6
	IV	1.7	1.1	1.5	6.4	21.1	4.2	1.3	4.6	1.9	1.4	1.2	1.7	15418.4	6260.6	29.6	87.5	15.2	2.7	0.7	2.7	1.1	2.6	3.1	2.4	118.6	81.4	143.7	128.4
	V	2.1	0.4	0.2	0.8	16.9	4.4	2.5	3.8	1.9	1.4	1.5	1.5	16799.1	4768.3	49.7	47.8	11.8	2.9	1.1	2.0	1.2	1.4	1.1	0.5	123.9	93.7	658.3	789.8
	Subtotal	7.2	0.8	1.2	3.6	24.3	4.0	2.5	4.5	1.9	1.4	1.4	1.6	29659.7	10491.5	410.7	717.9	18.3	2.6	1.4	2.7	1.2	2.9	3.6	3.3	120.3	84.8	305.1	250.8
Lugo	VI	39.8	1.1	3.6	2.9	74.6	3.0	3.6	3.0	1.8	1.3	1.3	1.5	51409.0	10761.0	1043.7	690.3	61.7	1.9	2.6	1.7	0.7	4.7	5.6	5.6	102.2	91.6	141.0	134.4
	VII*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	VIII	0.1	1.6	0.0	26.8	0.6	1.9	0.0	3.6	1.5	1.3	0.0	1.3	0.0	29.9	0.0	15.1	0.0	0.8	0.0	2.2	0.2	2.8	0.0	8.8	26226.7	657.5	0.0	107.0
	IX	0.7	1.5	0.4	4.0	3.0	4.8	0.7	2.7	1.5	1.5	1.3	1.4	287.9	637.8	0.9	23.4	1.5	2.8	0.2	1.6	2.6	3.0	1.0	2.9	426.3	361.3	1775.1	331.5
	X	0.4	0.6	0.2	1.9	4.3	7.4	1.2	4.0	1.5	1.5	1.3	1.6	2563.0	6689.9	18.6	352.4	2.3	4.9	0.4	2.2	2.0	2.5	1.2	4.6	256.4	146.1	1281.6	354.9
	Subtotal	10.3	1.2	1.4	8.9	20.6	4.3	1.8	3.3	1.6	1.4	1.3	1.5	13565.0	4529.7	354.4	270.3	16.4	2.6	1.1	1.9	1.4	3.3	2.6	5.5	6752.9	314.1	1065.9	231.9
Ourense	XI	0.1	2.7	0.0	7.1	3.5	17.6	0.0	4.5	1.5	1.6	0.0	1.5	104.0	5274.1	0.0	50.9	1.9	12.9	0.0	2.8	0.2	1.7	0.0	3.6	907.6	205.1	0.0	1417.1
	XII	0.1	3.4	0.0	0.5	2.8	10.1	0.0	0.1	1.1	1.6	0.0	1.0	1.5	348.0	0.0	0.0	1.5	6.8	0.0	0.0	0.0	1.6	0.0	3.7	-	483.0	0.0	0.0
	XIII	0.0	3.1	0.0	0.0	0.0	1.5	0.0	0.0	0.0	1.1	0.0	0.0	0.0	1.9	0.0	0.0	0.0	0.7	0.0	0.0	0.0	3.4	0.0	0.0	0.0	3262.1	0.0	0.0
	XIV*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	XV	0.0	0.7	0.0	0.6	0.0	2.0	0.0	2.3	0.0	1.3	0.0	1.3	0.0	8.8	0.0	6.9	0.0	0.9	0.0	1.0	0.0	1.3	0.0	1.1	0.0	2791.2	0.0	3890.7
	Subtotal	0.1	2.5	0.0	2.7	3.1	7.8	0.0	2.3	1.3	1.4	0.0	1.2	52.8	1408.2	0.0	19.3	1.7	5.3	0.0	1.3	0.1	2.0	0.0	2.8	907.6	1685.3	0.0	2653.9
Pontevedra	XVI	1.1	2.9	0.4	9.0	9.7	20.5	2.6	10.4	1.7	1.6	1.3	1.7	3594.3	15401.3	19.8	1174.6	6.3	15.8	1.4	7.5	0.6	1.0	0.3	2.8	281.5	143.9	2787.0	173.2
	XVII	0.8	5.5	1.7	15.7	18.4	14.3	0.7	1.6	1.9	1.5	1.3	1.5	4798.9	10220.7	6.6	61.2	13.2	10.6	0.2	0.4	0.6	1.7	10.6	37.6	157.9	81.7	359.4	98.9
	XVIII	2.2	1.3	0.1	9.8	20.0	7.9	0.5	32.7	1.9	1.4	1.2	2.0	8433.3	8501.2	2.1	422.1	14.5	5.8	0.1	26.4	0.7	1.7	0.8	0.8	189.8	82.9	755.1	1924.4
	XIX	2.0	1.3	0.4	5.4	25.0	6.0	1.6	16.8	1.9	1.5	1.4	2.0	19936.6	13942.7	32.9	553.5	18.6	4.0	0.6	11.3	0.9	2.9	1.2	1.1	139.8	77.2	771.5	1016.8
	Subtotal	1.5	2.8	0.7	10.0	18.3	12.2	1.3	15.4	1.9	1.5	1.3	1.8	9190.8	12016.5	15.3	552.9	13.1	9.1	0.6	11.4	0.7	1.8	3.2	10.6	192.3	96.4	1168.2	803.3
	TOTAL	5.6	1.7	1.1	6.4	18.9	6.9	2.0	6.5	1.7	1.4	0.0	1.6	15961.8	7310.3	264.8	433.8	14.2	4.7	1.1	4.4	1.0	2.5	3.2	5.6	2092.1	518.1	783.0	713.5

