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Ecological envelope maps and stand production of eucalyptus plantations and naturally regenerated maritime pine stands in the central inland of Portugal

Cristina Alegria[a,b,*], Nuno Pedro[a,c], Maria do Carmo Horta[a,b], Natália Roque[a], Paulo Fernandez[a,d]

[a] Instituto Politécnico de Castelo Branco, Escola Superior Agrária, Quinta da Senhora de Mércules, Apartado 119, 6001-909 Castelo Branco, Portugal
[b] CERNAS-IPCB – Pólo de Castelo Branco do Centro de Estudos de Recursos Naturais, Ambiente e Sociedade, Unidade de Investigação e Desenvolvimento do Instituto Politécnico de Castelo Branco, Portugal
[c] CITAB – Centro de Investigação e de Tecnologias Agro-Ambientais e Biológicas, Universidade de Trás-os-Montes e Alto Douro, Portugal
[d] ICAAM – Instituto de Ciências Agrárias e Ambientais Mediterrânicas, Universidade de Évora, Portugal

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ABSTRACT

Eucalyptus and maritime pine forests provide most of the wood harvested in Portugal. Due mainly to forest fires maritime pine forest has been converted to eucalyptus plantations. In the central inland of Portugal these species are well represented, and their productivities are quite the same. The objectives of the study were: (1) to assess average wood volume, biomass production and carbon content of eucalyptus plantations and naturally regenerated maritime pine stands; (2) to evaluate biomass nutrients concentration of eucalyptus sprouts selection and maritime pine non-commercial thinning; (3) to analyse these forests cover change in relation to the annual burnt areas; and (4) to produce the species ecological envelope maps to foresee future environmental impacts of these forests current distribution. Simulation models were used to assess wood volume, biomass production and carbon content. Field data was collected to evaluate biomass nutrients concentration and to validated simulated data. Forest inventory data and forest cover maps were used to analyse forest cover change. Biogeographical variables were used to produce species ecological envelope maps. It was found that eucalyptus plantations provide higher mean annual wood volume, biomass production and carbon content. Biomass nutrients concentration in eucalyptus sprouts selection were higher than in maritime pine non-commercial thinning, particularly in calcium and potassium. Overall eucalyptus forests area did not increase substantially but the fires in maritime pine forests gave the opportunity for eucalyptus afforestation. That has precluded the opportunity for introducing native broadleaves to respond to climate changes, improve landscape biodiversity and mitigate fire hazard. Implementing good management practices to prevent losses of soil fertility by nutrients exhaustion, organic matter depletion or erosion were found more relevant in eucalyptus plantations than in naturally maritime pine forest. Species ecological envelope maps and production simulation models are key tools for supporting decision in afforestation planning.

1. Introduction

Eucalyptus species have been exceptionally well disseminated outside its native range (Australia and nearby islands, namely Indonesia, Philippines and New Guinea) and widely planted for more than a century in many parts of the world (Turnbull, 1999; Richardson and Rejmánek, 2011). Regarding the species *Eucalyptus globulus* Labill. it has been increasingly used in forestry and is currently one of the most important pulpwood species in the world (Catry et al., 2015; Cerasoli et al., 2016). In Europe, this species covers 1.3 million hectares of forested area, mainly in the Iberian Peninsula (> 80%), France and Italy (Cerasoli et al., 2016).

Maritime pine (*Pinus pinaster* Aiton) is a species native to the western Mediterranean Sea. In the Mediterranean region this species has been extensively cultivated in large-scale afforestation programmes for wood production and land restoration (Jones et al., 2011).

* Corresponding author at: Instituto Politécnico de Castelo Branco, Escola Superior Agrária, Quinta da Senhora de Mércules, Apartado 119, 6001-909 Castelo Branco, Portugal.
E-mail addresses: crisalegria@ipcb.pt (C. Alegria), npedro@ipcb.pt (N. Pedro), carmoh@ipcb.pt (M. do Carmo Horta), nroque@ipcb.pt (N. Roque), palex@ipcb.pt (P. Fernandez).

