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National-scale assessment of forest site productivity in Spain

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ABSTRACT

Sustainable production of wood is one of the main services provided by forest systems. Site productivity in the case of forests is often evaluated through the site quality. However, most of the works addressing the site quality have been done at local or regional scale. In this work, we aim to develop site quality models for five dominant species in Spanish forests (*Fagus sylvatica*, *Pinus pinaster atlantica*, *Quercus pyrenaica*, *Pinus nigra*, *Pinus sylvestris*) and create site quality maps at a national-scale from these models. First, we develop site quality models using site form (height-diameter relationship) as the reference index and the Spanish National Forest Inventory as dataset. Then, we fit spatial additive models entering physiographic and climatic variables in order to predict the site quality over the whole country. Additionally, we plot site form maps for the five species in order to describe spatial pattern in site quality at a national scale. Altitude and aspect appeared to be fundamental variables in the assessment of site quality. The accuracy of the spatial additive models ranged from 38.2% to 47.9%. The correspondence between the predicted and observed maps of site qualities is clear. Our results provide a tool which could be used by forest managers in land use planning as well as in forest policy decision-making at a national scale. We suggest that this method could be used in other countries and that the maps could be expanded to the European scale to assessing the way in which site quality varies across Europe always considering that the relationships between forest productivity and environmental variables could vary among biogeoclimatic zones.

1. Introduction

Site quality has long been used in forestry as a proxy of site productivity. This variable is not only of interest for predicting growth and yield of forest stands (Álvarez-González et al., 2005; Clutter et al., 1983; Diéguez-Aranda et al., 2005) but also for studies on ecological diversity (Franklin et al., 1989), forest structure (Larson et al., 2008) and forest disturbances (Wei et al., 2003) among others. Site quality has traditionally been expressed as the relationship between dominant height and age (site index) for even aged forests. However, this definition is difficult to apply in forests with an uneven distribution of ages or in mixed-species forests, where the height-diameter relationship (site form) has proved to be a good measure of site productivity (Huang and Titus, 1993; McLintock and Bickford, 1957; Stout and Shumway, 1982; Vanclay, 1994). Site form can be also useful to determine the site quality of even-aged stands where the age is unknown, as occurs in the National Forest Inventories (NFIs) of some countries (Tomppo et al., 2010).

Abbreviations: AIC, Akaike's Information Criterion; B-R, Bertalanffy-Richards model; dbh, diameter at breast height; EF, expansion factor; EFT, European Forest Type; H-II, Hossfeld II model; NFI, National Forest Inventory

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Table 1
Number of plots of the National Forest Inventory (*N*), number of plots with basal area of the species in parenthesis larger than 90% ($N\ G \geq 90\%$), mean basal area (G in $m^2\ ha^{-1}$), mean dominant height (H_0 in m) and mean dominant diameter (D_0 in cm) in the selected European Forest Types. Minimum and maximum values in brackets.

European Forest Type	N	$N\ G \geq 90\%$	G	H_0	D_0
2.7 Atlantic maritime pine forest (*Pinus pinaster atlantica*)	3410	1568	18.0 (0.4–85.0)	15.2 (2.0–29.3)	30.5 (7.5–71.9)
7.1 South western European mountainous beech forest (*Fagus sylvatica*)	4449	1915	25.5 (0.4–64.2)	18.8 (3.7–36.5)	40.9 (7.5–158.8)
8.3 Pyrenean oak forest (*Quercus pyrenaica*)	5528	2889	10.9 (0.4–72.5)	9.9 (0.4–23.3)	24.2 (7.5–134.4)
10.2 Mediterranean and Anatolian black pine forest (*Pinus nigra*)	8352	3212	15.1 (0.4–80.4)	10.4 (2.6–33.3)	26.5 (7.5–100.3)
10.4 Mediterranean and Anatolian Scots pine forest (*Pinus sylvestris*)	10,919	5171	22.7 (0.4–83.8)	12.1 (2.0–30.5)	29.9 (7.5–64.8)

Site form, as well as site index, can be estimated via direct and indirect methods. Direct methods are based on the relationship between the height and diameter, in the case of site form, and between height and age, in the case of site index. Meanwhile indirect methods relate physiographic, climatic, edaphic variables and understory to site quality (Bravo and Montero, 2001; Pacheco Marques, 1991). Alternative base models have been employed to develop diameter-height relationships. Meyer's mathematical expression have been used for fitting site form curves in *Picea rubens* Sarg. (McLintock and Bickford, 1957) and in six hardwood species (Stout and Shumway, 1982) while Huang and Titus (1993) selected the Bertalanffy-Richards model as the base height-diameter function.