(1) *E. globulus* + *E. nitens* ($EU_{SNF4.5}$); (2) Native broadleaved forest (SH_{NBF}); Natural Protected Areas (NPA). * ForDis without surface of *E. globulus* suitable habitat.

Table 5- Forecasted future gains or losses (percentage) of suitability and potential expansion indicators under two future climate change scenarios.

		Total area								Areas included in NPAs							
		2050 under moderate climate change scenario				2050 under pessimistic climate change scenario				2050 under moderate climate change scenario				2050 under pessimistic climate change scenario			
	Feature	Suitability	Potential expansion			Suitability	Potential expansion			Suitability	Potential expansion			Suitability	Potential expansion		
	Indicator	DS (%)	PR (%)	PS (%)	PF (%)	DS (%)	PR (%)	PS (%)	PF (%)	DS (%)	PR (%)	PS (%)	PF (%)	DS (%)	PR (%)	PS (%)	PF (%)
A Coruña	I	4.7	5.8	9.9	12.4	2.9	5.8	9.9	12.4	11.7	11.4	15.0	16.7	11.7	11.4	15.0	16.7
	II	2.1	1.9	1.9	7.7	0.1	1.8	2.0	8.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	III	2.6	1.8	1.4	10.8	4.1	2.0	2.1	15.4	23.2	1.5	12.5	30.9	34.6	1.5	16.1	46.7
	IV	0.0	0.0	0.0	0.0	-1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	V	0.1	0.2	0.2	0.0	-1.8	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Subtotal	**2.2**	**2.5**	**1.7**	**6.0**	**1.3**	**2.6**	**1.9**	**7.0**	**11.0**	**9.5**	**8.9**	**14.9**	**13.1**	**9.5**	**9.7**	**18.7**
Lugo	VI	2.9	1.1	12.0	10.4	-7.6	0.0	6.9	3.4	15.6	6.6	37.3	16.4	5.4	2.9	22.0	2.8
	VII	0.5	0.6	0.7	0.2	0.3	0.3	0.4	0.3	0.6	0.8	1.2	0.2	0.2	0.2	0.5	0.1
	VIII	5.5	5.9	6.6	4.6	22.6	24.2	28.7	18.3	0.9	0.7	2.3	0.8	6.2	4.8	16.9	4.6
	IX	33.6	32.8	43.0	32.9	39.0	35.0	50.4	36.2	9.5	13.2	19.8	4.8	10.5	13.8	20.0	6.3
	X	45.8	57.6	62.0	43.2	47.4	52.2	61.0	36.9	34.7	69.3	31.6	24.9	19.2	59.0	22.8	6.7
	Subtotal	**17.6**	**19.4**	**28.9**	**16.8**	**15.4**	**22.5**	**36.3**	**19.2**	**6.6**	**7.1**	**9.9**	**5.9**	**5.3**	**7.0**	**12.3**	**3.1**
Ourense	XI	57.5	58.3	62.6	54.4	70.2	65.3	75.0	70.7	40.6	35.9	50.9	40.2	53.5	46.7	56.4	54.2
	XII	30.3	26.7	49.5	25.1	60.2	58.4	86.6	50.7	7.2	9.6	11.5	6.6	62.3	73.2	49.3	59.7
	XIII	0.1	0.5	0.0	0.0	0.7	1.8	1.2	0.3	0.1	0.4	0.0	0.0	0.4	1.3	0.0	0.2
	XIV	0.0	0.0	0.0	0.0	3.6	4.0	3.1	3.6	0.0	0.0	0.0	0.0	0.6	4.4	0.0	0.1
	XV	5.0	7.9	12.7	3.3	22.9	26.4	25.7	21.6	3.6	11.9	6.2	2.7	38.8	52.5	37.3	37.5
	Subtotal	**15.1**	**19.0**	**32.8**	**9.8**	**26.8**	**32.8**	**48.6**	**19.8**	**3.1**	**3.5**	**5.2**	**2.9**	**14.6**	**14.6**	**11.3**	**14.8**
Pontevedra	XVI	26.6	29.4	13.7	36.3	30.9	32.4	14.7	44.4	41.9	35.1	15.4	47.4	53.6	38.0	17.6	63.1
	XVII	13.0	5.1	10.6	24.6	15.5	5.1	10.6	29.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	XVIII	2.2	0.0	0.0	7.6	2.3	0.0	0.0	7.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	XIX	3.0	0.4	0.0	10.2	2.6	0.4	0.0	10.4	2.6	2.4	0.0	3.0	2.6	2.4	0.0	3.0
	Subtotal	**12.3**	**12.5**	**6.4**	**22.4**	**14.0**	**13.7**	**6.8**	**26.5**	**29.2**	**22.9**	**7.4**	**36.0**	**37.3**	**24.7**	**8.5**	**47.8**
	Total	**12.3**	**15.4**	**18.7**	**12.7**	**10.2**	**20.4**	**24.8**	**18.4**	**11.7**	**11.4**	**15.0**	**16.7**	**11.7**	**11.4**	**15.0**	**16.7**

