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REVIEW ARTICLE

Opportunities and challenges of *Eucalyptus* plantations in Europe: the Iberian Peninsula experience

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Abstract

Although native to Australia, *Eucalyptus* species are found throughout Europe. At present, they are located mainly in the Iberian Peninsula and *Eucalyptus globulus* is the most commonly planted species. Climate forecasts anticipate an expansion of *Eucalyptus* to other regions of Europe. The fast growth of *E. globulus*, together with its resprouting ability and wood properties, has promoted the use of this species in the Iberian Peninsula. The total volume of *E. globulus* harvested there was close to 14 million m^3 in 2019. *Eucalyptus* species represent the main source of raw material for the pulp and paper industries and provide an important source of income to non-industrial owners. Being exotic fast-growing trees, their expansion has also been associated with negative environmental impacts. The species therefore poses a series of challenges, while also generating opportunities. The objectives of this review paper are: (1) to summarize the importance of *Eucalyptus* plantations in Europe; (2) to analyse the opportunities and challenges of this genus in present and future plantations in Europe; (3) to assess to what extent forest management, at both stand and landscape levels, can reduce negative impacts; (4) to make policy and management recommendations that may support the use of this genus in other European regions. These aims are accomplished based on a thorough literature review, particularly focused on research developed in the Iberian Peninsula.

Keywords *Eucalyptus* spp. · *Eucalyptus globulus* labill. · Management and productivity · Biotic and abiotic risks · Environmental impacts · Land use planning

Introduction

Most species of the genus *Eucalyptus* are native to Australia (some species originate from New Guinea, Indonesia or the Philippines), where they occur within all but the driest parts of the continent and inhabit several distinctive climatic zones and vegetation types (Florence 1986). More than 700 species are currently recognized. Some are widely distributed, although discontinuously, while others are restricted to localized niches. Early Portuguese and Dutch navigators may have been the first Europeans to see *Eucalyptus* trees on the Australian continent, but there is no formal record of seed collection or plantings before the voyages of Captain Cook in 1770. *Eucalyptus* plantations worldwide probably cover more than 20 million ha at present (Rejmánek and Richardson 2011) and are dominated by a few species (*E. camaldulensis*, *E. grandis*, *E. tereticornis*, *E. globulus*, *E. nitens*, *E. urophylla*, *E. saligna*, *E. dunnii* and *E. pellita*) and their hybrids, which account for more than 90% of plantations (Stanturf et al. 2013). *Eucalyptus globulus* Labill. (blue

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gum) is one of the most widely planted and economically important hardwood species in temperate regions of the world (Potts et al. 2004).

At present, *Eucalyptus* represent the second most important exotic tree species in Europe, after *Robinia pseudoacacia* (Brus et al. 2019). They are recognized among the most important wood species in Europe, providing feedstock for the pulp and paper industries. However, there are concerns about their environmental impacts, mainly because *Eucalyptus* are exotic in Europe and phylogenetically very distant from European species. This paper has four objectives: (1) to summarize the present area of the genus in Europe; (2) to review and critically discuss the scientific evidence about the opportunities and challenges associated with *Eucalyptus* plantations in Europe; (3) to assess, using the review results, combined with silviculture principles and the ecology of the species, to what extent forest management, at both stand and landscape levels, can reduce the negative impacts; (4) finally, to make some management and policy recommendations needed in order to keep the advantages of using this important genus in European plantations while minimizing possible harmful environmental impacts. Particular emphasis is placed on *E. globulus* due to its importance in terms of area occupied and contribution to the economy, as well as to the availability of information.

Eucalyptus expansion in Europe

The first species of *Eucalyptus* to be planted in Europe was *E. obliqua*, in the greenhouses of the Kew Gardens (London) in 1774, whereas the first species planted outdoors was *E. robusta*, in the English Garden of the Royal Palace of Caserta (Italy) in 1792 (Silva-Pando and Pino-Pérez 2016). In most European countries, the first records of seed introduction date to the nineteenth century. The trees were initially mainly used for ornamental purposes and were planted close to farmhouses and beside roads and railways; they were also used to drain swampy areas (Goes 1977), and the wood was occasionally used for other purposes, for example, to make railway sleepers or mine pit props.

A few different species are cultivated in Europe, but *E. globulus* is preferred for its fast growth and wood properties and is by far the predominant species, especially in Portugal and Spain. *E. globulus* is therefore the most widely investigated *Eucalyptus* species in Europe, with studies addressing different topics ranging from productivity to environmental issues. In Portugal, *E. globulus* covers an area of 0.84 million ha (ICNF 2019), whereas the corresponding area (all *Eucalyptus* spp, but mostly *E. globulus*) in Spain is 0.64 million ha (MAPA 2019). Other species planted in Spain include *E. nitens* and *E. obliqua* in the north, and *E. camaldulensis* in the south. The area planted with *E. nitens* has increased greatly, in both Portugal and Spain, due to its fast growth in frost prone areas and its lower susceptibility to defoliation by *Gonipterus* (Pérez-Cruzado et al. 2011). At present, the annual consumption of *Eucalyptus* wood in Portugal is 7.8 million m^3 underbark (CELPA 2019). Considering the export and import (https://ine.pt/xportal), wood harvest can be estimated as close to 6.0 million m3 underbark. Eucalypt wood harvest in Spain is 7.6 million m^3 overbark (MAPA 2019).

In other European countries, *Eucalyptus* plantations occupy relatively small areas. In the southwest of France, plantations have been established with *E. gundal* hybrids (*E. gunnii* x *E. dalrympleana*), which now cover an area of almost 2000 ha (Melun 2018). However, the total area occupied in the country is negligible (Antoine Colin, French NFI, pers. comm.). The area covered by *Eucalyptus* in Italy is estimated to be 19,626 ha, mainly in Sardinia (17,396 ha) (Patrizia Gasparini, Italian NFI, pers. comm.). Species selection trials in Greece identified *E. bicostata*, *E. dalrympleana* and *E. viminalis* as the species that combine fast growth and suitability to local conditions. *E. camaldulensis* and *E. globulus* have also been reported to show some potential (Aravanopoulos 2010). Although we were not able to find any official documents reporting the area planted across Greece, it is known to be around 44,460 ha in the Peloponnese (https://greenagenda.gr/18366/). In 1939, *Eucalyptus* species began to be planted in the Mediterranean region (Tarsus-Mersin) of Turkey (Sivacioğlu and Şen 2017) and, according to the authors, *E. camaldulensis* plantations now occupy an area of 20,000 ha. Similarly, although several trials with different *Eucalyptus* species have been conducted in Ireland (Neilan and Thompson 2008), only *E. gunnii* was reported in the 2017 Forest Inventory statistics, covering an area of 10,000 ha (FS-DAFM 2018). After a long history of growing *Eucalyptus* species in arboriculture in Britain, different species have also been tested for forestry since 1950, leading to several species of interest for short rotation (Leslie et al. 2013; Purse and Leslie 2016a, b). The area covered nowadays by the genus is in the order of 300–400 ha, and the private estate plantings have become significant (Mason, pers. comm.)

The opportunities

The high productivity and suitability of *Eucalyptus* for industrial use have led to the development of a strong pulp and paper industry sector, contributing to national economies and providing an important source of income for small, non-industrial landowners. Intensive silviculture of the plantations, supported by tree breeding, has been crucial to achieving high productivity. Intensification of silviculture, based on monitoring in order to allocate the best management practices for each place and time, is expected to increase the productivity of future plantations.

Productivity

The success of these exotic species is due to their fast growth and ability to withstand and recover from harsh environmental conditions. According to Eldridge et al. (1993): "The present-day *Eucalyptus* have inherited many adaptations which allow them to take advantage of periods favourable to rapid growth between unfavourable periods". These adaptations include indeterminate shoot pattern, epicormic shoots, coppicing ability, lignotubers, fire-resistant bark and mechanisms to withstand drought and insect attack (Jacobs 1955).

Additionally, several other factors drive the fast growth of *E. globulus* such as its efficiency in the assimilation of carbohydrates (Chaves et al. 2004), the rapid development of leaf area after planting (Chaves et al. 2004; Soares et al. 2007), its high efficiency to absorb soil nutrients, particularly phosphorus, and to recirculate them via resorption or return to the soil as litterfall (through leaves, bark, low branches) or root death (Madeira et al. 2007; Viera et al. 2016). The efficiency in the use of water, measured as aboveground biomass yield per unit water transpired, can be as high as 3 kg/m^3 in this species, using the water consumption figures of Gras et al. (1993) and the rates of annual biomass increments.

E. globulus is considered a fast-growing tree in most countries where it is planted, allowing the application of common rotation lengths of 10 to 18 years for pulp production (Ruíz et al. 2008). In Portugal, the productivity strongly depends on the environmental conditions. Productivity in the best sites (13% of the stands) ranges from 24 to 30 m^3 ha^{-1} yr^{-1} (overbark stem volume) (Soares et al. 2007). However, in most stands the mean annual increment at 12 years is 7–18 m^3 ha^{-1} yr^{-1}. A recent evaluation of clonal and seedling plots in northern Spain reported a range of 5–35 m^3 ha^{-1} yr^{-1}, with the highest in deep soils at low elevations (García-Villabrille 2015). These values are lower than the ones reported in the absence of pest and diseases. The range observed in Southern Spain for clonal plantations is 12–30 m^3 ha^{-1} yr^{-1} for rotations of 10–15 years. Most long-term permanent trials have demonstrated that the yield from the second rotation (first felling after coppice) is 25% higher than the first, and that the third rotation is similar to the first. In Turkey, the mean annual increment value for stand volume was 3–35 m^3 ha^{-1} yr^{-1} (Sivacioğlu and Şen 2017).

A study conducted in Portugal to assess the potential productivity of *E. globulus* stands, including fertilization and irrigation treatments (described in Tomé et al. 1994; Madeira et al. 2002; Soares et al. 2007), showed productivity levels, at 6 years of age, ranging from 26 m^{3}ha^{-1} yr^{-1} to 47 m^{3}ha^{-1} yr^{-1}, respectively, in the control and fertilization plus irrigation treatments (mean value for each treatment). Higher values may be expected for older stands as mean annual increment had not yet peaked.

Forest management at stand level

The management of *E. globulus* plantations, grown as even-aged monocultures, has been intensified over time. The management system described below refers to well-managed plantations. Different management practices are used by non-industrial owners and pulp companies, with more intensive harvesting and fertilizing in the latter case.

A first rotation with planted seedlings is usually followed by 2–3 coppiced rotations, as additional rotations have been shown to lead to exhaustion of stumps ability to resprout (Ruíz et al. 2008). Planting stock is produced in containers, as either seedlings or rooted cuttings, although these produced fewer primary rots, often with no tap root and have a shallower root system (Sasse and Sands 1997). This problem has led to windthrow of planted stock in windy areas and eventually to the generalization of mini-cuttings propagation techniques. The use of good-quality planting stock has been shown to be key to the success of the plantation, and so standards have been established in Portugal, under which seedlings should be 3–12 months old and 10–40 cm tall with a root collar diameter > 2 mm. The plantation is usually manual and carried out in two periods: after the first rains in autumn and again in late winter, when the risk of frost is lower, until mid-spring while soil humidity is still enough. If plant mortality is higher than 10%, gaps are usually replanted up to 6 months after planting. Removal of the shrubs by harrowing or crushing is needed in scrubland areas, as well as controlling herbaceous weeds, as this species is particularly sensitive to early competition.

Depending on the soil type and depth, different site preparation techniques may be needed, such as subsoiling along the contours to a depth of 70 cm or digging of planting holes. Terraces (usually 3.5 m wide) have been dug in steeper terrain (slope > 25%), but this transformation hindered later plantation maintenance or logging operations and are no longer applied in new plantings (Ruíz et al. 2008). In soils where fertility is directly related to the conservation of organic matter in upper horizons, windrowing operations have been shown to be detrimental to early growth and nutrient status (Merino et al. 2003).

Nowadays, most new plantations involve replanting (after the usual 3 rotations) and the treatment of the stumps remains controversial. Stump removal is the most expensive technique and has uncertain effects on the productivity of the future plantations and is therefore being abandoned. Mechanical stump fragmentation followed by harrowing is the most commonly used operation. Stumps can also be chemically treated to avoid resprouting, with triclopyr being the active ingredient most frequently used, followed by soil preparation and planting between the previous planting lines. Even so, it should be considered that certification of sustainable forest management schemes (i.e. FSC) excludes the use of phytochemicals.

Final yield depends only slightly on stand density, even if mean annual increment peaks well before rotation age in dense stocked stands. For this reason, productivity of *E. globulus* evaluated at the usual rotation age can be highly dependent on spacing. For instance, in a trial located in Furadouro, Portugal, productivity at 14 years of age varied from 16 $m^3 ha^{-1} yr^{-1}$, in 5 × 4 m spacing blocks, to 26 $m^3 ha^{-1} yr^{-1}$, in one 3 × 2 m spacing block (Soares et al. 2004, 2007). In Spain, widely varying results have been obtained as regards the effect of initial spacing on *E. globulus* yield, probably because of inter-trial site variability, as well as the range of densities considered and the age of evaluation (Ruíz et al. 2008). In north-western Spain, an experiment comparing spacings from 2 × 2 to 3 × 3 m resulted in a 7–18% reduction in commercial volume in the least dense arrangement. As a result of the balance among initial investment, mortality rate, weeding needs and logging operations costs, the common range of plantation density is 1000–1250 trees ha^{-1} (Ruíz et al. 2008).

Seedlings are fertilized at planting with slow release fertilizer (NPKCaMgB) soluble NPK fertilizer or a combination of both. Additional applications of a nitrogenous fertilizer (which may contain P_2O_5 and K_2O) are carried out between the first and second years after planting and can be repeated throughout the rotation, depending on the soil conditions. The proposed practices and prescriptions for Spain have been reviewed on the basis of the results of trials, and the need to develop site specific practices has been considered (Viera et al. 2016). Nutrient management is essential to guarantee plantation economic profitability. Several silvicultural decisions, such as which biomass components should be harvested, promotion of rapid canopy closure, assessment of nutrient status or the use of forest residues as fertilizers, can reduce the need to apply more mineral fertilizers, thereby reducing the risk of environmental problems such as eutrophication (Viera et al. 2016).

