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Review

The fire ecology and management of maritime pine (*Pinus pinaster* Ait.)

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Abstract

Maritime pine (*Pinus pinaster* Ait.) is an important conifer from the western Mediterranean Basin. Fire is the most significant threat to maritime pine plantations but also a disturbance that plays a vital role in the perpetuation of natural stands. The species has physical characteristics that allow survival after low-intensity fire, namely thick bark, and reproduction processes that facilitate recovery after stand replacement fire from seeds stored in serotinous cones. These traits are consistent with the opposing strategies of fire resistance and fire evasion and can be interpreted as evolutionary adaptations to fire, but their development and coexistence are highly variable between populations, thus invalidating the classification of maritime pine in a general fire regime category. When the two strategies are concurrent the species should be able to persist under a variable or mixed fire regime. The quality, quantity and structural arrangement of fuels in maritime pine stands explain why they are so flammable. Thorough descriptions of the litter and understorey fuel complex are available in the literature, which makes custom fire behaviour prediction possible with software tools based on Rothermel's fire spread model; empirical fire behaviour models developed from experimental fire data are also available and are preferred to plan prescribed burning operations. There is ample evidence, although largely anecdotal, that surface, ladder and canopy fuel treatments mitigate wildfire intensity and burn severity and avoid crown fire in maritime pine stands. The optimization of fuel hazard management is nevertheless curtailed by the current state of knowledge about crown fire behaviour and fuel dynamics in relation to stand development and silviculture. The conservation and sustainable management of maritime pine in fire-prone landscapes should integrate the active use of fire and understand that effective protection from high-severity wildfire is not possible without sacrificing some stand volume.

Keywords: Fire effects; Fire regime; Fuel hazard; Fire behavior prediction; Fuel management; Prescribed burning

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Contents

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1. Introduction

Maritime pine (*Pinus pinaster* Ait.) is a conifer from the western Mediterranean Basin with a distribution exceeding 4

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million ha under broad ranges of elevation, climate and soil, and presenting remarkable genetic variation as a result (Alía et al., 1996). As with other European pines, encroachment of former agricultural fields and plantation programs motivated mainly by soil protection and reforestation of degraded areas have expanded maritime pine during the 19th and 20th centuries (Le Maitre, 1998). Intensive forestry plantations of the species were established in the southern hemisphere, namely in southwestern Australia with both economical and environmental objectives (Ritson and Sochacki, 2003).

The role of fire as a disturbance that generally favors the *Pinus* genus is well recognized, and most of its species have the ability either to evade or resist fire, respectively, by storing seeds in serotinous cones and insulating tissues from lethal temperatures; a few species can endure fire by resprouting (Agee, 1998). Fire is a major factor in the dynamics of Mediterranean pine forests (Barbéro et al., 1998), which are relatively more abundant at intermediate levels of fire recurrence, i.e. a fire every 10–40 years (Pausas, 1999). In Corsica (Carcaillet et al., 1997) and eastern Spain (Carrión et al., 2000) the Quaternary expansion of maritime pine was concurrent with an increase in fire frequency. Maritime pine communities of natural origin in Spain occur in lightning-prone mountains, where a natural ignition density of 0.03 $\mathrm{km}^{-2}\ \mathrm{year}^{-1}$ (Martín and Gil, 2000) exceeds the country's average by a factor of 27 (Vázquez and Moreno, 1998).

Fire is often vital to maintain pine status in ecosystems, but it is also a major hazard in plantations and the most significant threat to *Pinus* forests in the Mediterranean Basin (Barbéro et al., 1998). The closed canopy and high tree stocking that characterize silvicultural regimes focused on the maximization of biomass productivity generate accumulations of intrinsically flammable pine fuel with the potential for extreme fire behavior (Alexander, 1998), in the Mediterranean and elsewhere (e.g. Pearce and Alexander, 1994).