9. Figure Captions

Figure 1. Location of the study area (Galicia) within the Iberian Peninsula, showing the provinces and the forest planning units (forest districts are indicated by Roman numerals). **Forest districts:** I.-Ferrol; II.-Bergantiños-Mariñas Coruñesas; III.- Santiago-Meseta Interior; IV.- O Barbanza; V.- Fisterra; VI.- A Mariña Luguesa; VII.- A Fonsagrada-Os Ancares; VIII.- Terra de Lemos; IX.- Lugo-Sarria; X.- Terra Chá; XI.- O Riberiro-Arenteiro; XII.-Miño-Arnoia; XIII.- Valdeorras-Trives; XIV.- Verín-Viana; XV.- A Limia; XVI.- Deza-Tabeirós; XVII.- O Condado-A Paradanta; XVIII.- Vigo-Baixo Miño; XIX.- Caldas-O Salnés.

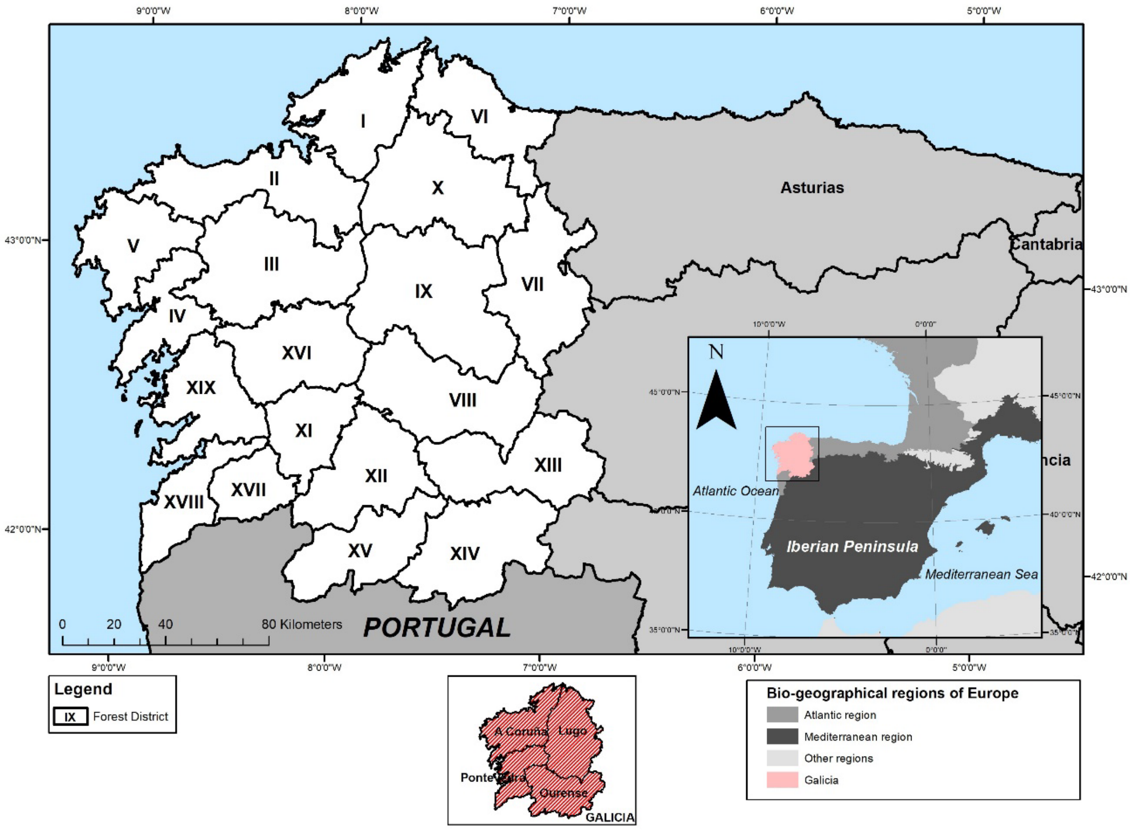
Figure 2. Workflow of the different processes used in the study.

Figure 3. Spatial distribution at ForDis level of eight metrics used to characterize eucalypt plantations and native broadleaved forest. DS=degree of suitability; DO=degree of occupancy; ER=economic relevance; PR=potential for replacement; PS=potential for substitution; PF=Potential for afforestation; LPI_EU=large patch index of eucalypt plantations; LPI_NBF=large patch index of native broadleaved forests; MPS_EU=mean patch size of eucalypt plantations; MPS_NBF=mean patch size of native broadleaved forest.

Figure 4. Map showing the large area of eucalypt plantations in ForDis VI- A Mariña Lucense (upper right) and the expansion of *E. nitens* in the ForDis X - Terra Chá (lower right).

S_{FSA}= area occupied by other natural and semi-natural land. S_{CMF}= area occupied by coniferous and mixed forest. S_{NBF}=area occupied by native broadleaved forest. $EUGL_{SNF4.5}$= area occupied by *E. globulus* plantations. $EUNI_{SNF4.5}$= area occupied by *E. nitens* plantations.

Fig 1.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XIII
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XV
XVI
XVII
XVIII
XIX
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Cantabria
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Iberian Peninsula
Mediterranean Sea
Legend
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A Coruña
Lugo
Ourense
GALICIA
Bio-geographical regions of Europe
Atlantic region
Mediterranean region
Other regions
Galicia

Fig. 2.