Along each rotation, mechanical or chemical weed control is carried out at least during the first year after plantation and 3 and 5 years (if required). In coppice management, reduction of shoots to yield a stand density close to that used in the first rotation takes place between the second and third year after harvesting. The first application of fertilizer to coppiced stands should take place before thinning the shoots, to promote good development of the shoots. Otherwise, the operations are similar to those carried out during the first high-forest rotation.

In the last few decades, important advances in forest genetics, tree breeding, nursery techniques, planting and tending operations or optimization of harvesting techniques have led to the intensification of management to the level of precision silviculture. This is mainly applied to plantations managed by pulp companies and is far from common in most of the area covered by *Eucalyptus* in Spain and Portugal.

Land use planning at management unit and/or catchment levels

Nowadays, most experts agree that there is the need to upscale forest management and planning from forest stands to larger areas. Decisions on land use—themselves management decisions—must be taken at management unit and/or catchment levels (Fernandes 2013). Regarding *Eucalyptus*, land planning must consider limits to the expansion of the area covered by the plantations, retaining a balance between land uses at a landscape scale and assisting active management of the stands. This is particularly important for controlling the risk of forest fires and post-fire spread via natural regeneration. Recent legislation in both Portugal and Spain, aimed at controlling the area currently occupied by *Eucalyptus* species, has established restrictions regarding planting in new areas.

At landscape level, measures should be taken to guarantee environmental protection such as protecting water streams, establishing ecological corridors or designing networks of fire breaks (Molinero and Pozo 2004; Fernandes 2013). Pulp and paper companies are already considering management at landscape level, and in Portugal, some policy measures that encourage this approach in small non-industrial landowners have been developed, including the promotion of forest intervention zones (associations of landowners within the same management plan for cooperation to improve forest management).

The promotion of forest owners' associations or forest growers' cooperatives in Spain is another example of collaboration throughout the forestry sector brought about by a forest management plan. These initiatives are key to complying with the increasing number of regulations regarding maintaining a distance between *Eucalyptus* plantations and roads, infrastructures, rural villages, streams and agricultural land.

Tree breeding

Genetic improvement of *E. globulus* was initially focused on increasing productivity, but there has been discussion about focusing on this objective (Potts et al. 2011). Wood density and pulp yield were first incorporated as selection criteria in Portugal and Spain followed later, and more gradually, by drought tolerance and pest resistance (Soria and Borralho 1997; Toro et al. 1998). The first breeding programmes were initiated in Portugal in 1966 by the Billerud Pulp Company

(Dillner et al. 1971) and involved massive selection for size, form and cellulose content, in plantations of Portuguese landraces. Progeny and clonal trials—and evaluation of the performance of the selected individuals—complemented by provenance trials to evaluate the variability—confirmed the superiority of certain varieties (Almeida et al. 1995; Borralho et al. 2007). Breeding programmes in both Portugal (Borralho and Cotterill 1994) and Spain (Vega et al. 1994) increased productivity by around 25- 60% (Borralho et al. 2007). Chambers and Borralho (1997) identified survival as a key trait of breeding programmes whenever early survival (in the years after planting) is less than 50%.

Poor rooting ability is a constraint to clonal selection and increases the cost per plant. However, using clones selection favours higher genetic gain, plant homogeneity and provides specific solutions for different environments. Clonal selection favours higher genetic gain, plant homogeneity and provides specific solutions for different environments. However, the poor rooting ability of this species is a constraint that increases the cost per plant.

The uncertainty caused by climate change is a new factor that must be considered. Genetic variation to climate-stress drivers exists among and within *Eucalyptus* species and provenances, even in commercially important species where genetic selection was first carried out to improve growth. However, the extent to which selection for growth may reduce adaptability is an important, but understudied question. This information is crucial to guaranteeing a broad genetic base in breeding programmes and would enable the design of appropriate management strategies that could reduce climate-associated risks. *Eucalyptus* plantations have a high adaptive capacity, and it is possible to take advantage of short rotations that allow the optimization of silvicultural practices and planting different genotypes in site-specific climatic conditions (Booth 2013). It is important to understand the mechanisms behind stress tolerance and to optimize early selection tools by characterizing the most important traits associated with drought- and/or heat-stress tolerance in order to identify and recommend genotypes that will be suitable for the predicted conditions (Correia et al. 2016, 2018a, b).

More recently, comprehensive analyses using post-genomic techniques such as transcriptomics, proteomics and metabolomics have proved very useful for monitoring and linking specific physiological variations that increase our understanding of drought stress adaptation, tolerance and the complex regulatory networks (Warren et al. 2011; Correia et al. 2016).

Frost tolerance is of increasing importance in areas experiencing rapid climate changes. Leading breeders are thus seeking cold tolerant germplasm to expand plantations towards colder areas. In France, the FCBA (formerly known as AFOCEL) has been breeding *Eucalyptus* for frost-tolerance and growth rate in southern France (Potts and Potts 1986), producing highly cold-tolerant hybrids with vigorous growth and wide adaptability (Harvengt et al. 2017).

Disease and pest resistance have increasing relevance in *Eucalyptus* genetic improvement and selection programs. Research has been conducted searching for *Eucalyptus* species less susceptible to the *Eucalyptus* snout weevil (e.g. Gonçalves et al. 2019) as well as *E. globulus* genetic materials resistant to *Mycosphaerella* leaf disease (Pérez et al. 2016). Some selected genetic materials are now used by enterprises for plantation in areas at high risk of a specific agent.

Contribution to the income of landowners

E. globulus plantations provide an important source of income for small non-industrial forest owners. Plantations of this species rank high among the economic investments in forest plantations because of the relatively rapid payback and the relatively high price of the standing wood (Díaz-Balteiro et al. 2009). In a survey of 45 stakeholders in the Spanish forestry sector, the criterion of the net present value (€/ha) ranked highest among 9 criteria of sustainable forest management for *E. globulus* (Díaz-Balteiro et al. 2016). This team proposed multi-criteria models in order to include the preferences of stakeholders regarding sustainability, including social and environmental criteria in addition to economic criteria.

Costs and revenues depend on both the silvicultural operations required and site productivity. The GLOBULUS model (Tomé et al. 2006), implemented in the StandsSIM forest simulator (Barreiro et al. 2016), integrated in the sIMfLOR platform (Faias et al. 2012), simulates stand development according to user-defined forest management approaches (by indicating the calendar for the silvicultural operations). The costs and revenues, and other benefits such as C sequestration, are among the simulation outputs as well as the net present value. An example of the range of net present values that can be achieved by the landowners, productivity and profitability estimates, based on StandsSIM stand level simulations, for the range of site indices of *E. globulus* plantations in Portugal, is shown in Fig. 1.

Potential for bioeconomy and non-wood products

The main product of eucalypt plantations is pulpwood, able to produce kraft or dissolving pulp, obtained using the coppiced system described before. But single stem systems for solid wood production have also been proposed and applied in commercial plantations (Nutto and Touza 2006). Industrial uses for solid wood include veneer, plywood, parquet, flooring or laminated woods (Sepliarsky 2006).

A sound development of the bioeconomy will likely benefit new potential uses. Eucalypt wood and even bark are

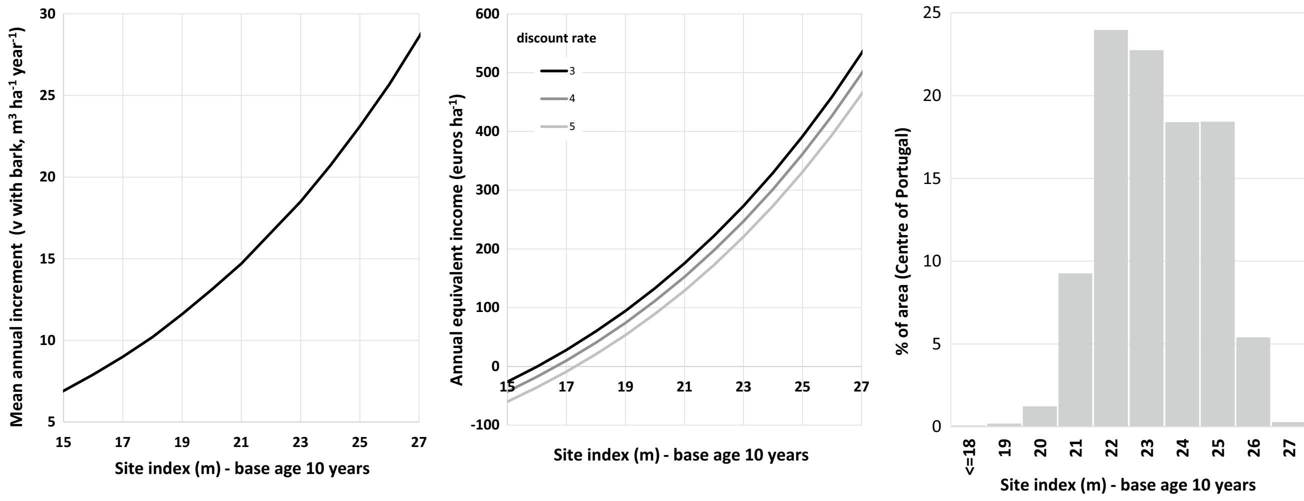


Fig. 1 Productivity (left), profitability expressed by the annual equivalent income for the range of site indices (base age 10) of eucalypt plantations in Portugal (centre) and distribution of area per site index (right) (own calculations using the StandsSIM simulator)

being tested to be used for textile fibres (lyocell) and other innovative and sustainable products in the last years. Wood, bark and even stumps could be sources of bioactive compounds with pharmacological properties, e.g. anti-inflammatory, antimicrobial, antibacterial, and probiotic properties as natural antioxidants (Domingues et al. 2011; Neiva et al. 2018), organic growing media formulation (Chematova et al. 2018) or biofuel production (Neiva et al 2020).

Eucalyptus biomass is also used for bioenergy. In Portugal, the bark and other industry residues are used to produce electricity, part of it being used by the industry (that is self-sufficient), but a large part included in the national energy network, representing a share of 6.1% of the energy produced in the country (CELPA 2019).

E. globulus are a major source of both nectar and pollen for honeybees because flowering is abundant and lasts for long periods (Rejmánek and Richardson 2011). In northern Spain, old plantations yield several species of edible mushrooms, particularly *Cantharellus*, *Tricholoma* and *Boletus*, especially when brush cleaning operations or grazing is applied (Blanco-Dios 2012).

Contribution to national carbon accounting

Eucalyptus plantations display a remarkable ability to sequester carbon; however, several components (soil, aboveground and belowground biomass) and processes (reduction of standing biomass due to felling or fires, transformation of wood into products that have very different lifespans, or bioenergy substitution) should be addressed in the long term (Pérez-Cruzado et al. 2012b). Research on these processes has been conducted in both Portugal and Spain.

Measurements from a flux tower established in an average site in Portugal (Correia et al. 2007) revealed values of C sequestration of 8.6 Mg ha^{-1} in a wet year, but only 3.3 Mg C ha^{-1} in a very dry year, with an average for 2002–2006 of 5.8 Mg C ha^{-1}. In a study using the inventory method, estimates at age 6 years in a trial with irrigation and fertilization treatments showed increases in C (aboveground + belowground + soil) after afforestation of between 58.6 Mg C ha^{-1} in the control plots and 114 Mg C ha^{-1} in the irrigated + fertilized plots (Madeira et al. 2002). Carbon in soil also increased relative to the amount prior to afforestation, probably because the soil was not particularly rich in organic matter. The average annual increment ranged from 13.7 Mg C ha^{-1} yr^{-1} to 22.9 Mg C ha^{-1} yr^{-1}.

The carbon storage capacity of the biomass is an evident result of the ability of *E. globulus* to grow at a fast rate (see section on productivity). Soares et al. (2007) reported a mean annual increment in aboveground biomass in the first rotation, ranging from 9 Mg C ha^{-1} yr^{-1} in the northern coastal to 3 Mg C ha^{-1} yr^{-1} in the Tagus valley. Biomass carbon accumulation rates of 8–11 Mg C ha^{-1} yr^{-1} have been reported for northern Spain (Pérez-Cruzado et al. 2012a). Nonetheless, soil carbon can decrease after planting. In former pasture land (rich in C) planted with *E. globulus*, soil carbon was reduced by the land use change (Pérez-Cruzado et al. 2012a), at least during the first 10 years after afforestation. Use of the CO2Fix model also revealed that the management practices considering short rotation for pulp or bioenergy production led to decreases in soil carbon, particularly when logging residues were removed (Pérez-Cruzado et al. 2012b).

On a nationwide scale, the trends in carbon stocks in biomass clearly depend on the changes in harvests derived from the future wood demand and forest fires. Simulations of C sequestration and stock obtained with the SIMPLOT forest simulator applied to all *Eucalyptus* plots measured in the fourth National Forest Inventory (1995–1997) in Portugal showed a negative balance for a scenario considering an increased wood demand to reflect the expected increase in the capacity of the wood pulp industry (Barreiro and Tomé 2011). A new set of simulations using the fifth National Forest Inventory (2005–2006) data were run using the same forest simulator under four scenarios combining different levels of wood harvest and fire occurrence (Fig. 2). Between 2006 and 2019, real data for wood harvest and burnt area were used. From 2020 onwards, the scenarios represent different combinations of future wood demand (higher and lower, WD1 and WD2) and wildfires (higher and lower constant burned areas, F1 and F2,) as shown in Fig. 2. The results show clear impacts on the C stock and C sequestration with scenarios corresponding to less wood harvest and a less severe occurrence of wildfires leading to steeper increases in C stock and to higher values of C sequestration (from − 0.128 Gg yr^{-1} of C sequestered in 50 years to 5.818 Gg yr^{-1}). Note that the graphs show C sequestration in the forest (C sequestered in products is not considered).

Sustained increases in total carbon sequestration have been found at stand scale when bioenergy substitution and the carbon stored in products were also considered in a continuous series of rotations (Pérez-Cruzado et al. 2012b). This study also showed that a sawn wood production regime was most effective for storing carbon in the soil (because of the longer rotation and more frequent slash input derived from pruning and thinning) and in wood products.

The challenges

Eucalyptus plantations in Europe face several challenges: (1) possible negative impacts on the environment; (2) vulnerability to hazards, namely pests and diseases, wildfires and climate change; (3) poor management in a large proportion of the plantations owned by small non-industrial owners. Some of them are generic and affect plantation forestry of other species.