The wildfire problem associated with maritime pine stands is especially acute in the western part of the Iberian Peninsula, at the intersection of Mediterranean and Atlantic climate influences, i.e. where summer drought and high plant productivity coexist. Here, fuels can build-up to levels which are probably unequalled by pine stands in temperate climates elsewhere (Vega, 2001). The afforestation of communal lands in the 20th century has replaced the traditional matrix of grazed shrubland and pasture with dense stands of maritime pine, often extending over thousands of hectares of rough terrain, thus allowing landscape fire propagation in the years to come in a context of increasing depopulation and poor management (Rego, 1992).

In Spain, maritime pine totaled 35% of the burned forest area between 1974 and 1994 (Pausas and Vallejo, 1999), and was affected by wildfires in 38% of its area during the 1968–1990 period (Tapias et al., 2004). In Portugal, 48% of the forested area that burned in the 1990s consisted of pure maritime pine stands (Pereira and Santos, 2003). Landscape-level analysis in NW Portugal indicates that maritime pine burns proportionally to its extent when fires are small, i.e. less than 500 ha (Moreira et al., 2001). However, very large fires (>1500 ha) select maritime pine, i.e. the burned area is higher than what would be expected from the species land cover importance (Nunes et al., 2005), suggesting a fuel type effect that exacerbates the weather-induced potential for fire conflagrations. In the summer of 2003 a single fire burned more than 36,000 ha in a mountain range of central Portugal dominated by the species (DGF, 2003).

Under the current fire return interval – around 20 years in many regions and consequently not compatible with sustainable commercial forestry (Pereira et al., 2006) – young stands are gradually more represented in the age class distribution of maritime pine in Portugal (Bento, 1994). This creates a shrubland-like structure that greatly increases the probability of fire (Moreira et al., 2001). The species apparently faces a disappearance risk in many areas, since regenerating pines are unable to reach reproductive maturity between successive fires, especially considering that the likelihood of fire occurrence increases after the first fire (Vázquez and Moreno, 2001).

The successful management of maritime pine in fire-prone regions is undoubtedly a challenging task that should be informed by comprehensive fire ecology knowledge. In this review we describe the strategies and adaptations of the species in relation to fire, characterize it as a fuel and indicate the available options to quantify fire behavior, and finally discuss the strategies for protecting maritime pine stands from destructive wildfire.

2. Response to fire

2.1. Fire resistance: individual survival

The main fire resistance trait of maritime pine is a relatively thick bark, which develops quite early (Ryan et al., 1994). According to Jackson et al. (1999), investment in bark formation by pine and oak species subjected to low-intensity and frequent fire is disproportionately higher in juvenile plants. The bark thickness of maritime pine is nevertheless somewhat variable (Tapias et al., 2004). A vertical gradient of decrease is evident, especially in young individuals (de Ronde, 1982): basal bark thickness at the age of 10 years almost doubles the value at breast height (1.3 m). Burrows et al. (2000) specify a 1.5–4 cm variation in trees whose diameter at breast height is in the 20–30 cm range.

Tapias et al. (2004) have studied, among other maritime pine traits, the interspecific variation of bark thickness at breast height in 26-year-old trees from 28 provenances. Mean values were 2.4, 2.2 and 1.8 cm, respectively, for the Atlantic, Mediterranean European and Maghrebian (North-African) genetic groups. These results oppose earlier claims of thicker bark in Mediterranean populations (Nicolas and Gandullo, 1967).

The fissured character of maritime pine bark should facilitate heat transfer to cambial tissue and thus increase the likelihood of necrosis. Bark fissures, however, can experience lesser temperatures than bark plates, which might compensate for the shallower depth (Fahnestock and Hare, 1964). Fissured barks are also usually lower on density and thermal conductivity (Hengst and Dawson, 1994). The bark of maritime pine is laminated and, unlike other pine species (*Pinus nigra*, *P. sylvestris*), the outer layers are exfoliated during combustion (pers. obs.), which should contribute to expel heat from the bole.