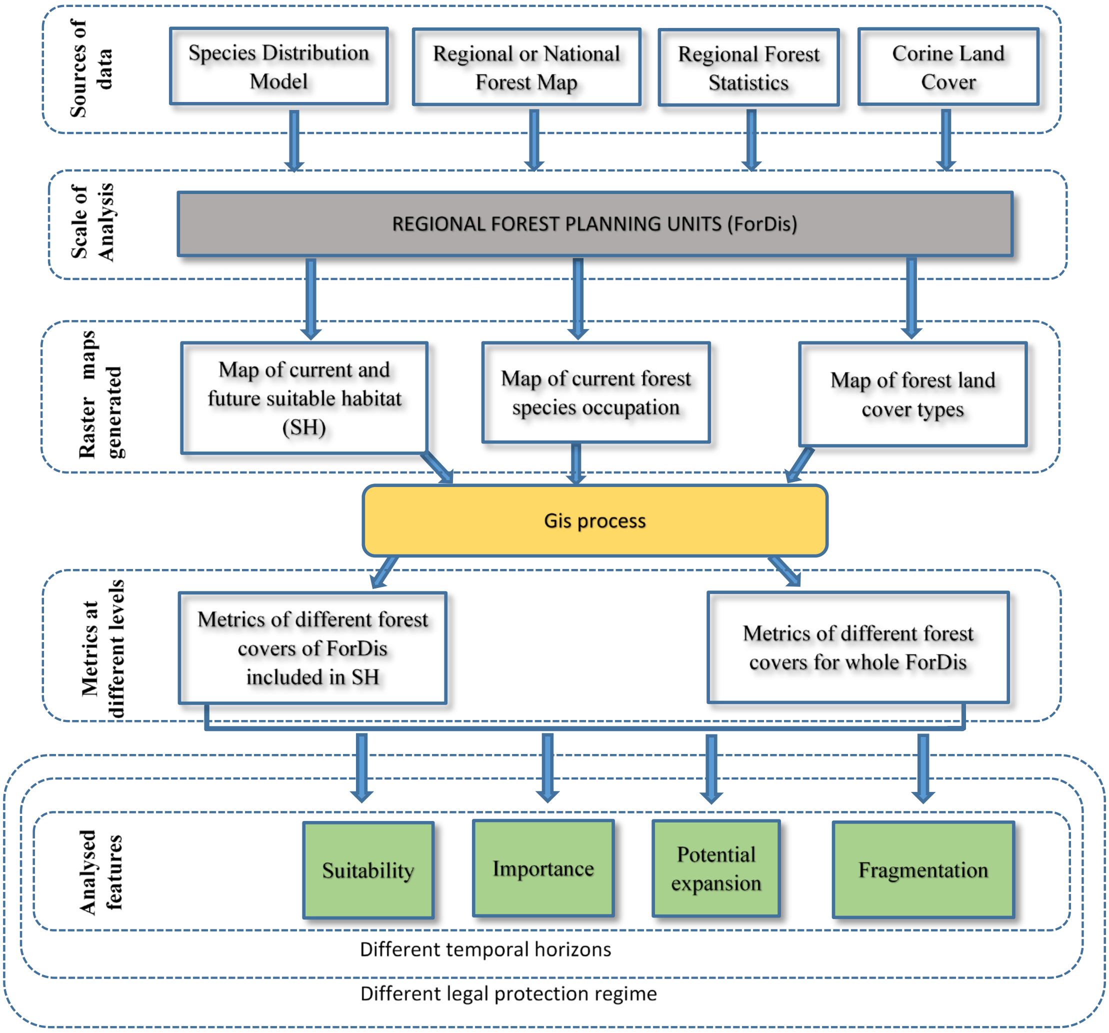