Environmental impacts

As fast-growing exotics, *Eucalyptus* species have raised several concerns about their impact on the environment. The most commonly studied impacts are related to water use, soil degradation, loss of biodiversity and the potential invasion of neighbouring ecosystems.

Water use

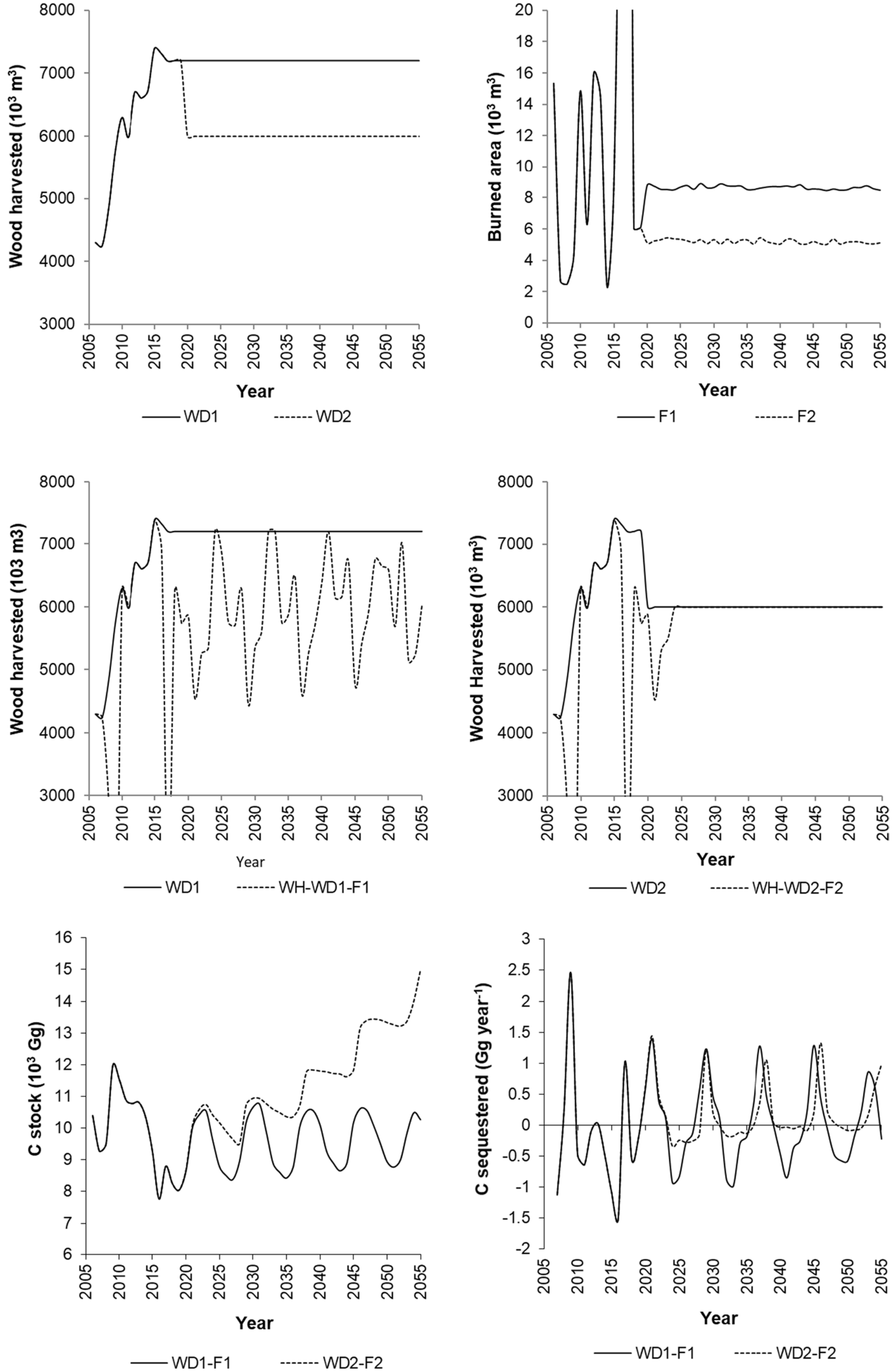
Concerns about water use by *E. globulus* in Portugal and Spain have led to several research studies, as summarized by David et al. (2007). Studies conducted at stand level or in small catchments showed that water loss via interception was lower in *E. globulus* stands (11–15%) than in *Pinus pinaster* Ait. stands (17–25%) (Gras et al. 1993; Valente et al. 1997) as a result of the lesser ability of leaves to retain water and the sparse crowns (David et al. 2007). Water storage in crowns was found to be 0.41 mm for pines and only 0.21 mm for *E. globulus*, being throughfall and stemflow relevant processes in plantations (Valente et al. 1997).

Transpiration was similar in *P. pinaster* and *E. globulus*, 3.0 and 3.6 mm day^{-1} in spring and 0.8 and 0.5 mm day^{-1} in summer, respectively (Loustau et al. 1996; David et al. 1997). Evapotranspiration in *E. globulus* stands is similar to that in other dense forest types, but is higher than in open forest or pastures (Almeida and Riekerk 1990; Rodríguez-Suárez et al. 2014). Water use levels of up to 1000–1100 mm $year^{-1}$ have been recorded in north-western Spain (Gras et al. 1993, where the percentage of rainfall used is on average 65% for stands of age 5–10 years (Rodríguez-Suárez et al. 2014). In terms of biomass production per unit of water used, this species is very efficient, as has been mentioned in the section on productivity.

The water yield of catchments covered by *E. globulus* greatly depends on the regime of perturbations (clearcutting, forest fires, defoliation or silviculture practices such as coppice sprout selection). Flow increases only occur shortly after clearcutting or any perturbation leading to a decrease in foliar area (David et al. 1994; Fernández et al. 2006). These hydrological effects were always short lived and depended on the rainfall level in the years following disturbance.

Probably the most important hydrological impacts of *E. globulus* are due to changes in land use, e.g. from pasture to fast-growing plantations. Relative to the previous pasture, afforestation produced a water yield reduction around 2000 mm (22% of total stream discharge) during the first 10 years of planting (Rodríguez-Suárez et al. 2014). Reduction in water yield became evident after canopy closure at age 3 years. Moreover, the relative reduction in discharge was greater in summer. Soil water uptake is restricted to depths having a relevant presence of fine roots, with 80% of root biomass within the top 60 cm of the soil.

Runoff can be increased as a consequence of soil water repellency associated with *E. globulus*, particularly in summer and after fire (Ferreira et al. 2000; Varela et al. 2005). This effect is important for defining post-fire rehabilitation treatments. In a study of 16 headwater streams in NW Spain, Cordero-Rivera et al. (2017) found that streams with drainage basins mainly covered with *E. globulus* were prone to drying up in summer.



Wood harvested (10³ m³)
Year
WD1
WD2
Burned area (10³ m³)
Year
F1
F2
Wood harvested (103 m3)
Year
WD1
WH-WD1-F1
Wood Harvested (10³ m³)
Year
WD2
WH-WD2-F2
C stock (10³ Gg)
Year
WD1-F1
WD2-F2
C sequestered (Gg year⁻¹)
Year
WD1-F1
WD2-F2

◂**Fig. 2** Changes in wood harvested, carbon stock and carbon sequestration in the forest for the whole of Portugal considering four scenarios that combine two levels of wood demand with two fire scenarios (own simulations with the StandsSIM simulator). Top row: wood demand scenarios on the left (WD1 and WD2) and fire scenarios on the right (F1, F2): middle row; comparison of wood demand and wood harvested for scenarios WD1-F1 (left) and WD2-F2 (right); bottom row: evolution of the C stock (left) and of the C sequestered (right) for WD1-F1 and WD2-F2 scenarios

Impacts on soil

As a fast-growing species managed on short rotations, *E. globulus* extracts large amounts of nutrients from the soil that are immobilized in the aboveground biomass. Research has shown that if only the wood component is extracted, fellings are less likely to result in a reduction in soil nutrient content (Merino et al. 2005). In addition, mycorrhizal symbiosis is very important in *E. globulus*, leading to very efficient nutrient use (especially of N and P) (Madeira et al. 2007).

Immobilization of Ca in the aboveground biomass was found to be greater than 700 kg ha^{-1} in Portugal (Madeira and Ribeiro 1995) and greater than 350 kg ha^{-1} in Spain (Rodríguez-Soalleiro et al. 2018), although mainly involving bark and leaves. Identification of the best biomass fractions to be harvested thus decreases the possible impacts on soil productivity. Nonetheless, negative balances for nutrients are frequent in the case of intensive silviculture entailing the removal of logging residues or bark, which is the rule in the case of small non-industrial forest owners (Merino et al. 2005). Mean annual removal of nutrients via harvesting has been found to be lower in native stands (*Quercus robur*, rotation age 120 years) than in fast-growing *E. globulus* stands, especially for the same harvesting extraction methods (Gómez-García et al. 2016).

Erosion can produce soil losses, particularly in new plantations or after logging or fire, and a sound choice of techniques for soil preparation, wood exploitation and post-fire rehabilitation is essential, particularly in steep slopes (Madeira et al. 2007). The importance of maintaining the organic layers of the soil so that the biological cycle of soil nutrients is not affected has also been highlighted (Jones et al. 1999). The application of fertilizers to *E. globulus* plantations also has positive implications regarding the impact on soil nutrients (Madeira and Pereira 1990).

Intense site preparation and harvesting operations may lead to alterations in soil and impacts on the ecosystem (Madeira et al. 2002). In some sites, productivity remained the same after less intense site management, indicating that site preparation should be adapted to soil characteristics in order to minimize the impacts on soil.

Findings on litter decomposition are rather inconsistent. Litter decomposition on a sandstone bedrock increased the amount of exchangeable Ca, leading to pH values close to neutral (Madeira and Ribeiro 1995), thereby indicating that keeping leaves on site after harvesting will contribute to replenishing most of the nutrients extracted. Decomposition has been found to occur faster in *E. globulus* stands than in *P. pinaster* (Ribeiro et al. 2002), *Castanea sativa* and *Quercus faginea* (Canhoto and Graça 1996) but slower than in *Alnus glutinosa* stands (Pozo et al. 1998). However, the opposite has been found in a comparison between *E. globulus*, *Q. robur* and *P. pinaster* in acid soils (Castro-Díez et al. 2012). A more recent meta-analysis showed that decomposed litter inputs to small streams in *E. globulus* plantations were significantly inhibited relative to the litter decomposition in native forests (Ferreira et al. 2016).

The physical properties of the soil in *E. globulus* stands are somewhat different from those of soil in *Q. suber* and *P. pinaster* stands in which no biomass extraction nor soil perturbation occurred during several years (Madeira et al. 2007), i.e. lower total porosity and greater compaction. Differences were also detected in soil hydraulic conductivity and soil infiltration rate. Complementary studies showed that these effects are mainly due to soil management and silviculture and are not directly due to the species (Madeira et al. 1989, 2002).

Loss of biodiversity

In a global context of increasing wood demand, plantations are sometimes associated with the protection and restoration of natural forests. However, most planted forests are grown primarily for wood production and are typically characterised by lower levels of biodiversity than mixed natural forests (Brockerhoff et al. 2013). There is also scientific evidence of a negative impact of *E. globulus* plantations on biodiversity, when compared to native ecosystems. This has been demonstrated by numerous studies developed both in Portugal and Spain, for all major groups of species. Table 1 presents a summary of studies comparing the biodiversity of *E. globulus* stands with ecosystems mostly dominated by species that are locally native. The results are quite impressive, as no study has detected a positive effect of *E. globulus* on the diversity (expressed as species richness or other diversity indices) of any group of species. Whether this impact is related to the intensive silviculture that is typical of *E. globulus* stands, or whether it is related to the intrinsic nature of the species, it is not always easy to tell. The lack of co-evolution with local species may explain part of this impact, but there is also evidence that management can make a difference. Fabião et al. (2007) reviewed research conducted in several related experiments in Portugal on the impacts of different management alternatives on the understory vegetation of *E. globulus* plantations (Cerveira et al. 1999; Jones et al. 1999; Fabião et al. 2002; Carneiro et al.

Table 1 Summary of research studies comparing the diversity of major species groups, between *E. globulus* stands and local ecosystems, in Portugal and Spain

Species group	References	Country	Impact on diversity			Reference genus
			Negative	Neutral	Positive	
Fungi	Bärlocher and Graca (2002)	Portugal	X			*Castanea, Quercus, Pinus*
	Chauvet et al. (1997)	Spain		X		*Alnus*
Lichens	Calviño-Cancela et al. (2013)	Spain	X	X		*Pinus, Quercus*
	Calviño-Cancela et al. (2020)	Spain	X			*Pinus*
Plants	Araújo (1995)	Portugal	X			*Quercus*
	Calviño-Cancela et al. (2012)	Spain	X	X		*Quercus, Pinus, Ulex, Erica*
	Goded et al. (2019)	Spain	X			*Quercus, Castanea, Betula*
	Lomba et al. (2011)	Portugal	X			*Pinus*
	López et al. (2018)	Spain	X			*Quercus*
	Proença et al. (2010)	Portugal	X	X		*Quercus, Pinus*
	Vaz et al. (2019)	Portugal		X		*Pinus*
Invertebrates	Abelho and Graça (1996)	Portugal		X		*Castanea, Quercus*
	Cabral and Martins (1985)	Portugal	X			*Pinus*
	Cordero–Rivera et al. (2017)	Spain	X			*Alnus, Betula, Quercus, others*
	Serralheiro and Madeira (1990)	Portugal	X			*Quercus*
	Sousa et al. (2000)	Portugal	X			*Quercus, Pinus*
Vertebrates	Araújo (1995)	Portugal	X			*Quercus*
	Bongiorno (1982)	Spain	X			*Pinus, Quercus, Ulex*
	Calviño-Cancela (2013)	Spain	X	X		*Pinus, Quercus*
	Goded et al. (2019)	Spain	X			*Quercus, Castanea, Betula*
	López et al. (2018)	Spain	X			*Quercus*
	Proença et al. (2010)	Portugal	X	X		*Quercus, Pinus*

Impact on diversity is presented according to statistical evidence as negative, non-significant and positive. Column "Reference genus" indicates the genus of dominant native woody species used for comparison in each study

2007, 2008, 2009). The intensity of harvesting, residue extraction and soil disturbance had a significant impact on understory diversity. The highest number of species in most years occurred in plots where slash was removed, but differences in the proportion of plant soil cover were never significant. Differences in diversity were also detected as a consequence of soil disturbance (Carneiro et al. 2007, 2008), with lower diversity observed in treatments including harrowing.