Different statistical methodologies have been used to determine the influence of environmental variables on the site quality, such as linear models (Chen et al., 2002; Pacheco Marques, 1991; Seynave et al., 2005), discriminant analysis (Bravo-Oviedo and Montero, 2005; Bueis et al., 2016) or regression trees (Álvarez-Álvarez et al., 2011). The group of variables selected for site quality models and those variables found as significantly associated to site quality have varied among species and study sites. Bravo-Oviedo et al. (2011) stated that variations in site quality of Mediterranean *Pinus pinaster* Ait stands are mainly explained by climate variables. Other authors, however, only considered edaphic and physiographic variables in site quality models (Bravo et al., 2011; Bueis et al., 2016; Seynave et al., 2005). Aspect, latitude, content of nutrients, soil moisture, soil texture, pH or soil depth appeared to be related to site quality (Bravo and Montero, 2001; Bueis et al., 2016; Seynave et al., 2005). Nevertheless, the effects of a variable on the site quality of a given species may change among regions (Chen et al., 2002). Additionally, some of these relationships might not be linear as in the case of the site quality-altitude (Seynave et al., 2005). In these cases, linear models cannot identify complex relationships among variables. Therefore, approaches, such as additive models, describing nonlinear and complex relationships between the site quality and the predictors can be very useful (Hastie and Tibshirani, 1989; Wood, 2006).

Most of the studies assessing the quality site have been carried out at local or regional scales (Bueis et al., 2016; Seynave et al., 2005) whereas the knowledge of forest productivity at larger geographic scales is scarce (Chen et al., 2002). In this regard, some authors affirm that the representativeness at a coarser scale of forest productivity from restricted area data is questionable (Charru et al., 2010). In this sense, NFIs provide the broadest source of knowledge on the status of the forests at national level in many countries (Barbati et al., 2014). In fact, NFIs have been used to estimate production (Charru et al., 2010), aboveground biomass (Avitabile and Camia, 2018), carbon storage (Woodall et al., 2008) and monitoring species distribution (Hernández et al., 2014; Moreno-Fernández et al., 2016) or assessment of biodiversity (Andersson and Östlund, 2004) and abiotic damages (Jalkanen and Mattila, 2000). Additionally, the NFIs have been used as datasets in scientific studies to model recruitment (Lexerød, 2005), tree biomass (Ruiz-Peinado et al., 2011), tree mortality (Ruiz-Benito et al., 2013), deadwood volume (Crecente-Campo et al., 2016) as well as site quality (Adame et al., 2006).

International institutions and processes, however, favor using international rather than national criteria (FAO, 2015; Gabler et al., 2012) to monitor sustainable forest management practices and forest state at international scales (Larsson, 2001). In this context, Barbati et al. (2014) and Barbati et al. (2007a) have proposed a classification to categorize the forest of the Pan-European region into 14 European Forest Types (EFTs) categories (category level) and the categories into 78 EFTs (type level) according to ecological sound units. The EFTs classify forest features by aggregating and averaging data from NFIs into ecologically homogeneous strata of European relevance, i.e. the 14 EFTs categories (Barbati et al., 2014). Therefore, reporting forest productivity through an index independent of the forest structure and following EFTs classification would contribute to standardize assessment resources in Europe or even abroad.

In this work, we aim to develop site quality models at a national-scale using site forms for five species, and display the results spatially. In the first step, we fit site form models (diameter-height curves) for the five species using NFI as dataset. We then model the site form using spatial additive models including environmental variables as predictors. Finally, we used these spatial additive models to create site quality maps by species at a national-scale.

2. Material and methods

2.1. Species studied and National Forest Inventory dataset

We used the EFT classification to select the target species. We selected five species widely distributed in Spain and which form genuine, monodominant forest according to the EFT classification (Barbati et al., 2014, 2007b): *Pinus pinaster* Ait. ssp *atlantica* (*P. pinaster*, hereafter), *Fagus sylvatica* L., *Quercus pyrenaica* Willd., *Pinus nigra* Arn. and *Pinus sylvestris* L. (Table 1). Hereafter, each EFT is named after the dominant species present. All of the species are found mainly in montane areas with the exception of *P. pinaster* which is quite common at sea level (Ruiz de la Torre, 2006).

The Third Spanish NFI, conducted between 1997 and 2007, was used to model and predict the site quality in Spanish forests. The NFI plots were only established in woodland areas, according to the FAO definition (FAO, 2001) (i.e. none in non-forested areas) with an intensity of one sampling point every 1 km^2 (1 × 1 km grid). At each sampling point, diameter and height of the trees were measured in four concentric circular subplots with increasing radii from 5 to 25 m. In the 5 m radius subplot, trees with a diameter at breast height (dbh) ≥7.5 cm were measured. In the 10 m radius subplot, trees with dbh ≥12.5 cm were measured. In the 15 m radius subplot, trees with dbh ≥22.5 cm were measured. Finally, in the 25 m radius subplot, trees with dbh ≥42.5 cm were measured. The attributes of the trees measured in each concentric subplot were expanded to per-hectare values by considering a different expansion factor (EF) for each subplot size,