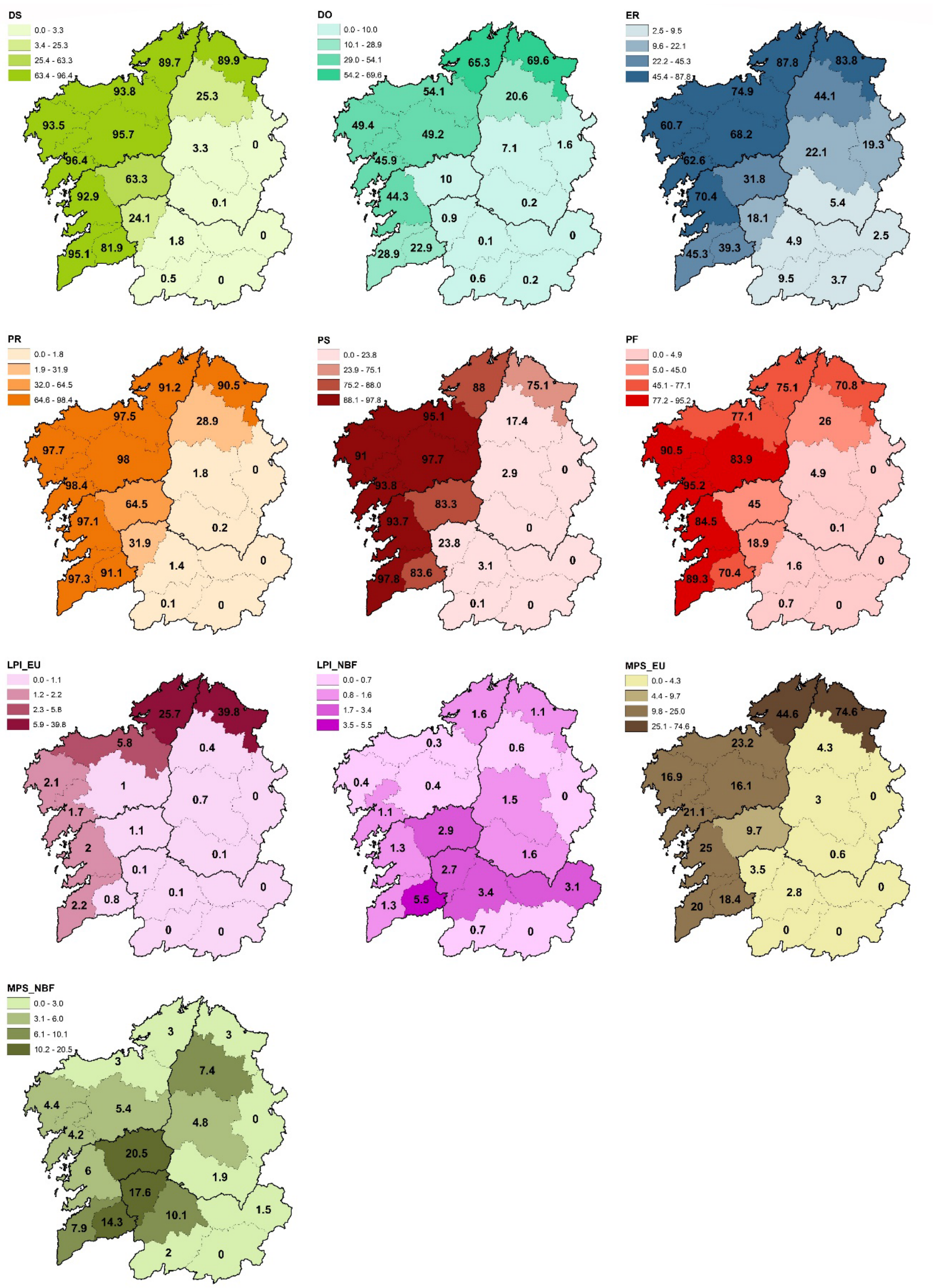