Plantations managed using low-intensity approaches can harbour large amounts of plant biomass in the understory, although with relatively low local diversity. Although successional changes were found within the understory of *E. globulus* plantations with increasing age, key components of the flora of native forests were not found in mature plantations (Calviño-Cancela et al. 2012). In a study of 16 headwater streams in NW Spain, Cordero-Rivera et al. (2017) found that macroinvertebrate richness and diversity decreased as the area of land covered by *E. globulus* plantations increased. A recent study has shown that structural tree diversity, but not species richness, is higher in pine stands in Portugal than in *E. globulus* stands, which, in turn, hold larger numbers of exotic species (Vaz et al. 2019). These differences appear to result from the inherent characteristics of the species but also from the different management practices applied to each forest type. Besides the direct effect of *E. globulus* on biodiversity because of a disruption of food chains and habitat loss, there is also evidence of strong negative allelopathic effects on understorey vegetation (del Moral and Muller 1969; Molina et al. 1991; Souto et al. 2001). Interestingly, these effects were found to be more important in the introduced range (including Portugal) than in the native range of *E. globulus* (Becerra et al. 2018).

In the case of vertebrates, the studies are quite consistent in showing the negative impact of *E. globulus* on species diversity, in many cases accompanied by a decrease in plant diversity (e.g. Calviño-Cancela 2013; López et al. 2018), in comparison with native ecosystems.

Invasiveness

The invasiveness of *Eucalyptus* trees is not clear and tends to be controversial, probably because invasion events are strongly context-dependent. *Eucalyptus* are generally less successful invaders than other widely planted trees such as

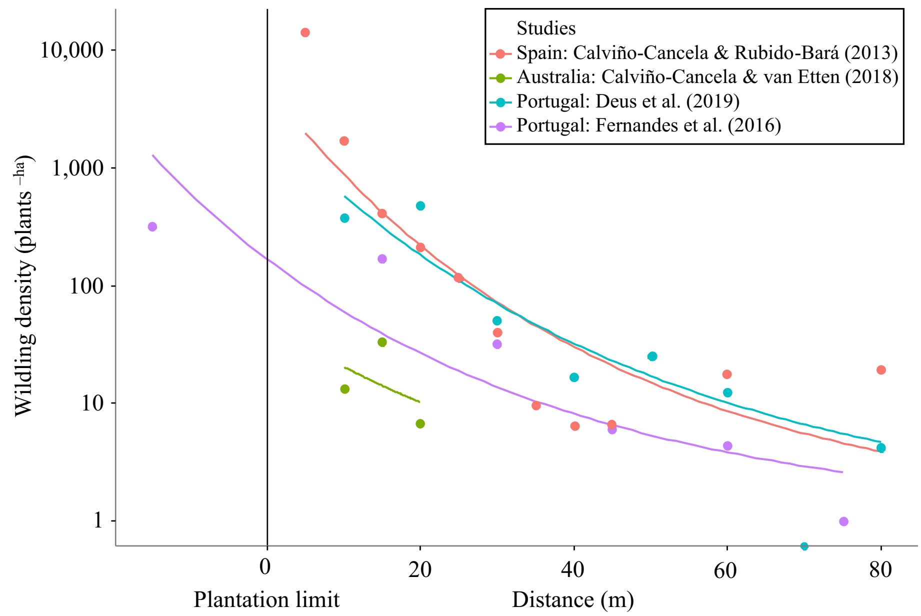


Fig. 3 Average density of *E. globulus* wildlings and distance from plantation edge, according to four different studies (only survey transects with registered plants). Negative exponential curves fitted to the data from each study. Data retrieved from plots in the studies

Pinus spp., *Acacia* spp. and *Proposis* spp. (Rejmánek and Richardson 2011; Fernandes et al. 2016). Nevertheless, there is growing concern about *Eucalyptus* invasiveness. In Europe, all research on this topic has so far been conducted in the Iberian Peninsula region and was focused exclusively on *E. globulus*.

Some studies have shown that *E. globulus* can generate abundant offspring close to parent plants in many parts of the Iberian Peninsula (Catry et al. 2015; Díaz 2016; Águas et al. 2017; Fernandes et al. 2018). Surveys conducted outside plantations showed that *E. globulus* can spread into adjacent habitats (Águas et al. 2014; Fernandes et al. 2016; Deus et al. 2019; Vaz et al. 2019), even though habitats such as native forests seem to be more resistant to invasion (Calviño-Cancela and Rubido-Bará 2013; Fernandes et al. 2017). Despite high mortality rates in the first months (Calviño-Cancela and Rubido-Bará 2013; Fernandes et al. 2017), field surveys confirmed that *E. globulus* wildings can overcome the most critical stages of survival, both inside (Águas et al. 2014) and outside of plantations (Fernandes et al. 2016; Deus et al. 2019). In fact, many wildings reach sexual maturity (Deus et al. 2019), a key step in the processes of naturalization and invasion.

The seeds of *E. globulus* lack specific adaptations for distance dispersal. Some observations on the spread from plantations in different studies are illustrated in Fig. 3. All studies show that wilding density decreases sharply with distance from the plantation (note the logarithmic scale). The spread from plantations is considerably lower in SW Australia (max. 20 m). Studies conducted in Portugal yielded similar recruitment curves, decreasing up to 75–76 m from plantations (Fernandes et al. 2016; Deus et al. 2019), although with different values, which can be partly explained by differences in sampling methods and study regions. The dispersal distance was found to be enhanced by dominant winds and natural drainage lines (Deus et al. 2019). In NW Spain, seeds have been found at distances of up to 80 m from plantations (Calviño-Cancela and Rubido-Bará 2013). The higher dispersal potential in Spain can probably be explained by the use of a stochastic model using data from sowing experiments and seed dispersal, which may have led to overestimation of wilding density.

Research in the Iberian Peninsula region has uncovered some key factors influencing *E. globulus* recruitment. Climatic variables such as annual precipitation and temperature seem to be decisive in explaining regional differences in *E. globulus* recruitment (Catry et al. 2013, 2015; Deus et al. 2016; Díaz 2016; Queirós et al. 2020). At a local scale, disturbance plays a key role. For example, artificial disturbance (vegetation removal and soil scarification) favoured the germination of seeds (Fernandes et al. 2017), similar to harrowing (Nereu et al. 2019). Surveys outside plantations showed that the level of soil disturbance is positively related to the abundance of *E. globulus* wildings (Fernandes et al. 2018). Small seeds imply that the seedling have small reserves and are therefore very sensitive to competition. Plant competition thus seems to be a major limitation to recruitment (Deus et al. 2019; Nereu et al. 2019). Fire is perhaps the most important disturbance associated with *E. globulus* recruitment (Águas et al. 2014; Calviño-Cancela et al. 2018). Apart from a competition-free soil bed, fire promotes massive, synchronized, fire-triggered seed dehiscence in the weeks following fire (Santos et al. 2015). Other studies have shown that *E. globulus* recruitment is positively influenced by the age and number of rotations of plantations (Larcombe et al. 2013; Águas et al. 2017), which is probably related to their reproductive output (Larcombe et al. 2013; Deus et al. 2019). The higher recruitment, compared to the native range, found in Portugal by Águas et al. (2017), may be in part explained by the smaller number of animal species that feed on *E. globulus* seeds (Deus et al. 2018b).

Control of *E. globulus* is simpler than that of exotic species that form a long-lived soil seed bank (*Acacia* spp.) or resprout from root suckers (e.g. *Ailanthus altissima*). The risk of invasion by *E. globulus* is generally low, provided that active management of adjacent areas is carried out or that safety belts are created by clearing land or encouraging growth of grasslands or stable native forests around plantations (Calviño-Cancela and Rubido-Bará 2013). However, this does not generally occur in Portugal and Spain, where the frequent abandonment of plantations and surrounding areas (Vaz et al. 2019), associated with the occurrence of wildfires, may provide favourable conditions for invasion.

Vulnerability to hazards

The main risks to *E. globulus* plantations are fire and pests and diseases. Being a cultivated species, the risks that the stands face depend on the management decisions (plant material, planting stock) and the frequency of silvicultural operations such as understorey management, shoot selection, pruning in solid wood schemes, fertilization and others. Climate change can play a determining role in the risks faced by plantations, since drought episodes are expected to be longer and more severe.

Pests and diseases

Since *Eucalyptus* were first introduced to Europe in the nineteenth century, for decades the trees have been characterized by their extraordinary health. This exceptional situation can be attributed to two main factors. First, only a few native European insect pests sporadically feed on trees, because of the lack of co-evolutionary history. Secondly, *Eucalyptus* were originally introduced to Europe free of their native insect fauna.

Regarding native European insect pests, it is worth to note that about 170 years after plantations were first established, and despite the large areas occupied by the species, no native insect pest represents a particular risk to *Eucalyptus* plantations in Europe. Still, some polyphagous species occasionally feed on trees (Branco et al. 2015). These include insect pests in two main groups: (1) xylophagous species that feed on the tree trunk, or stumps, and (2) root feeders. The former are generally associated with decaying trees or dead wood, and do not represent a potential problem for plantations. Reported species include some ambrosia beetles, such as *Xyleborinus saxesenii*, *Xyleborus dispar* and *Platypus cylindrus* (Lombardero and Fernández 1997), and generalist xylophages (Cabral 1983). The second group is mainly represented by cockchafers (in the family of scarab beetles), such as *Melolontha* spp. and *Anoxia villosa* (Col: Scarabaeidae; Melolonthinae), which feed on the root system of young plants (Ferreira 1998). These polyphagous beetles may occasionally cause significant mortality of seedlings in young plantations. Nevertheless, the problems associated with cockchafers are restricted to particular conditions that favour build-up of the insect populations, such as the presence of dense shrubby vegetation before plantation and sandy soils (Ferreira 1998). Highly generalist defoliators such as the gypsy moth, *Lymantria dispar*, are sporadically observed feeding on *Eucalyptus* trees. By contrast, in regions of South America and Asia that are home to many native tree species within the Myrtaceae family, several native insect pests were observed to expand their host range from native flora to *Eucalyptus* trees inflicting significant damage on plantations (Zanuncio et al. 1994).

The healthy status of *Eucalyptus* trees has gradually changed with the arrival and establishment in Europe of Australian insect pests and pathogens. This invasive process began in the 1920s, but only became noticeable after the 1970s and increased exponentially thereafter, following global trends of biological invasions (Hurley et al. 2016). The psyllid *Ctenarytaina eucalypti* (Maskell) (Hem., Psylloidea) was the first to arrive in Europe in the 1920s and was first found in England and France (Mercier and Poisson 1926). This psyllid mainly affects young trees and is very host-specific; in Portugal, it only became an important problem in the 1970s as the area occupied by plantations increased (Azevedo and Figo 1979). The next serious problem was caused by the wood borer *Phoracantha semipunctata* (Col: Cerambycidae). In Portugal, this species was first reported in 1980 and within four years caused high mortality rates in affected trees (Araújo et al. 1985). Other species also arrived, and there are currently at least 16 invasive insect species and numerous pathogens that affect *Eucalyptus* plantations in Europe. The insect species are represented by distinct feeding guilds, including 6 sap suckers, 4 defoliators, 4 gall wasps and 2 wood borers (Table 2).

As observed with insect pests, opportunistic pathogens occasionally infest trees, usually under conditions of stress. These are mainly fungi such as *Armillaria* spp. and *Phellinus torulosa*, which cause root rot and wood decay. Since the 1990s, a complex of fungal species native to Australia, commonly known as *Mycosphaerella*, has been causing leaf necrosis and severe defoliation, especially in young plantations (Branco et al. 2014). Fungi such as *Botryosphaeria* spp. and *Neofusicoccum* spp., which cause trunk canker, have also been reported in stands suffering from severe dieback. Tree stress due to drought may particularly increase the susceptibility of *Eucalyptus* trees to these diseases (Barradas et al. 2018, 2019).

Table 2 List of invasive pests affecting *Eucalyptus* spp. in Europe (Branco et al. 2014; Hurley et al. 2016)

Insect	Family (Order)	Feeding guild	Countries affected[a]	Date of first record in Europe
Ctenarytaina eucalypti	Psyllidae (Hem.)	Sap-sucker	UK, FR, ES, PT	1922
Phoracantha semipunctata	Cerambycidae (Col.)	Wood borer	IT, PT, ES, FR	1970
Gonipterus sp.	Curculionidae (Col.)	Defoliator	IT, FR	1975
Gonipterus platensis	Curculionidae (Col.)	Defoliator	ES, PT	1991
Phoracantha recurva	Cerambycidae (Col.)	Wood borer	ES, PT, IT	1998
Ophelimus maskelli	Eulophidae (Hym.)	Gall-former	IT, ES, PT	1999
Leptocybe invasa	Eulophidae (Hym.)	Gall-former	IT, ES, PT	2000
Ctenarytaina spatulata	Psyllidae (Hem.)	Sap-sucker	ES, PT	2002
Blastopsylla occidentalis	Psyllidae (Hem.)	Sap-sucker	IT, ES, PT	2006
Glycaspis brimblecombei	Psyllidae (Hem.)	Sap-sucker	PT/ ES, IT	2007
Ctenarytaina peregrina	Psyllidae (Hem.)	Sap-sucker	UK/IE	2007
Ophelimus mediterraneus	Eulophidae (Hym.)	Gall-former	FR, IT, PT	2011
Thaumastocoris peregrinus	Thaumastocoridae (Hem.)	Sap-sucker	IT, PT, ES	2011
Paropsisterna selmani	Chrysomelidae (Col.)	Defoliator	UK/IE	2014
Trachymela sloani	Chrysomelidae (Col.)	Defoliator	SP	2014
Epichrysocharis burwelli	Eulophidae (Hym.)	Gall-former	PT	2015

[a]Countries appear by order of first records

Countries abbreviations: ES—Spain; FR—France; IE—Ireland; IT—Italy; PT—Portugal; UK—United Kingdom

Insect pests and pathogens have changed forest management in the affected areas. Following the establishment of *P. semipunctata* in Portugal in the 1980s, marginal areas for the production of *E. globulus* shifted to other types of land use. *Gonipterus platensis* is the main pest in Iberian Peninsula. In Portugal, it was estimated to have caused an economic impact of 648 million euros due to wood loss over 20 years (between 1996 and 2016) (Valente et al. 2018). In the areas mostly affected by *G. platensis* (higher elevations and shallow soils), *E. globulus* is being replaced by *E. nitens*, a less susceptible species. Use of selected genetic material is also one of the main strategies considered for the areas affected by *Mycosphaerella* leaf disease (Pérez et al. 2016), as the continuous use of fungicides is environmentally and economically unviable.