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In Portugal forest area has increased considerably throughout the 20th century. In 1985 forest area represented only 7% of country's area. But, due to the national afforestation programmes, in 1962 the expression of forest area reached to 33% and continued to increase to 39% up until 2005 (around 3.5 million ha) (AFN, 2010). In the period of 1938–1977, under the Portuguese afforestation plan (290,673 ha), the species maritime pine was extensively used in dunes and mountain areas afforestation for protection reasons. The expansion of eucalyptus plantations in the country only occurred since the mid-20th century, closely followed by the development of the Portuguese pulp and paper industries (Teixeira and Matos, 2000; Alves et al., 2007; Radich, 2007; Catry et al., 2015). So, in the period of 1965–1983, under the private afforestation policy (126,934 ha), that supported 50% of installation costs, the species eucalyptus was favoured to respond to the need of Portuguese pulp industry wood supply (Leite and Martins, 2000; Jones et al., 2011).

Despite the wide spreading of forest fires in the last decades (1980–2010) in Portugal (e.g., 3% of forest area annually burnt – an average of 108,951 ha yr^{-1}) forest area did not substantially decrease in 2010 (35%; 3.2 million ha) partly due to a natural process of conversion of grazing land, uncultivated land and marginal agricultural areas. Yet, since 1995 a strong trend regarding the decrease of maritime pine forest area conversely to the rapid increase of eucalyptus forests area and the relative stability of the forest area of other species was noticed (Leite and Martins, 2000; ICNF, 2013). As a result, although maritime pine has been the most widespread species until 2005, the eucalyptus species is presently the most abundant (26%; 811,943 ha) followed by cork oak (*Quercus suber* L.; 23%; 736,775 ha), maritime pine (23%; 714,445 ha) and holm oak (*Quercus rotundifolia* Lam..; 11%; 331,179 ha) (ICNF, 2013).

The forests of eucalyptus and maritime pine provide most of the wood harvested in Portugal used mainly as raw materials for the wood-based industry (INE, 2011). The usual destination of eucalyptus wood is to the pulp industry. Maritime pine wood destination can be either to the pulp industry or to the sawing industry. Currently, more than 75% of eucalyptus and maritime pine wood used in the pulp and paper industry is provided by the national market (CELPA, 2016). More recently, with the development of the industry of bioenergy production from biomass residues, another industrial destination is available for both species.

Eucalyptus stands are more abundant both on the Atlantic coast (e.g., productivities higher than 15 $m^3 ha^{-1} yr^{-1}$) and in the Tagus valley region (e.g., productivities between 10–15 $m^3 ha^{-1} yr^{-1}$). In low productivity regions for this species, such as the inland of the country, productivities can be lower than 10 $m^3 ha^{-1} yr^{-1}$ (Borralho and Silva, 2006; Dias and Arroja, 2012). *E. globulus* is planted on 95% of the eucalyptus forest area (Borralho et al., 2007). Maritime pine stands are mainly in the northern and central regions of the country. This species productivity (for fully mature trees 35–45 years old) is about 5–10 $m^3 ha^{-1} yr^{-1}$ in the north of the Tagus river and generally lower at about 4 $m^3 ha^{-1} yr^{-1}$ to the south of the Tagus river. Much lower productivities of around 0.7–3.4 $m^3 ha^{-1} yr^{-1}$ are found in poor-quality areas, such in coastal dunes (Santos and Almeida, 2014).