Sources of data
Species Distribution Model
Regional or National Forest Map
Regional Forest Statistics
Corine Land Cover
Scale of Analysis
REGIONAL FOREST PLANNING UNITS (ForDis)
Raster maps generated
Map of current and future suitable habitat (SH)
Map of current forest species occupation
Map of forest land cover types
Gis process
Metrics at different levels
Metrics of different forest covers of ForDis included in SH
Metrics of different forest covers for whole ForDis
Analysed features
Suitability
Importance
Potential expansion
Fragmentation
Different temporal horizons
Different legal protection regime

Fig. 3.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93.5
95.7
3.3
0
96.4
63.3
92.9
0.1
24.1
1.8
0
95.1
81.9
0.5
0
DO
0.0 - 10.0
10.1 - 28.9
29.0 - 54.1
54.2 - 69.6
65.3
69.6
54.1
20.6
49.4
49.2
7.1
1.6
45.9
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44.3
0.2
0.9
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0
28.9
22.9
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0.2
ER
2.5 - 9.5
9.6 - 22.1
22.2 - 45.3
45.4 - 87.8
87.8
83.8
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44.1
60.7
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62.6
31.8
70.4
5.4
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4.9
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45.3
39.3
9.5
3.7
PR
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1.9 - 31.9
32.0 - 64.5
64.6 - 98.4
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97.5
28.9
97.7
98
1.8
0
98.4
64.5
97.1
0.2
31.9
1.4
0
97.3
91.1
0.1
0
PS
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88.1 - 97.8
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75.1
95.1
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97.7