The introduction of natural enemies brought from Australia, through classical biological control, has been the most helpful strategy. A good example is the success achieved in controlling *C. eucalypti* by release of the parasitoid *Psyllaephagus pilosus* Noyes (Hym: Encyrtidae) in France and in Ireland (Chauzat et al. 2002). Similarly, the introduction of the egg parasitoid *Anaphes nitens* in the 1970s successfully controlled *Gonipterus* sp. in Italy and France. *A. nitens* was also released in the Iberian Peninsula region to act against *G. platensis*. Although in this case success was restricted to a few areas (Reis et al. 2012), the programme was still highly economically profitable (Valente et al. 2018). Another Australian egg parasitoid, *Anaphes inexpectatus*, was introduced in Portugal following biological and risk assessment studies (Valente et al. 2017a, b). Although a small number of parasitized egg masses were observed in the field after release, its establishment status is still uncertain. Further, the establishment of the parasitoid population could have been compromised by the large forest fires that occurred in 2017 and burned the plantation area where *A. inexpectatus* has been released (C. Valente, pers. communication). In addition, some parasitoids have arrived by chance: for example, *Avetianella longoi* (Hym: Encyrtidae), an egg parasitoid of *P. semipunctata*, was found to occur in Italy and Portugal (Siscaro 1992). More recently, the parasitoid *Psyallaephagus blitaeus* has been also recorded in Europe, and probably arrived together with its host *Gonipterus brimblecombei*. However, to date no classical biological control has been used to control some of the insect pests. In the case of psyllid species, many predators native to Europe, such as lacewings, ladybirds, predatory bugs and spiders, may still exert some natural control on these species (Azevedo and Figo 1979; Valente and Hodkinson 2009).

Wildfire

The annual average area of *Eucalyptus* forest burnt between 1996 and 2012 was 15 thousand ha in Portugal (ICNF 2015) and 5 thousand in Spain (MAPAMA 2019), with an increasing trend of megafires larger than 500 ha. A study carried out in Portugal ranking the risk of susceptibility to fire damage of the main forest species showed that *E. globulus* plantations were second in the ranking, among eight species, after *P. pinaster* (Silva et al. 2009). A recent study by Fernandes et al. (2019) could not find a relationship between the expansion of *E. globulus* stands and the increase in the burned area in Portugal, probably because this expansion replaced previously existing highly flammable fuel types, including shrublands and pine stands. Nonetheless, as these authors point out, the fire hazard associated with eucalypt-dominated stands may increase in the future because of the high proportion of abandoned plantations (see section on management). Mixed stands of *E. globulus* and *P. pinaster*, which occur as a consequence of abandonment, are very common and represent the highest fire hazard among all forest types in Portugal (Moreira et al. 2009). Another problem frequently reported by fire fighters is that fire suppression is difficult because of intense spotting at the fire front (Ganteaume et al. 2010). However, this topic remains poorly studied and warrants further research.

Although the combustibility of *E. globulus* plantations depends on the type of management, the stands tend to be highly flammable (Mirra et al. 2017). The understorey rapidly accumulates litter and debris, including exfoliating bark, as well as understory bushes (Arellano et al. 2016). These plantations are inherently vulnerable to fire, and fuel control should be conducted every 3 to 5 years in areas where there is a high recurrence of ignitions (Mirra et al. 2017). On the other hand, *E. globulus* has a remarkable capacity to withstand and recover from fire, thus rapidly attaining fire hazard levels (fine fuel loads) similar to the pre-fire situation (Gouveia et al. 2010). The threats that forest fires pose to rural communities have led to the need for the law to be enforced on several occasions to ensure that forest owners maintain plantations with low load of brush biomass and the *Eucalyptus* trees are at a safe distance from villages.

Prescribed burning has frequently been proposed as a potentially useful management tool for reducing fire hazard in *E. globulus* stands by modifying the understory fuel structure (Fernandes et al. 2013; Jiménez et al. 2012). Its operational adoption has, nevertheless, been slow, uneven and inconsistent, as its implementation is constrained by regulations and by cultural and socioeconomic factors (Fernandes et al. 2013). Studies in Galicia have revealed that young *E. globulus* stands can be treated with prescribed burning without crown scorching and without any apparent decrease in diameter growth, provided that the damage is restricted to the stem (Jiménez et al. 2012). However, because of the thin bark, epicormic basal shoots are relatively frequent when the fireline intensity is higher than 300 kW m^{-1} (Vega 1985).

Risks associated with climate change

According to the IPCC (2014), surface temperature is projected to rise in the twenty-first century in all emissions scenarios assessed. It is almost certain that there will be more frequent hot and fewer cold temperature extremes over most areas of land on daily and seasonal timescales, as the global mean surface temperature increases. Heatwaves are expected to occur with a higher frequency and longer duration. Occasional cold winter extremes will continue to occur. Changes in precipitation will not be uniform. Predicted scenarios for the European climate at the end of this century suggest a slight reduction in annual precipitation and an extension of rainy seasons. In the Mediterranean area, drought periods will probably become more frequent and longer.

The climatic scenarios available for the Portuguese territory as well as the trends in the last 30 years suggest an increase in the frequency of dry years and a decrease in spring precipitation. In this context, the impact of climate change on *E. globulus* stands in Portugal has been studied using the GOTILWA + model, with a predicted increase in productivity in northern regions and, probably, in the central coastal regions, but a reduction in productivity in regions to the south of the Tagus river as a consequence of the increased drought (Correia et al. 2007). The interest in maintaining plantations in this region of the country is therefore questionable and, consequently, climate change may determine the displacement of species according to the optimum climate zone for growth. Productivity may increase in some European plantations and decrease in others. Deus et al. (2018a) modelled the future distribution of *E. globulus* plantations in the Iberian Peninsula region by considering two ICPP representative (greenhouse gas) concentration pathways (RCP): RCP2.6 and RCP8.5. The results suggest that the suitable range will decrease slightly under the best scenario (RCP2.6) but is expected to be drastically reduced (to half of the current range) under the worst scenario (RCP8.5). However, both scenarios show a gain in new areas for cultivation towards inland areas in the northern regions and towards higher elevations. Moreover, in both scenarios, there will be an overall improvement in the suitability for *E. globulus* plantations within the receding ranges. A similar study has also shown that current bioclimatic zones associated with *E. globulus* will be reduced slightly (under RCP4.5 and RCP8.5) and relocated (Costa et al. 2017).

The use of hybrids may help to find adequate genotypes for each environment. For instance, some frost resistant hybrids are already being used: *E. gundal*, an hybrid *E. gunnii* × *E.dalrympleana*; *E. globulus* × *E. viminalis*; *E. globulus* × *E. gunni*; *E. globulus* × *E. cypelocarpa*.

Under future climate scenarios, trees will experience new biotic and abiotic environments and stresses, such as drought, temperature extremes, flooding, wildfire and novel insect and disease pressures (Correia et al. 2018a, b). The REINFFORCE[1] arboreta network, with 38 sites between latitudes 37° and 57°, include *E. nitens, E. globulus* and a clone of *E. gunnii x dalrympleana*. After four years, the best climatic predictor explaining the survival of broadleaved species was precipitation-transfer distance, and annual height increment was mainly explained by an annual dryness index (ADI) calculated as the square root of growing season degree-days divided by annual precipitation in both conifers and broadleaved trees (Correia et al. 2018a, b). The clone *E. gunnii x dalrympleana* showed a very high growth potential and also considerable variability along the arboreta network. The height growth of *E. globulus* was reasonably constant along the ADI gradient, with a slight increase in growth at higher ADI values (Correia et al. 2018a, b).

The frequency of storms has increased in Europe as a result of climate change. In Portugal, some episodes have also occurred and this hazard is beginning to be considered important. *E. globulus* trees are windfirm by the time they reach sapling size, but because the root system develops slowly, seedlings or saplings can be windthrown (Skolmen and Ledig 1990). In northern Spain, where winter windstorms are frequent, most damage occurs as stem breakage.

Consequences of poor management

In Portugal and Spain, most *Eucalyptus* plantations are owned by small non-industrial private owners, a large majority of whom do not implement the management practices needed at stand level to obtain high productivity. In addition, most of these owners do not participate in associations that could maintain the mosaic of landscapes needed to promote sustainable forest management. Rural areas in both countries face serious problems of depopulation, agriculture abandonment and lack of active forest management. In areas where small non-industrial forest owners have very small plots of land, active management is usually uncommon. However, the degree of involvement in land management varies among regions (Rodríguez-Vicente and Marey 2009).

In both countries, forest and tax regulations require detailed consideration of management decisions, accounting and felling licences, as well as revision of management plans (even for simple forest management plans) and bureaucratic issues with different administrations and even certification activities (certification of small non-industrial forest owners' groups has been successful). Professionalization of silvicultural activities is therefore required and is still far from being achieved.

[1] RÉseau INFrastructure de recherche pour le suivi et l'adaptation des FORêts au Changement climatiquE.

Genetically improved material is mainly used in plantations owned/managed by the forest industry, and only a small proportion of the private plantations (10% according to Almeida et al. 2005) use this type of material, partly due to shortage of nursery supplies. Clones derived from several generations of breeding are now often commercially available in Spain (Ruíz et al. 2008), where site and clone specific silviculture is envisaged, but has not yet been fully achieved.

When *Eucalyptus* trees became popular in Portugal, several private landowners rapidly took the decision to plant *E. globulus* without prior analysis of the suitability of the land for the species. Therefore, the present area includes many inland areas where growing *E. globulus* is not profitable. This has also led to the abandonment of such plantations.

Abandonment of plantations by individual landowners is often motivated by the recurrence of fire, which discourages investment in stand management (Silva et al. 2011). In 2005, mixed stands, corresponding largely to abandoned plantations, covered an area of 173,000 ha, representing an increase of 75% relative to the previous national forest inventory (AFN 2010; Silva and Tomé 2016).

Converting plantations located in unsuitable areas to other land uses, preferably native forests, and bringing poorly managed plantations to their potential productivity is one of the greatest challenges related to *E. globulus* in the Iberian Peninsula region.

Using the opportunities while caring for the challenges: the importance of good management and appropriate forest policy measures

E. globulus is the second most planted exotic tree species in Europe (Brus et al. 2019), and its importance to the economy of some countries, particularly in the Iberian Peninsula, is remarkable. In previous sections, the outlined opportunities and challenges associated with the species have highlighted the existing controversy. Pulp and paper industries and private landowners are aware of the importance of *E. globulus*, which forms the basis of an important industry at country level and provides useful income for those private landowners who apply good management practices. On the other hand, part of society is concerned about possible environmental damage such as water consumption, invasiveness and biodiversity loss. The most frequent opinion in increasingly urban societies is that *Eucalyptus* forestry and nature conservation are separate issues. This particularly applies to densely populated semi-urban areas in coastal regions, where these large evergreen trees dominate the landscape. *Eucalyptus* stands are also increasingly vulnerable to hazards, especially pests and diseases, wildfire and climate.

Analysis of the opportunities and challenges leads to some recommendations for maintaining plantations in order to support the pulp and paper industry and to provide income to small non-industrial owners, while keeping environmental impacts at an acceptable level. The analyses show that a sound forest management can reduce many of the impacts and hazards that *E. globulus* areas face. Even so, active management can hardly reduce the diversity reduction or the increase in water consumption derived from fast biomass production, particularly in the case of land use changes. The extent of impact and hazard reduction by management is still a subject of further research.

The most important recommendations, most of which require policy measures that will incentivize/support private landowners, are as follows:

- Use *Eucalyptus* in the areas of high productivity
  Definition of the potential productivity of *E. globulus* in each region will enable forest managers and owners to make well-founded decisions regarding selection of this species as a good choice for afforestation/reforestation and to provide a benchmark for the plantation productivity once the decision is taken. Planting *E. globulus* should be avoided in regions where the potential productivity is not sufficient for the species to be profitable because of the frost regime, drought or vulnerability to pests or diseases. The use of growth models and decision support systems may support such decisions. The consideration of alternative species already present in both countries (*E. nitens* or *E. camaldulensis*) and/or of hybrids must be taken into consideration. This implies making available in the market productive plants, genetically diverse, tolerant to adverse climatic factors and with adequate wood properties for the pulp and paper industry and using them when establishing new plantations.
- Conversion of plantations located outside the areas of high productivity
  Eucalyptus plantations should be restricted to appropriate sites where the species can be legally planted. This will require the conversion of some existing plantations that are currently poorly managed, which is not possible without some support programme. *E. globulus* is often present due to unintentional spread as a result of decades of abandonment and wildfires. If the plots have low potential productivity, transformation of the degraded stand should be envisaged. The transformation process encompasses the felling of trees and exploitation of timber or biomass, stump management to prevent resprouting, and establishment or natural regeneration of alternative native species (single or multiple). Programmes of this type represent a good opportunity to restore native forest ecosystems in former plantations or invaded areas.
- Bring poorly managed plantations in areas of high productivity close to the potential
  Measures should be established to bring poorly managed plantations located in the area suitable for *Eucalyptus* to productivity close to the potential. This implies making available and using the best plant material when establishing new plantations and optimizing forest management at stand level. To achieve this goal, the recognition of owners or owners' associations as active forest managers may lead to the implementation of policy measures aimed at encouraging a professional approach to silviculture. This type of approach would obviously benefit owners already belonging to an association, owners of larger plots and forest companies. In Portugal, the pulp and paper companies have invested in the dissemination of good management practices using mainly the web (e.g. https://florestas.pt/, http://www.celpa.pt/melhoreucalipto, https://www.e-globulus.pt/).
- Management at the landscape level
  Management should be carried out at a landscape level. Decisions cannot be made in relation to individual stands, as each stand forms part of the landscape mosaic. Most impacts on the environment will be minimal if forest management decisions take the entire management unit into account. Correct management at landscape level, with the creation of a mosaic of different types of land use and a network of well-planned firebreaks, is also essential to minimize the risk of fire and attack by pests and diseases. Such land use patterns must be considered within the framework of land use planning in rural areas, particularly considering the high density of small villages in some regions and the forest-urban interfaces. A large majority of *Eucalyptus* plantations are privately owned and occur in areas with very small properties where good management at landscape level becomes a challenge and needs the support of policy measures to motivate private landowners towards this new way of managing their land.
- Promoting group certification
  Promotion of group certification initiatives is probably the most direct way of ensuring that the previous two issues can be addressed correctly. If the procedures are properly implemented, forest certification can improve the level of forest management. Ideally, all wood should be certified before entering industrial facilities, but the current level scarcely reaches 20%. Support to forest owners' associations via training and information is needed and although certification schemes are private initiatives, a proactive approach by the forest administration appears necessary.
- Increasing the knowledge on the functioning of *Eucalyptus* ecosystems
  A network of permanent plots and trials should be maintained to increase knowledge of the functioning

of *Eucalyptus* ecosystems, i.e. the impacts on water and soil. The findings will support future management decisions and help tackle the changes derived from the anthropogenic climate change.