The length of time it takes to kill the cambium of a tree increases with the square of bark thickness (Peterson and Ryan, 1986; Rego and Rigolot, 1990), though stem necrosis from heat released by flaming combustion is theoretically bounded by a bark thickness of 2.6 cm (Ryan, 1998). For maritime pine, and according to data in Tapias et al. (2004), this threshold is equivalent to a mean dbh of 20 cm with a variation of 17–27 cm.

The maximum cambium temperature measured by Vega et al. (1998) in maritime pine trees during experimental fires never reached the lethal level of 60 °C; fire intensity ranged from 92 to 5443 kW m^{-1}, and dbh and bark thickness at 1 m height varied in the intervals of 9–40 and 0.7–3.3 cm, respectively. Similar experimentation in wind tunnel fires with tree boles rarely resulted in lethal cambium heating (Hernando et al., 2000).

When bark thickness exceeds 1 cm, injury to the bole is an irrelevant contributor to maritime pine mortality under prescribed burning conditions, as long as smouldering combustion is avoided or minimized (Ryan et al., 1994). Deep forest floor consumption can result in tree death by basal stem girdling independently of surface fire intensity (Burrows et al., 2000).

Maritime pine needles survive to temperatures in the ranges of 55–65 and 65–75 °C, respectively, for a minute and a second (Freitas, 1995; Duhoux, 1994). *Pinus halepensis* and *P. pinea* needles are comparatively less tolerant of thermal stress (Duhoux, 1994), an outcome consistent with their higher density (Daligault, 1991) and surface area to volume ratio (e.g. Fernandes and Rego, 1998). Maritime pine foliage is less susceptible to heat injury than the above-mentioned Mediterranean pines and the North America conifers *Larix occidentalis*, *Pinus ponderosa*, *Sequoia sempervirens* and *Pseudotsuga menziesii* (Ryan et al., 1994). Fig. 1, built with equations in Botelho et al. (1998a) and Rigolot (2004), compares the likelihood of post fire survival for *P. pinaster*, *P. pinea* and *P. halepensis*, suggesting that the first two species are far more resistant to a given level of crown scorch.

The lethal temperature threshold is higher for maritime pine buds than for its needles (Duhoux, 1994), presumably owing to the large size of the former – a cross-sectional bud to needle ratio of 5.5, as inferred from Daligault (1991) and Tapias et al. (2004) – and consequent higher heat capacity. It adds that terminal buds are shielded by scales, and are surrounded by long needles that increase the resistance to convective heat transfer (Michaletz and Johnson, 2006). Hence, needle kill is not always synonymous with crown kill, at times allowing tree survival after total defoliation, as reported by de Ronde et al. (1990) and Botelho et al. (1998a).

Several studies have examined the effects of surface fire on maritime pine trees, especially in the frame of prescribed burning studies. Tree vigor (Vega et al., 1983, 1985) and growth rate (Peet and McCormick, 1971; Rego, 1986; Vega et al., 1993a) in adult stands are not impacted if foliar damage is minimal. On the contrary, substantial growth losses occur when scorch affects more than a quarter of the crown's length (McCormick, 1976) or more than half of its biomass (de Ronde, 1983). Young trees are comparatively less affected by needle kill, and their growth tends to increase when defoliation is restricted to the lower quarter of the crown (Botelho, 1996; Botelho et al., 1998b).

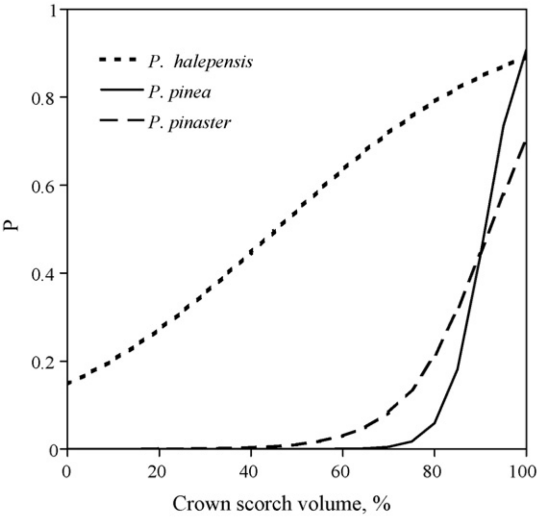

Fig. 1. Probability of tree mortality P as a function of percent crown scorch volume for *Pinus pinaster* (Botelho et al., 1998a) in comparison with the Mediterranean pines *P. pinea* and *P. halepensis* (Rigolot, 2004).