2.9
0
93.8
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23.8
3.1
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97.8
83.6
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PF
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77.2 - 95.2
75.1
70.8
77.1
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95.2
45
84.5
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89.3
70.4
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0
LPI_EU
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1.2 - 2.2
2.3 - 5.8
5.9 - 39.8
25.7
39.8
5.8
0.4
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0.7
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1.7
1.1
2
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0.1
0.1
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2.2
0.8
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LPI_NBF
0.0 - 0.7
0.8 - 1.6
1.7 - 3.4
3.5 - 5.5
1.6
1.1
0.3
0.6
0.4
0.4
1.5
0
1.1
2.9
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3.4
3.1
1.3
5.5
0.7
0
MPS_EU
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4.4 - 9.7
9.8 - 25.0
25.1 - 74.6
44.6
74.6
23.2
4.3
16.9
16.1
3
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21.1
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2.8
0
20
18.4
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MPS_NBF
0.0 - 3.0
3.1 - 6.0
6.1 - 10.1
10.2 - 20.5
3
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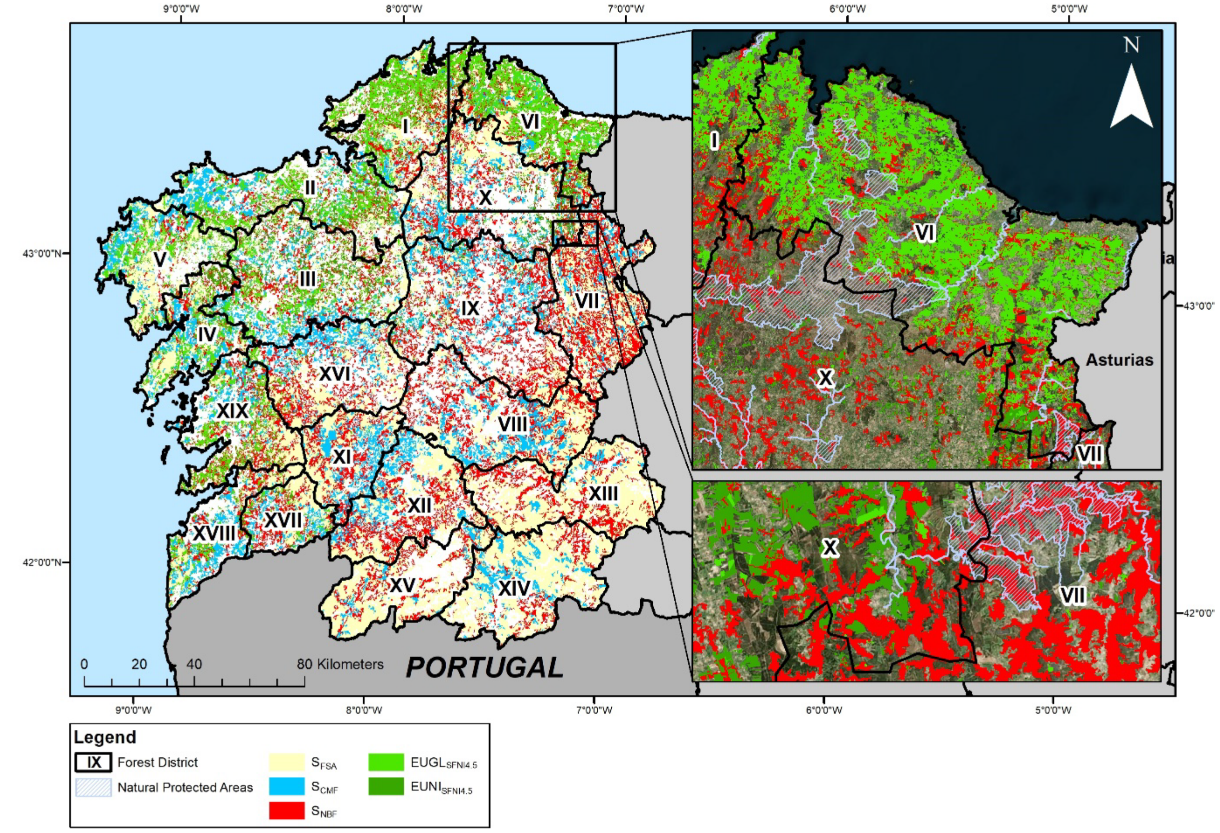
Fig. 4.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XVIII
XIX
Asturias
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Legend
IX Forest District
Natural Protected Areas
S_{FSA}
S_{CMF}
S_{NBF}
$EUGL_{SFNI4.5}$
$EUNI_{SFNI4.5}$