- The need for a program focused on maintaining the health of *Eucalyptus* plantations

  It is important to be aware of the real risk that the increasing number of pests and diseases affecting the species are causing and to establish measures to deal with this problem. To ensure that the area of land devoted to *Eucalyptus* culture is managed efficiently to provide high productivity, it seems essential that state and/or regional administrations take an active role in this process.

Conclusions

This review paper characterizes *Eucalyptus* plantations in Europe. A review of country data on the area of *Eucalyptus* showed that *E. globulus* is by far the most common species planted and that most of the area occupied by the species is located on the Iberian Peninsula. However, the existing climate scenarios led to the anticipation of the possibility of enlarging the area of *Eucalyptus* to other regions of Europe. The conclusions and recommendations of this paper may therefore be relevant to support possible scientific based decisions of using *Eucalyptus* as one of the plantation species in Europe.

E. globulus is a highly productive species and is important for small private landowners and for maintaining existing pulp and paper industries. However, as an exotic tree species cultivated in intensive silviculture, it may cause some environmental problems if not well managed, especially if not managed at landscape level. The main message is that the best way to maintain the benefits of plantations for the economy of the countries where it is grown and for the income of private landowners while maintaining its eventually harmful environmental impacts at a minimum is to carefully manage *E. globulus* plantations both at stand and landscape level. This includes the selection of areas of high productivity, the landscape design as a mosaic of different uses, the promotion of the best stand management according to each site and the maintenance of healthy plantations.

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Compliance with ethical standards

Conflict of interest All the authors declare that they have no conflict of interest.

References

Abelho M, Graça MAS (1996) Effects of eucalyptus afforestation on leaf litter dynamics and macroinvertebrate community structure of streams in Central Portugal. Hydrobiologia 324:195–204. https://doi.org/10.1007/bf00016391

AFN (2010) Relatório Final do 5° Inventário Florestal Nacional Autoridade Florestal . Nacional, Lisbon, Portugal

Águas A, Ferreira A, Maia P, Fernandes PM, Roxo L, Keizer J, Silva JS, Rego FC, Moreira F (2014) Natural establishment of *Eucalyptus globulus* Labill. in burnt stands in Portugal. For Ecol Manage 323:47–56. https://doi.org/10.1016/j.foreco.2014.03.012

Águas A, Larcombe MJ, Matias H, Deus E, Potts BM, Rego FC, Silva JS (2017) Understanding the naturalization of *Eucalyptus globulus* in Portugal: a comparison with Australian plantations. Eur J Forest Res 3(136):433–446. https://doi.org/10.1007/s10342-017-1043-6

Almeida AP, Riekerk H (1990) Water balance of *Eucalyptus globulus* and *Quercus suber* forest stands in south Portugal. For Ecol Manage 38(1–2):55–64. https://doi.org/10.1016/0378-1127(90)90085-P

Almeida MH, Pereira H, Miranda I, Tomé M (1995) Provenance trials of *Eucalyptus globulus* Labill. in Portugal. In: Potts BM, Borralho NM, Reid JB, Cromer RN, Tibbits WN, Raymond CA (eds) Proceedings of the CRCTHF-IUFRO Conference eucalypt plantations: improving fibre yield and quality pp 195–198

Almeida MH, Araújo C, Araújo JA, Costa e Silva F, Neves I, Paiva V, Santiago A, Ribeiro D, (2005) Melhoramento genético do eucalipto: que impacto na realidade? In: Silva R, Páscoa F (eds) A Floresta e as gentes, 5° Congresso Florestal Nacional. Sociedade Portuguesa de Ciências Florestais, Viseu, Portugal, pp 145–146

Araújo J, Meierrose C, Carvalho AS (1985) Distribuição de *Phoracantha semipunctata* Fab. (Coleoptera, Cerambycidae) no sul de Portugal - observações preliminares. Atas do II Congresso Ibérico de Entomologia. Bol Soc Port Entomol 4:317–322

Araújo MB (1995) The effect of *Eucalyptus globulus* Labill. plantations on biodiversity: a case study in Serra Portel (South Portugal). Dissertation, University College London

Aravanopoulos FA (2010) Breeding of fast growing forest tree species for biomass production in Greece. Biomass Bioenerg 24:1531–1537. https://doi.org/10.1016/j.biombioe.2010.06.012

Arellano S, Vega JA, Ruiz AD, Arellano A, Álvarez JG, Vega DJ, Pérez E (2016) Foto-guía de combustibles forestales de Galicia y comportamiento del fuego asociado. Andavira Editora, Santiago de Compostela

Azevedo F, Figo ML (1979) *Ctenarytaina eucalypti* Mask (Homoptera, Psyllidae). Bol Serv Plagas Forestales 5:41–46

Bärlocher F, Graca MA (2002) Exotic riparian vegetation lowers fungal diversity but not leaf decomposition in Portuguese streams. Freshwat Biol 47:1123–1135. https://doi.org/10.1046/j.1365-2427.2002.00836.x

Barradas C, Pinto G, Correia B, Castro B, Phillips AJ, Alves A (2018) Drought × disease interaction in *Eucalyptus globulus* under *Neofusicoccum eucalyptorum* infection. Plant Pathol 67:87–96. https://doi.org/10.1111/ppa.12703

Barradas C, Pinto G, Correia B, Jesus C, Alves A (2019) Impact of *Botryosphaeria*, *diplodia* and *Neofusicoccumspecies* on two eucalyptus species and a hybrid: from pathogenicity to physiological performance. For Path e12493. https://doi.org/https://doi.org/10.1111/efp.12493

Barreiro S, Tomé M (2011) SIMPLOT: simulating the impacts of fire severity on sustainability of Eucalyptus forests in Portugal. Ecol Indic 11:36–45. https://doi.org/10.1016/j.ecolind.2009.06.015

Barreiro S, Rua J, Tomé M (2016) StandsSIM-MD: a Management Driven forest SIMulator. Forest Systems 25(2), eRC07. https://doi.org/https://doi.org/10.5424/fs/2016252-08916

Becerra PI et al (2018) Inhibitory effects of *Eucalyptus globulus* on understorey plant growth and species richness are greater in non-native regions. Global Ecol Biogeogr 27:68–76. https://doi.org/10.1111/geb.12676

Blanco-Dios JB (2012) Especies comestibles que se poden encontrar en platacións de eucalipto. Tarrelos 14:31–33

Bongiorno SF (1982) Land use and summer bird populations in northwestern Galicia Spain. Ibis 124:1–20. https://doi.org/10.1111/j.1474-919X.1982.tb03736.x

Booth TH (2013) Eucalypt plantations and climate change. For Ecol Manage 301:28–34. https://doi.org/10.1016/j.foreco.2012.04.004

Borralho NMG, Cotterill PP (1994) Genetic improvement of *Eucalyptus globulus* for pulp production. In: Pereira JS, Pereira H (eds) Eucalyptus for biomass production. Commission of the European Communities, pp 85–99

Borralho NMG, Almeida MH, Potts BM (2007) O melhoramento do eucalipto em Portugal. In: Alves AM, Pereira JS, Silva JMN (eds) O eucalipto em Portugal - impactes ambientais e investigação científica. ISA Press, Lisboa, pp 61–112

Branco M, Bragança H, Sousa E, Phillips AJ (2014) Pests and diseases in Portuguese forestry: current and new threats. In: Forest Context and Policies in Portugal, Springer International Publishing, pp 117–154

Branco M, Brockerhoff EG, Castagneyrol B, Orazio C, Jactel H (2015) Host range expansion of native insects to exotic trees increases with area of introduction and the presence of congeneric native trees. J Applied Ecol 52:69–77. https://doi.org/10.1111/1365-2664.12362

Brockerhoff EG, Jactel H, Parrotta JA, Ferraz SFB (2013) Role of eucalypt and other planted forests in biodiversity conservation and the provision of biodiversity-related ecosystem services. For Ecol Manage 301:43–50

Brus R, Pötzelsberger E, Lapin K, Brundu G, Orazio C, Straigyte L, Hasenauer H (2019) Extent, distribution and origin of non-native forest tree species in Europe. Scand J For Res. https://doi.org/10.1080/02827581.2019.1676464

Cabral MT (1983) Contribuição para o estudo da biodegradação das toiças de *Eucalyptus globulus* Labill. Dissertation, Universidade Técnica Lisboa, Portugal

Cabral MT, Martins SC (1985) Estudo comparativo da fauna do solo de povoamentos de *Eucalyptus globulus* Labill. de várias idades e de *Pinus pinaster* Ait. Bol Soc Port Entomologia 3:75–84

Calviño-Cancela M (2013) Effectiveness of eucalypt plantations as a surrogate habitat for birds. For Ecol Manage 310:692–699. https://doi.org/10.1016/j.foreco.2013.09.014

Calviño-Cancela M, Rubido-Bará M, Van Etten EJB (2012) Do eucalypt plantations provide habitat for native forest biodiversity? For Ecol Manage 270:153–162. https://doi.org/10.1016/j.foreco.2012.01.019

Calviño-Cancela M, Rubido-Bará M (2013) Invasive potential of *Eucalyptus globulus*: seed dispersal, seedling recruitment and survival in habitats surrounding plantations. For Ecol Manage 305:129–137

Calviño-Cancela M, de Silanes MEL, Rubido-Bará M, Uribarri J (2013) The potential role of tree plantations in providing habitat for lichen epiphytes For Ecol. Manage 291:386–395

Calviño-Cancela M, Lorenzo P, González L (2018) Fire increases *Eucalyptus globulus* seedling recruitment in forested habitats: effects of litter, shade and burnt soil on seedling emergence and survival. For Ecol Manage 409:826–834

Calviño-Cancela M, Neumann M, López De Silanés ME (2020) Contrasting patterns of lichen abundance and diversity in *Eucalyptus globulus* and *Pinus pinaster* plantations with tree age. For Ecol Manage 462:117994. https://doi.org/10.1016/j.foreco.2020.117994

Canhoto C, Graça MA (1996) Decomposition of *Eucalyptus globulus* leaves and three native leaf species (*Alnus glutinosa*, *Castanea sativa* and *Quercus faginea*) in a Portuguese low order stream. Hydrobiologia 333:79–85

Carneiro M, Fabião A, Martins MC, Cerveira C, Santos C, Nogueira C, Lousa M, Hilário L, Fabião A, Abrantes M, Madeira M (2007) Species richness and biomass of understory vegetation in a *Eucalyptus globulus* Labill. coppice as affected by slash management. Eur J For Res 126:475–480

Carneiro A, Fabião A, Martins MC, Fabião A, da Silva MA, Hilário L, Lousa M, Madeira M (2008) Effects of harrowing and fertilisation on understory vegetation and timber production of a *Eucalyptus globulus* Labill. plantation in Central Portugal. For Ecol Manage 255:591–597

Carneiro M, Serrão V, Fabião A, Madeira M, Balsemão I, Hilário L (2009) Does harvest residue management influence biomass and nutrient accumulation in understory vegetation of *Eucalyptus globulus* Labill. plantations in a Mediterranean environment? For Ecol Manage 257:527–535

Castro-Díez P, Fierro-Brunnenmeister N, González-Muñoz N, Gallardo A (2012) Effects of exotic and native tree leaf litter on soil properties of two contrasting sites in the Iberian Peninsula. Plant Soil 350:179–191

Catry FX, Moreira F, Tujeira R, Silva JS (2013) Post-fire survival and regeneration of *Eucalyptus globulus* in forest plantations in Portugal. For Ecol Manage 310:194–203

Catry FX, Moreira F, Deus E, Silva JS, Águas A (2015) Assessing the extent and the environmental drivers of *Eucalyptus globulus* wildling establishment in Portugal: results from a countrywide survey. Biol Invasions 17:3163–3181

CELPA (2019) Boletim Estatístico da Indústria Papeleira Portuguesa. Celpa, Lisboa Portugal, p 112

Cerveira C, Lousã M, Fabião A, Madeira M, Tomé M (1999) Influência de técnicas de instalação e condução do eucaliptal na diversidade da vegetação sob coberto. Rev Cienc Agrar 22:49–63

Chambers PGS, Borralho NMG (1997) Importance of survival in short-rotation tree breeding programs. Can J For Res 27:911–917

Chauvet E, Fabre E, Elósegui A, Pozo J (1997) The impact of eucalypt on the leaf-associated aquatic hyphomycetes in Spanish streams. Canadian J Botany 75:880–887. https://doi.org/10.1139/b97-097

Chauzat MP, Purvis G, Dunne R (2002) Release and establishment of a biological control agent, *Psyllaephagus pilosus* for eucalyptus psyllid (*Ctenarytaina eucalypti*) in Ireland. Ann Appl Biol 141:293–304

Chaves MM, Pereira JS, Osorio J (2004) Water use efficiency and photosynthesis. In: Bacon M (ed) Water use efficiency in plant biology. Blackwell Publishing, London, pp 42–74

Cordero-Rivera A, Martínez-Álvarez A, Álvarez M (2017) Eucalypt plantations reduce the diversity of macroinvertebrates in small forested streams. Anim Biodiv Conserv 40:87–97

Correia AC, Pereira JS, Mateus J, Pita G, Rodrigues A, Miranda P, Correia AV (2007) Influência das alterações climáticas na cultura do eucalipto: cenários possíveis. In: Alves AM, Pereira JS, Silva JMN (eds) O eucalipto em Portugal - impactes ambientais e investigação científica. ISA Press, Lisboa, pp 357–379

Correia AH, Almeida MH, Branco M et al (2018a) Early survival and growth plasticity of 33 species planted in 38 arboreta across the European Atlantic Area. Forests 9(10):630. https://doi.org/10.3390/f9100630

Correia B, Valledor L, Hancock R, Renault J, Pascual J, Soares AMVM, Pinto G (2016) Integrated proteomics and metabolomics to unlock global and clonal responses of *Eucalyptus globulus* recovery from water deficit. Metabolomics 12(8):1–12

Correia B, Hancock RD, Amaral J, Gomez-Cadenas A, Valledor L, Pinto G (2018) Combined drought and heat activates protective responses in *Eucalyptus globulus* that are not activated when subjected to drought or heat stress alone. Front Plant Sci 9.