After exposure to low to moderate intensity fires (up to 1000 kW m^{-1}), maritime pine mortality is very low and increasingly unlikely when tree dbh exceeds 5 cm (Vega, 1978; Botelho, 1996; Botelho et al., 1998c; Rigolot, 2000; Fernandes et al., 2005). Larger, dominant trees are killed by surface fires in the moderate intensity range (1000–4000 kW m^{-1}), but the thinning effect is highly variable and dependent of the interaction between fire behavior and stand structure (Fernandes, 2002a).

The thicker bark and taller crown of large trees reduce their exposure to heat and hence increase the odds of surviving a fire (Ryan, 1998). Prediction models for maritime pine fire-induced mortality based on data from low intensity fire experiments explore this variability in tree size and fire effects. A crown injury descriptor is combined with bark thickness (Ryan et al., 1994) or dbh (Botelho et al., 1998a, Fig. 2) to estimate the live or dead status of individual trees after prescribed burning.

Mortality modeling of maritime pine has not included delayed but fire-associated mortality caused by insects or fungi. Post burn attacks by aggressive *Scolitydae* insect species are not uncommon in NW Iberia overstocked and mature stands (Silva, 1997), while slash pile burning (Ana-Magán, 1982) and deep duff consumption (pers. observ.) can trigger root rot mortality.

Relatively sparse foliage characterizes maritime pine (Alía et al., 1996), with a leaf area index varying from 1 to 3 (Berbigier and Bonnefond, 1995; Oliveira et al., 2000). While it has been suggested that open crowns reduce needle scorch

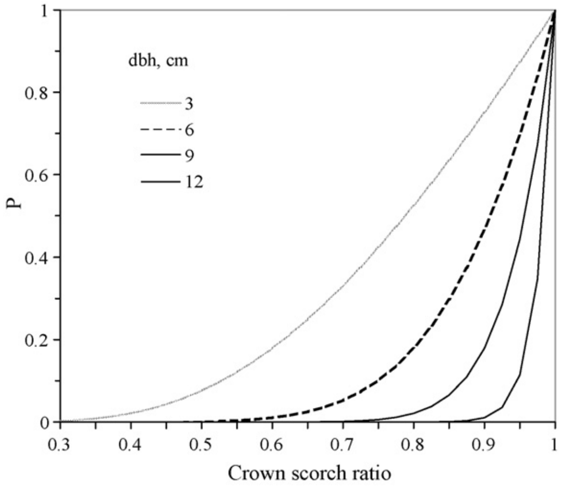

Fig. 2. Probability of tree mortality P for maritime pine as a function of crown scorch ratio (RCs,) and dbh (Botelho et al., 1998a), where $P = \exp[-10.306((\mathrm{RCs}-1)/\mathrm{RCs})(\mathrm{dbh}/(\mathrm{dbh}-15))]$; concordance between observations and estimates is 95.0%.

(Peterson, 1985), more relevant to fire resistance is the direct effect of canopy structure on crown fire hazard. A low canopy base facilitates crown ignition, while foliar density thresholds condition the possibility of active crown fire propagation (Van Wagner, 1977). Maritime pine ranks intermediate in a scale of self-pruning (Keeley and Zedler, 1998), and this trait is more developed in Mediterranean populations (Alía et al., 1996). Dense stands of the Atlantic sub-species favor death of the lower canopy branches (Maugé, 1987), which are retained and often carry a significant quantity of suspended dead needles, establishing continuity with the live crown and, consequently, implying high crowning potential (e.g. Fernandes et al., 2005).