Eucalyptus is an exotic, light-demanding and fast-growing species, mostly planted and managed through a coppice system of three short harvesting cycles (e.g. 10–12-year rotations) for high wood production and removal (Soares et al., 2007; Águas et al., 2014). Due to this species intensive management some adverse environmental effects may have to be taken in consideration, such as soil compaction, soil erosion, nutrients export and pollution by the use of fertilizers and pesticides (FAO, 1993). Maritime pine is a native pioneer, light-demanding and fast-growing species, grown mainly located in naturally regenerated stands in medium to long revolutions (e.g. more than 35 years) for wood production (Oliveira, 1999). Overall, there is evidence that, for the same management scenario intensity (high, medium or low), the impacts of maritime pine wood production in Portugal are smaller than those of eucalyptus wood production (e.g., abiotic resource depletion, global warming over 100 years, photochemical oxidant formation, acidification and eutrophication) (Dias and Arroja, 2012).

In Portugal, since 1988 that several legal frameworks have been published to establish the conditions for eucalyptus plantations afforestation to mitigate its environmental impacts, namely on soil and water resources (Teixeira and Matos, 2000). Cork and holm oaks forests are protected by several legal frameworks since 2001. More recently, in 2006 the National Strategy for Forests (DR, 2006a) established the following goals to be attain until 2030: a strong decrease of eucalyptus area (−60%), a slight decrease of maritime pine area (−6%) and a strong increase of cork oak and oak areas (3 and 4 times more the existing area in 2005, respectively). However, the eucalyptus area did not only decrease but is presently the most abundant species according to the last National Forest Inventory (ICNF, 2013). In 2015, the revised National Strategy for Forests established a new goal for eucalyptus forest: to maintain this species current area over the next 15 years (DR, 2015).

In the last two decades (1990–2006) the main driving forces of Portuguese land cover change have been due to the action of forest fires and both to the increase of abandonment agricultural land and the afforestation under investment (Jones et al., 2011). Between 1995 and 2010 maritime pine area decreased 263 thousand ha mainly due to the forest fires. Most of this area was converted in scrubland and pastures (63%; 165 thousand ha) and in eucalyptus forest (27%; 70 thousand ha) (ICNF, 2013).

It is clear and understandable the motivation that has driven private forest owners to choose eucalyptus for afforestation rather than other species (e.g. maritime pine or oaks). In fact, the perception that a lower economic risk is associated to eucalyptus production due to its high productivity, short harvesting cycles (e.g. 10–12-year rotations) and the guarantee for wood destination to the national pulp and paper industry are the main reasons that have supported the increase of this species area during the past 20 years (Fidalgo and Páscoa, 2007). For that reason, the distribution of eucalyptus in Portugal has been mainly determined by economic factors rather than by environmental limitations (Alves et al., 2012).

However, eucalyptus plantations are commonly managed throughout three rotations that correspond to revolutions ranging from 30 to 36 years that are comparable to the ones recommended for maritime pine stands management. Likewise, the eucalyptus clear-cuts schedule has a correspondence in maritime pine thinning schedule and final clear-cut (e.g., Oliveira, 1999; Louro et al., 2002). Moreover, in low productivity regions for the eucalyptus species, such as the central inland of Portugal (e.g., lower than 10 $m^3 ha^{-1} yr^{-1}$) (Borralho and Silva, 2006) the productivity of eucalyptus plantations, is comparable to the productivity of maritime pine forest (about 5–10 $m^3 ha^{-1} yr^{-1}$) (Santos and Almeida, 2014).

Therefore, due to the trend of converting maritime pine forest to eucalyptus plantations after the forest fires, the inter-municipal community of Beira Baixa (CIMBB), in the central inland Portugal, where both species are well represented, was considered as study area. The objectives of the study were: (1) to assess average wood volume, biomass production and carbon content of eucalyptus plantations and naturally regenerated maritime pine stands; (2) to evaluate biomass and nutrients concentration of eucalyptus sprouts selection and maritime pine non-commercial thinning; (3) to analyse these forests cover change in relation to the annual burnt areas; and (4) to produce ecological envelope maps for the species to foresee future environmental impacts of these forests current distribution.

2. Materials and methods

2.1. Study area and data

The study area is in the central inland Portugal (Lat.: 39°53′10.6″N