Costa R, Fraga H, Fernandes PM, Santos JA (2017) Implications of future bioclimatic shifts on Portuguese forests. Reg Environ Change 7(1):117–127

David JS, Henriques MO, David T, Tomé J, Ledger DC (1994) Clearcutting effects on streamflow in coppiced *Eucalyptus globulus* stands in Portugal. J Hydrol 162:143–154

David JS, David TS, Valente F (2007) O eucaliptal e os recursos hídricos. In: Alves AM, Pereira JS, Silva JMN (eds) O Eucalipto em Portugal - Impactes Ambientais e Investigação Científica. ISA Press, Lisboa, pp 113–135

David TS, Ferreira MI, David JS, Pereira JS (1997) Transpiration from a mature *Eucalyptus globulus* plantation in Portugal during a spring-summer period of progressively higher water deficit. Oecologia 110:153–159

del Moral R, Muller CH (1969) Fog drip: a mechanism of toxin transport from *Eucalyptus globulus*. B Torrey Bot Club 467–475

Deus E, Silva JS, Catry FX, Rocha M, Moreira F (2016) Google Street View as an alternative method to car surveys in large-scale vegetation assessments. Environ Monit Assess 188:1–14

Deus E, Silva JS, Castro-Díez P, Lomba A, Ortiz ML, Vicente J (2018) Current and future conflicts between eucalypt plantations and high biodiversity areas in the Iberian Peninsula. J Nature Conserv 45:107–117

Deus E, Silva JS, Marchante H, Marchante E, Félix C (2018) Are post-dispersed seeds of *Eucalyptus globulus* predated in the introduced range? Evidence from an experiment in Portugal. Web Ecol 18(1):67–79

Deus E, Silva JS, Larcombe MJ, Catry F, Queirós L, Santos P, Matias H, Águas A, Rego F (2019) Investigating the invasiveness of *Eucalyptus globulus* in Portugal: site-scale drivers, reproductive capacity and dispersal potential. Biol Invasions 21:2027–2044

Díaz-Balteiro L, Bertomeu M, Bertomeu M (2009) Optimal harvest scheduling in Eucalyptus plantations A case study in Galicia (Spain). Forest Policy Econ 11:548–554

Díaz-Balteiro L, Bertomeu M, Ezquerro M, Giménez J, González-Pachón J, Romero C (2016) Using quantitative techniques to evaluate and explain the sustainability of forest plantations. Can J For Res 46(9):1157–1166

Díaz O (2016) Modelling the potential distribution and naturalization of *Eucalyptus globulus* in the Iberian Peninsula. Dissertation, Alcalá University, Spain

Dillner B, Ljunger A, Herub OA, Thune-Larsen E (1971) The breeding of *Eucalyptus globulus* on the basis of wood density, chemical composition and growth rate. In Symposium on the Production and Industrial Utilization of Eucalyptus, pp 120–153. Genéve: United Nations

Domingues RMA, Sousa GDA, Silva CMM, Freire CSR, Silvestre AJD, Neto CP (2011) High value triterpenic compounds from the outer barks of several Eucalyptus species cultivated in Brazil and in Portugal. Ind. Crops Prod. 33:158–164. https ://doi.org/https://doi.org/10.1016/j.indcr op.2010.10.006

Eldridge K, Davidson J, Harwood C, Van Wyk G (1993) Eucalypt domestication and breeding. Claredon Press, Oxford

Fabião A, Carneiro M, Lousã M, Madeira M (2007) Os impactes do eucaliptal na biodiversidade da vegetação sob coberto. In: Alves AM, Pereira JS, Silva JMN (eds) O Eucalipto em Portugal - Impactes Ambientais e Investigação Científica. ISA Press, Lisboa, pp 178–206

Fabião A, Martins MC, Cerveira C, Santos C, Lousã M, Madeira M, Correia A (2002) Influence of soil and organic residue management on biomass and biodiversity of understory vegetation in a *Eucalyptus globulus* Labill. plantation. For Ecol Manage 171:87–100. https://doi.org/10.1016/s0378-1127(02)00463-2

Faias SP, Palma JHN, Barreiro S, Paulo JAP, Tomé M (2012) sIMfLOR - platform for Portuguese forest simulators. For Syst 21:543–548

Fernandes P (2013) Fire-smart management of forest landscapes in the Mediterranean basin under global change. Landscape and Urban Planning 110:175–182

Fernandes P, Davies GM, Ascoli D, Fernández C, Moreira F, Rigolot E, Molina D (2013) Prescribed burning in southern Europe: developing fire management in a dynamic landscape. Frontiers Ecol Environ 11(s1):e4–e14

Fernandes P, Antunes C, Pinho P, Máguas C, Correia O (2016) Natural regeneration of *Pinus pinaster* and *Eucalyptus globulus* from plantation into adjacent natural habitats. For Ecol Manage 378:91–102

Fernandes P, Máguas C, Correia O (2017) Combined effects of climate, habitat, and disturbance on seedling establishment of *Pinus pinaster* and *Eucalyptus globulus*. Plant Ecol 218(5):501–515

Fernandes P, Máguas C, Correia O, González-Moreno P (2018) What drives *Eucalyptus globulus* natural establishment outside plantations? The relative importance of climate, plantation and site characteristics. Biol Invasions 20:1129–1146

Fernandes P, Guiomar N, Rossa CG (2019) Analysing eucalypt expansion in Portugal as a fire-regime modifier. Sci Total Environ 666:79–88

Fernández C, Vega JA, Gras JM, Fonturbel T (2006) Changes in water yield after a sequence of perturbations and forest management practices in an *Eucalyptus globulus* Labill. watershed in Northern Spain. For Ecol Manage 234:275–281

Ferreira AJD, Coelho COA, Walsh RPD, Shakesby RA, Ceballos A, Doerr SH (2000) Hydrological implications of soil water-repellency in *Eucalyptus globulus* forests, north-central Portugal. J Hydrology 231–232:165–177

Ferreira MC (1998) Manual dos insectos nocivos às plantações florestais. Plátano Editora, Lisboa

Ferreira V, Koricheva J, Pozo J, Graça MA (2016) A meta-analysis on the effects of changes in the composition of native forests on litter decomposition in streams. For Ecol Manage 364:27–38

Florence RG (1986) Cultural problems of eucalyptus as exotics. Commonw Forest Rev 65:141–163

FS-DAFM, (2018) Ireland's National Forest Inventory 2017- Results. Forest Service, Department of Agriculture Food and the Marine, Wexford, Ireland

Ganteaume A, Lampin-Maille C, Guijarro M, Hernando C, Jappiot M, Fonturbel T, Pérez-Gorostiaga P, Veja JA (2010) Spot fires: fuel bed flammability and capability of firebrands to ignite fuel beds. Int J Wildland Fire 18:951–969

García-Villabrille JD (2015) Modelización del crecimiento y la producción de plantaciones de *Eucalyptus globulus* Labill. en el noroeste de España. Dissertation, University of Santiago de Compostela

Goded S, Ekroos J, Domínguez J, Azcárate JG, Guitián JA, Smith HG (2019) Effects of eucalyptus plantations on avian and herb species richness and composition in North-West Spain. Global Ecol Conserv 19:e00690. https://doi.org/10.1016/j.gecco.2019.e00690

Goes E (1977) Os eucaliptos (ecologia, cultura, produções e rentabilidade). Portucel, Lisboa

Gómez-García E, Diéguez-Aranda U, Cunha M, Rodríguez-Soalleiro R (2016) Comparison of harvest-related removal of aboveground biomass, carbon and nutrients in pedunculate oak stands and in fast-growing tree stands in NW Spain. For Ecol Manage 365(1):119–127

Gonçalves CI, Vilas-Boas L, Branco M, Rezende GD, Valente C (2019) Host susceptibility to *Gonipterus platensis* (Coleoptera: Curculionidae) of *Eucalyptus* species. Annals For Sci 76(3):63

Gouveia C, Camara C, Trigo R (2010) Post-fire vegetation recovery in Portugal based on spot/vegetation data. Nat Hazard Earth Syst 10:673–684

Gras JM, Vega JA, Bará S (1993) Six years of study on fast growing forest plantations catchments in the Northwest of Spain. Acta Geolog Hispan 28(2–3):111–117

Harvengt L, Alazard P, Fraysse J-Y, de Boissesson J-M, Fauconnier T, Canlet F, Reymond I, Durandeau K, Debille S, Melun F, Tronti J-F, Bailly A, Vidal M (2017) Breeding of deep frost-tolerant eucalyptus for sustainable biomass production under climate change. Poster at the IUFRO 125th Anniversary Congress, Freiburg, Germany, Session no 153 - Genetics and Genomics for Conservation, Climate Adaptation and Sustainable Management of forests, Abstract book pg 382

Hurley BP, Garnas J, Wingfield MJ, Branco M, Richardson DM, Slippers B (2016) Increasing numbers and intercontinental spread of invasive insects on eucalypts. Biol Invasions 18:921–933

ICNF (2015) Áreas ardidas anuais por tipo de ocupação do solo. Instituto da Conservação da Natureza e das Florestas, Lisboa, Portugal

ICNF (2019) 6° Inventário Florestal Nacional - Relatório Final. Instituto da Conservação da Natureza e das Florestas Lisboa, Portugal

IPCC (2014) Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the 5th Assessment Report of the Intergovernmental Panel on Climate Change, Core Writing Team, RK Pachauri, LA Meyer (eds). Geneva, Switzerland

Jacobs MR (1955) Growth habits of the eucalypts. Forestry and Timber Bureau, Canberra, Australia

Jiménez E, Vega J, Fernández C, Pérez-Gorostiaga P, Cuiñas P, Fonturbel T, Alonso M, Rozados M, Bará S (2012) Changes in *Eucalyptus globulus* Labill. saplings growth and physiological parameters following fire-induced stem and crown damage in a plantation in north-western Spain. Eur J Forest Res 131:1967–1978. https://doi.org/10.1007/s10342-012-0647-0

Jones HE, Madeira M, Herraez L, Dighton J, Fabião A, Gonzalez-Rio F, Marcos MF, Gomez C, Tomé M, Feith H, Magalhães MC, Howson G (1999) The effect of organic-matter management on the productivity of *Eucalyptus globulus* stands in Spain and Portugal: tree growth and harvest residue decomposition in relation to site and treatment. For Ecol Manage 122:73–86. https://doi.org/10.1016/s0378-1127(99)00033-x

Larcombe MJ, Silva JS, Vaillancourt RE, Potts BM (2013) Assessing the invasive potential of *Eucalyptus globulus* in Australia: quantification of wildling establishment from plantations. Biol Invasions 15:2763–2781

Leslie A, Mencuccini M, Perks MP (2013) Growth and Survival of provenances of snow gums (*Eucalyptus pauciflora*) and other hardy eucalypts at three trials in England. Scottish Forestry 67(2):30–39

Lomba A, Vicente J, Moreira F, Honrado J (2011) Effects of multiple factors on plant diversity of forest fragments in intensive farmland of Northern Portugal. For Ecolog Manage 262:2219–2228. https://doi.org/10.1016/j.foreco.2011.08.014

Lombardero M, Fernández A (1997) Nuevos insectos perforadores asociados al eucalipto en Galicia (Coleoptera: Scolytidae y Platypodidae). Boletín Sanidad Vegetal nº 23

López SB, Rivera JG, Bernal MS (2018) Biodiversidad en plantaciones de eucalipto y en bosques de carballo del sur de Galicia: plantas y aves. Nova Acta Científica Compostelana 25

Loustau D, Berbigier P, Roumagnac P, Arruda-Pacheco C, David JS, Ferreira MI, Pereira JS, Tavares R (1996) Transpiration of a 64-year-old maritime pine stand in Portugal. 1 - Seasonal course of water flux through maritime pine. Oecologia 107:33–42

Madeira MVA, Melo MG, Alexandre CA, Steen E (1989) Effects of deep plowing and superficial disk harrowing on physical and chemical soil properties and biomass in a new plantation of *Eucalyptus globulus*. Soil Till Res 14:163–175

Madeira M, Pereira JS (1990) Productivity, nutrient immobilization and soil chemical-properties in an *Eucalyptus globulus* plantation under different irrigation and fertilization regimes. Water Air Soil Poll 54:621–634

Madeira M, Ribeiro C (1995) Influence of leaf-litter type on the chemical evolution of a soil parent material (sandstone). Biogeochemistry 29:43–58

Madeira MV, Fabião A, Pereira JS, Araújo MC, Ribeiro C (2002) Changes in carbon stocks in *Eucalyptus globulus* Labill. plantations induced by different water and nutrient availability. For Ecol Manage 171:75–85

Madeira M, Cortez N, Azevedo A, Magalhães MC, Ribeiro C, Fabião A (2007) As plantações de eucalipto e o solo. In: Alves AM, Pereira JS, Silva JMN (eds) O eucalipto em Portugal - impactes ambientais e investigação científica. ISA Press, Lisboa, pp 138–174

MAPA (2019) Anuário de Estadística Forestal 2016. Ministerio de Agricultura, Pesca y Alimentación, Madrid, Spain

MAPAMA (2019) Estadística General de Incendios Forestales. Gobierno de España, Ministerio de Agricultura, Pesca, Alimentación y Medio Ambiente, Dirección General de Desarrollo Rural y Política Forestal, Área de Defensa contra Incendios Forestales. https://www.mapa.gob.es/es/desarrollo-rural/estadisticas/Incendios_default.aspx. Accessed December 2019

Melun F (2018) L'eucalyptus en France; production des plantations sur 3 rotations. FCBA INFO 10:1–4