2.2. *Fire evasion: post burn reproduction*

Vigorous maritime pine individuals flower at the age of 7–8 years (Maugé, 1987). Populations that experience frequent fires can however flower as early as 4 years, with the first fructification between 5 and 12 years (Martín and Gil, 2000; Tapias et al., 2001).

Although Keeley and Zedler (1998) and Schwilk and Ackerly (2001) refer to maritime pine as non-serotinous, the species should in fact be broadly described as partially serotinous, a trait which is displayed less frequently than in *Pinus halepensis* (Reyes and Casal, 2002; Tapias et al., 2004). Intraspecific variation in cone serotiny of pines is well known, e.g. Muir and Lotan (1985). The categorization of thermodeiscence for maritime pine varies in the literature, probably because cone serotiny variation is high among provenances and among individuals of the same population. The percentage of closed cones varied between 2% and 97% in 14 Spanish populations, the frequency of serotinous cones being higher in the youngest stands of the same population (Martín and Gil, 2000). Tapias et al. (2004) report variations of 1–73% and 3–97% in 26 southwestern Europe populations, respectively, for the percentages of serotinous cones and of trees with serotinous cones, and indicate that serotinous individuals bear more cones; serotiny was absent from two Atlantic provenances.

Non-serotinous cones start falling 2–3 years after maturation (Martín and Gil, 2000), but serotinous cones can persist in the crown up to 40 years, and seeds can remain viable for 30 years (Tapias et al., 2004). Seeds stored in the canopy of a maritime pine stand can reach more than four million units per hectare, but ample variation is possible depending of stand age and density, site quality and degree of serotiny (Martín and Gil, 2000). In contrast, the forest floor seed bank is scarce (Valbuena and Calvo, 1998; Reyes and Casal, 2001) and transient (Martínez-Sánchez et al., 1995; Martín and Gil, 2000).

The serotinous cones of maritime pine begin opening at temperatures around 50 °C (Martín and Gil, 2000; Tapias et al., 2001). The species has larger cones than most pines (Maugé, 1987), providing effective mechanical and thermal protection to the seeds. Reyes and Casal (2002) exposed cones to 26 time–temperature combinations, from 500 °C for 1 min to 100 °C for 30 min, i.e. gradually increasing exposure time and reducing temperature until relatively low temperatures and long residence times were reached. None of the treatments affected the germination viability of seeds extracted from the cones. Freitas (1995) however, reports near full viability in seeds from cones that had withstand temperatures of 200 and 400 °C for 3 min, but a viability of 10% only after cone heating for 5 min. Seed germination is not heat-stimulated (Martínez-Sánchez et al., 1995; Reyes and Casal, 2001; Escudero et al., 1999; Alvarez et al., 2005). On the contrary, the probability of germination decreases on seeds directly subjected to temperatures higher than 130 °C (Escudero et al., 1999) or 200 °C (Martínez-Sánchez et al., 1995); seed exposure for 5 min to temperatures equal to or above 150 °C resulted in almost total lack of germination in the study of Alvarez et al. (2005). These results suggest that crown fires have a negative effect on the success of post burn regeneration, and are consistent with Martínez et al. (2002): a crown fire resulted in less dispersion, higher damage rate, and decreased viability and emergence rate of the seeds in comparison with a surface fire.

The size of maritime pine seeds is large, with an average weight of 0.05–0.07 g (Escudero et al., 2000; Reyes and Casal, 2001; Tapias et al., 2004), ranking second in heat resistance among southern Europe pines, after *P. pinea* (Escudero et al., 1999). The species also has the largest wings among southwestern Europe pines (Tapias et al., 2004). The ratio of seed weight to wing length or area is a reasonable indicator of the relative seed dispersal distance of pine species (Landers, 1991). Wind dispersal should be less effective for *P. pinaster* than for *P. halepensis*, judging from their respective seed mass to wing length ratios of 1.70 and 1.06 mg mm^{-1} in Tapias et al. (2004). Cones open gradually in the two or three days that follow the thermal shock (Reyes and Casal, 2002), such that when seed dispersion begins the fire is extinct and seeds land on a cool bed of ashes. Martínez et al. (2002) and Tapias et al. (2004) report that 80–90% and 30–95% of the seeds are dispersed, respectively, in the two first months and in the first months after fire.