Mercier L, Poisson R (1926) Un hémiptère homoptère de la famille des psyllines, parasite d'eucalyptus cultivés à Cherbourg. Bulletin Société Linnéan Normandie Series 7(9):34–37

Merino A, Rodríguez López A, Brañas S, Rodríguez-Soalleiro R (2003) Nutrition and growth in newly established plantations of *Eucalyptus globulus* in northwestern Spain. Annals For Sci 60(6):509–517

Merino A, Balboa MA, Rodríguez-Soalleiro R, Álvarez-González JG (2005) Nutrient exports under different harvesting regimes in fast-growing forest plantations in southern Europe. For Ecol Manage 207(3):325–339

Mirra IM, Oliveira TM, Barros AMG, Fernandes PM (2017) Fuel dynamics following fire hazard reduction treatments in blue gum (*Eucalyptus globulus*) plantations in Portugal. For Ecol Manage 398:185–195

Molina A, Reigosa MJ, Carballeira A (1991) Release of allelochemical agents from litter, throughfall, and topsoil in plantations of *Eucalyptus globulus* Labill. in Spain. J Chem Ecol 17:147–160

Molinero J, Pozo J (2004) Impact of a eucalyptus (*Eucalyptus globulus* Labill.) plantation on the nutrient content and dynamics of coarse particulate organic matter (CPOM) in a small stream. Hydrobiologia 528:143–165

Moreira F, Vaz P, Catry F, Silva JS (2009) Regional variations in wildfire susceptibility for land cover types in Portugal: implications for landscape management to minimize fire hazard. Int J Wildland Fire 18:563–574

Neilan J, Thompson D (2008) Eucalyptus as a potential biomass species for Ireland. Reproductive Material No. 15. COFORD, Dublin, Ireland

Neiva DM, Luís A,·Gominho J, Domingues F, Duarte AP, Pereira H, (2020) Bark residues valorization potential regarding antioxidant and antimicrobial extracts. Wood Sci Technol 54:559–585. https://doi.org/10.1007/s00226-020-01168-

Nereu M, Silva JS, Deus E, Nunes M, Potts B (2019) The effect of management operations on the demography of *Eucalyptus globulus* seedlings. For Ecol Manage 453:117630. https://doi.org/10.1016/j.foreco.2019.117630

Nutto L, Touza M (2006) Modelos de producción de madera sólida en plantaciones de *Eucalyptus globulus* de Galicia. Boletín del CIDEU 2:37–50

Pérez-Cruzado C, Merino A, Rodríguez-Soalleiro R (2011) A management tool for estimating bioenergy production and carbon sequestration in *Eucalyptus globulus* and *Eucalyptus nitens* grown as short rotation woody crops in north-west Spain. Biomass Bioenerg 35:2839–2851

Pérez-Cruzado C, Mansilla-Salinero P, Rodríguez-Soalleiro R, Merino A (2012) Influence of tree species on carbon sequestration in afforested pastures in a humid temperate region. Plant Soil 353:333–353

Pérez-Cruzado C, Mohren GMJ, Merino A, Rodríguez-Soalleiro R (2012) Carbon balance for different management practices for fast growing tree species planted on formed pastureland in southern Europe: a case study using the CO2Fix model. Eur J For Res 131:1695–1716

Pérez S, Renedo C, Ortiz A, Ortiz F, Tejedor C (2016) Strategies to combat *Mycosphaerella* leaf disease in *Eucalyptus globulus* plantations in northern Spain. Forests 7(9):190

Potts BM, Potts WC (1986) Eucalypt breeding in France. Australian Forestry 49:210–218

Potts BM, Vaillancourt RE, Jordan GJ, Dutkowski GW, Costa e Silva J, McKinnon GE, Steane DA, Volker PW, Lopez GA, Apiolaza LA, Li Y, Marques C, Borralho NMG, (2004) Exploration of the *Eucalyptus globulus* gene pool. In: Borralho NMG, Pereira JS, Marques C, Coutinho J, Madeira M, Tomé M (eds) Eucalyptus in a changing world. RAIZ, Aveiro, Portugal, pp 46–61

Potts BM, Hamilton M, Blackburn D (2011) Genetics of eucalypts: traps and opportunities. In: Walker J (ed) Developing a eucalypt resource: learning from Australia and elsewhere. University of Canterbury, New Zealand, Wood Technology Research Centre, pp 1–29

Pozo J, Basaguren A, Elósegui A, Molinero J, Fabre E, Chauvet E (1998) Afforestation with *Eucalyptus globulus* and leaf litter decomposition in streams of Northern Spain. Hydrobiologia 373:101–109

Proença VM, Pereira HM, Guilherme J, Vicente L (2010) Plant and bird diversity in natural forests and in native and exotic plantations in NW Portugal. Acta Oecologica 36:219–226. https://doi.org/10.1016/j.actao.2010.01.002

Purse J, Leslie A (2016) Eucalyptus part 1: species with potential in the British Isles. Quarterly J Forestry 110(2):88–97

Purse J, Leslie A (2016) Eucalyptus part 2: findings from trial plantings, and silvicultural requirements in the British Isles. Quarterly J Forestry 110(3):161–168

Queirós L, Deus E, Silva J, Vicente J, Ortiz L, Fernandes P, Castro P (2020) Assessing the drivers and the recruitment potential of *Eucalyptus globulus* in the Iberian Peninsula. For Ecol Manage 466:118147. https://doi.org/10.1016/j.foreco.2020.118147

Reis AR, Ferreira L, Tomé M, Araújo C, Branco M (2012) Efficiency of biological control of *Gonipterus platensis* (Coleoptera: *Curculionidae*) by *Anaphes nitens* (Hymenoptera: *Mymaridae*) in cold areas of the Iberian Peninsula: implications for defoliation and wood production in *Eucalyptus globulus*. For Ecol Manage 270:216–222

Rejmánek M, Richardson DM (2011) The eucalypts. In: Simberloff D, Rejmánek M (eds) Encyclopedia of biological invasions. University of California Press, Berkeley and Los Angeles, pp 203–209

Ribeiro C, Madeira M, Araújo M (2002) Decomposition and nutrient release from leaf litter of *Eucalyptus globulus* grown under different water and nutrient regimes. For Ecol Manage 171:31–41

Rodríguez-Soalleiro R, Eimil-Fraga C, Gómez-García E, García-Villabrille JD, Rojo-Alboreca A, Muñoz F, Oliveira N, Sixto H (2018) Exploring the factors affecting carbon and nutrient concentrations in tree biomass components in natural forests, forest plantations and short rotation forestry. Forest Ecosystems 5:35

Rodríguez-Suárez JA, Diaz-Fierros F, Perez R, Soto B (2014) Assessing the influence of afforestation with *Eucalyptus globulus* on hydrological response from a small catchment in Northwestern Spain using the HBV hydrological model. Hydrol Process 28:5561–5572

Rodríguez-Vicente V, Marey M (2009) Land-use and land-base patterns in non-industrial private forests: Factors affecting forest management in Northern Spain. Forest Policy Econ 11:475–490

Ruíz F, López G, Toval G, Alejano R (2008) Selvicultura de *Eucalyptus globulus* Labill. In: Serrada R, Montero G, Reque JÁ (eds) Compendio de selvicultura aplicada en España. INIA, Madrid, Spain, pp 117–154

Santos P, Matias H, Deus E, Águas A, Silva JS (2015) Fire effects on capsules and encapsulated seeds from *Eucalyptus globulus* in Portugal. Plant Ecol 216:1611–1621

Sasse J, Sands R (1997) Configuration and development of root systems of cuttings and seedlings of *Eucalyptus globulus*. New For 14:85–105

Sepliarsky F (2006) Nuevos usos industriales de la madera de *Eucalyptus globulus*. Boletín Informativo CIDEU 2:93–102

Serralheiro F, Madeira M (1990) Changes in arthropod soil fauna due to afforestation with *Eucalyptus globulus*. Agrochemistry Soil Sc 39:602–606

Silva JS, Moreira F, Vaz P, Catry F, Godinho-Ferreira P (2009) Assessing the relative fire proneness of different forest types in Portugal. Plant Biosystems 143:597–608

Silva JS, Tomé M (2016) Tasmanian blue gum in Portugal - opportunities and risks of a widely cultivated species. In: Krumm F, Vítková L (eds) Introduced tree species in European forests: opportunities and challenges. European Forest Institute, Freiburg, pp 352–361

Silva JS, Vaz P, Moreira F, Catry F, Rego FC (2011) Wildfires as a major driver of landscape dynamics in three fire-prone areas of Portugal. Landscape and Urban Planning 101:349–358

Silva-Pando FJ, Pino-Pérez R (2016) Introduction of *Eucalyptus* into Europe. Australian Forestry 79:283–291

Siscaro G (1992) *Avetianella longoi* sp. n. (Hymenoptera Encyrtidae) egg parasitoid of *Phoracantha semipunctata* F. (Coleoptera Cerambycidae). Boll Zool Agr Bachic 24:205–212

Sivacioğlu A, Şen G (2017) Turkey. In non-native tree species for European forests: experiences, risks and opportunities. In: Hasenauer H, Gazda A, Konnert M, Lapin K, Mohren GMJ, Spiecker H, van Loo M, Pötzelsberger E (eds) COST Action FP1403 NNEXT, Country Reports, 3rd edn. University of Natural Resources and Life Sciences, Vienna, Austria, pp 394–413

Skolmen RG, Ledig FT (1990) Bluegum eucalyptus. In: Burns RM, Honkala BH (eds) Silvics of North America: 1.conifers; 2.hardwoods. Agriculture Handbook 654, US Department Agriculture, Forest Service, Washington, vol 2

Soares P, Aires N, Tomé M, Araújo C, Pina JP (2004) Analysis of the two first cutting cycles of an *Eucalyptus globulus* spacing trial. In: Borralho NMG, Pereira JS, Marques C, Coutinho J, Madeira

M, Tomé M (eds) Eucalyptus in a changing world. RAIZ, Aveiro, Portugal, pp 283–289

Soares P, Tomé M, Pereira JS (2007) A produtividade do eucaliptal. In: Alves AM, Pereira JS, Silva JMN (eds) O eucalipto em Portugal - impactes ambientais e investigação científica. ISA Press, Lisboa, pp 27–59

Soria F, Borralho NMG (1997) The genetics of resistance to *Phoracantha semipunctata* attack in *Eucalyptus globulus* in Spain. Silvae Genetica 46:365–369

Sousa J, da Gama M, Ferreira C, Barrocas H (2000) Effect of eucalyptus plantations on Collembola communities in Portugal: a review. Belg J Entomol 2(1):187–201

Souto XC, Bolaño JC, González L, Reigosa MJ (2001) Allelopathic effects of tree species on some soil microbial populations and herbaceous plants. Biol Plant 4:269–275. https://doi.org/10.1023/a:1010259627812

Stanturf JA, Vance ED, Fox TR, Kirst M (2013) Eucalyptus beyond its native range: environmental issues in exotic bioenergy plantations. Int J For Res Article ID 463030

Tomé M, Tomé JA, Araújo MC, Pereira JS (1994) Intraspecific competition in irrigated and fertilized eucalypt plantations. For Ecol Manage 69:211–218

Tomé M, Oliveira T, Soares P (2006) O modelo Globulus 3.0. GIMREF-RC2/2006 Depart Eng Flor, Instituto Superior Agronomia, Lisboa, Portugal

Toro MA, Silio L, Rodriguez MC, Soria F, Toval G (1998) Genetic analysis of survival to drought in *Eucalyptus globulus* in Spain. 6th World Congress of Genetics Applied to Livestock Production, 6WCGALP, vol 27. Armidale, Australia, pp 499–502

Valente C, Hodkinson I (2009) First record of the red gum lerp psyllid, *Glycaspis brimblecombei* Moore (Hem.: Psyllidae) in Europe. J Applied Entomology 133(4):315–317

Valente C, Afonso C, Gonçalves CI, Alonso-Zarazaga MA, Reis A, Branco M (2017) Environmental risk assessment of the egg parasitoid *Anaphes inexpectatus* for classical biological control of the Eucalyptus snout beetle Gonipterus platensis. Biocontrol 62(4):457–468

Valente C, Gonçalves CI, Reis A, Branco M (2017) Pre-selection and biological potential of the egg parasitoid *Anaphes inexpectatus* for the control of the Eucalyptus snout beetle, *Gonipterus platensis*. J Pest Sci 90(3):911–923

Valente C, Gonçalves CI, Monteiro F, Gaspar J, Silva M, Sottomayor M, Branco M (2018) Economic outcome of classical biological control: a case study on the eucalyptus snout beetle, *Gonipterus platensis*, and the parasitoid *Anaphes nitens*. Ecol Econ 149:40–47

Valente F, David JS, Gash JHC (1997) Modelling interception loss for two sparse eucalypt and pine forests in central Portugal using reformulated Rutter and Gash analytical models. J Hydrology 190(1–2):141–162

Varela ME, Benito E, de Blas E (2005) Impact of wildfires on surface water repellency in soils of northwest Spain. Hydrol Process 19:3649–3657

Vaz AS, Honrado JP, Lomba A (2019) Replacement of pine by eucalypt plantations: effects on the diversity and structure of tree assemblages under land abandonment and implications for landscape management. Landscape Urban Plann 185:61–67. https://doi.org/10.1016/j.landurbplan.2019.01.009

Vega G, Toval G, Basurco F, Rodriguez R (1994) Early growth of 260 families of *Eucalyptus globulus* in North Spain. In: Pereira JS, Pereira H (eds) Eucalyptus for biomass production. Commission of the European Communities, pp 115–132

Vega JA (1985) Empleo del fuego prescrito en eucaliptales de Galicia. In: Ministerio de Agricultura, Pesca y Alimentación (ed) Estudios sobre prevención y efectos ecológicos de los incendios forestales. ICONA, MAPA, pp 37–49

Viera M, Ruíz-Fernández F, Rodríguez-Soalleiro R (2016) Nutritional prescriptions for *Eucalyptus* plantations: lessons learned from Spain. Forests 7:84

Warren CR, Aranda I, Cano FJ (2011) Responses to water stress of gas exchange and metabolites in *Eucalyptus* and *Acacia* spp. Plant, Cell Environ 34:1609–1629

Zanuncio J, do Nascimento EC, Garcia JF, Zanuncio TV, (1994) Major lepidopterous defoliators of eucalypt in southeast Brazil. For Ecol Manage 65:53–63