Luis-Calabuig et al. (2002) and Madrigal et al. (2005) indicate that post fire seed germination goes on for more than 2 years. Maritime pine seedling density is positively correlated with the remaining litter cover (Castro et al., 1990) and with other indicators of germination bed availability (Madrigal et al., 2005), which again implies that post burn regeneration is less favored by severe fires. Larger seeds develop into seedlings more vigorous and with a lower death rate than seedlings from smaller propagules (Reyes and Casal, 2001). In response to the selective pressure of fire, a compromise in seed size variability is conceivable between post fire dissemination effectiveness and the competitive ability of the seedlings to survive (Escudero et al., 2000). Mortality of maritime pine seedlings is essentially affected by interspecific competition, although physiography and site quality play a role (Madrigal et al., 2005).

2.3. *Fire-related traits and fire regimes*

Plant species thriving under different fire regimes should display different combinations of life-history traits. Keeley and Zedler (1998) and Schwilk and Ackerly (2001) have used distinct approaches to analyze the structural and functional characteristics of pines. They have arrived at two categories, respectively, thick-barked, self-pruning species, and serotinous species, i.e. fire resistant or fire surviving and fire evader or fire embracing pines. These groups are essentially equivalent to the dichotomy proposed by Landers (1991) between (i) investment in defense—open canopy species with large propagules and well-developed structural stability, and (ii) investment in early reproduction—species with dense canopy and small, numerous seeds. Ground (Keeley and Zedler, 1998), understory (Brown, 2000) or low-severity fire (Agee, 1998), and stand-replacement or high-severity fire are the corresponding fire regimes; in-between situations are included in the stand-thinning, mixed-severity or moderate-severity fire regime, where morphological variation has an important role in fire survival. The different fire regimes arise as combinations of fire return interval and site productivity (Keeley and Zedler, 1998).

Keeley and Zedler (1998) and Martín and Gil, 2000 classify maritime pine as a stand-replacement fire pine. However, a maritime pine stand in the Sierra Bermeja, southern Spain, was characterized by a stand-thinning fire regime during the period of 1817–1997, with a mean fire interval of 14 years (Vega, 2000), and Tapias et al. (2004) identify Spanish locations subjected to natural and frequent low severity fires. The species is highly variable in morphology and in attributes interpreted as evolutionary adaptations to fire (Alía et al., 1996; Tapias et al., 2004), suggesting that it does not fit in a single general fire regime category.

In the study of Tapias et al. (2004) serotiny was independent of geographical location and genetic proximity. Highly serotinous, thin-barked populations were recognized, as well as non-serotinous, moderate-bark-thickness provenances, which hints at the opposing strategies of fire evasion and fire resistance; weakly to moderately serotinous populations either had thin or thick bark. According to the authors, the main reason for this variability is variation in crown fire susceptibility – as determined by understorey shrub development and tree height – rather than natural fire frequency. A combined strategy regarding fire would allow a population to cope with a variable fire regime, as it seems to be the case with *P. patula* in Mexico (Rodríguez-Trejo and Fulé, 2003).

3. Fuel hazard and fire behaviour

The degree of fuel hazard in a pine stand depends on the nature, amount and structural arrangement of dead and live biomass. In a pine forest, the fuel complex comprises up to four distinct layers: the forest floor, understorey vegetation, ladder fuels – i.e. tree regeneration, tall shrubs, and suspended needles and twigs in the lower branches of the trees – and the pine canopy itself. Fire hazard in pine stands responds to the temporal dynamics of fuel accumulation and stand structure. Flammability is especially high at an early age, before and during a few years following pruning and thinning (Alexander, 1998). de Ronde (1990) attributes the most severe hazard to partially closed stands with ladder fuels, either young or mature, and to closed stands with well-developed understory and ladder fuels. The analysis of the National Forest Inventory data made by Godinho-Ferreira et al. (2005) indicates that closed maritime pine forests in Portugal typically have higher shrub cover and height than open stands; the shrub strata is particularly prominent in low and dense stands, where fire hazard is further aggravated by the existing vertical continuity.

Cheney and Richmond (1980) emphasize the fire vulnerability of maritime pine plantations, because of the highly flammable litter and crown fire potential in the unpruned state. The litter of maritime pine is prone to easy ignition, fast and complete combustion, and high heat release (e.g. Guijarro et al., 2002), due to the physical and chemical properties of the species' relatively coarse needles (Table 1) and to its high airflow capacity (Dupuy, 1995). Litter compactness is similar to other medium to long-needled pines, can be qualified as moderately packed, and does not increase with litter quantity (McCormick, 1973; Cheney and Richmond, 1980; Fernandes et al., 2002a). The bulk density of maritime pine litter approaches 30 kg m^{-3} (McCormick, 1973; de Ronde, 1993; Fernandes et al., 2002a). The L layer, the top undecomposed needles, has a bulk density of 22 kg m^{-3}, while the partially decomposed litter (F layer) is less porous, with 48 kg m^{-3} (Fernandes et al., 2002a). Annual litterfall values reported in the literature (Hernandez et al., 1992; Berg et al., 1999; Fernandes et al., 2002a; Roig et al., 2005) vary in the range of

Table 1
Fuel properties of maritime pine dead needles, summarized from studies conducted in Portugal, Spain and France (Cohen et al., 2003)

Fuel property	Range	Mean
Surface area to volume ratio (cm^{-1})	29.3–55.1	43.1
Mass to volume ratio (kg m^{-3})	490–660	593
Heat content (kJ kg^{-1})	20,700–21,800	21,225
Ash content (%)	1.16–2.55	2.05

2–6 t ha^{-1}. The main period of litter deposition is from July to October (Fernandes et al., 2002a; Roig et al., 2005), i.e. is coincident with the fire season.

Several studies have accomplished comprehensive and detailed forest floor and understory vegetation fuel inventories in the Iberian Peninsula. Total fuel loadings above 50 t ha^{-1} are relatively common (Vega et al., 2000; Vega, 2001), of which one-third to two thirds is humus, available for smoldering combustion only. Botelho et al. (1994) indicate litter loads from 1.2 to 6.3 t ha^{-1} for 10–18-year-old stands in northern and central Portugal. Fuel inventories in mature stands in NW Spain (Vega et al., 2000; Vega, 2001), NW Portugal (Fernandes et al., 1991) and southern Spain (Vega et al., 2000) report accumulated litter loads in the ranges of 6.0–14.6, 5.8–19.9, and 3.6–11.0 t ha^{-1}, respectively. First and second rotation stands in South Africa have a comparable litter load, but humus accumulation is markedly higher due to poor breakdown, and forest floor loadings in excess of 120 t ha^{-1} have been recorded (de Ronde, 1993).

The studies mentioned in the last paragraph found quite variable quantities of woody fuels above and within the litter, from 0.7 to 14.1 t ha^{-1}. This is also true for understory vegetation, and estimates around 30 t ha^{-1} have been reported for the gorse-dominated (*Ulex* sp.) shrub stratum of NW Portugal stands (Fernandes and Botelho, 2004), although none of the destructive sampling studies reports figures beyond 15 t ha^{-1}. For the understory communities prevailing in N and C Portugal – species of the genus *Erica*, *Calluna*, *Ulex* and *Pterospartium* – shrub fine fuel (i.e., thinner than 6 mm) load in t ha^{-1} can be estimated by the equation $x = 0.555\mathrm{IV}^{0.743}$ ($r^2 = 0.94$, standard error of the estimate = 2.31 t ha^{-1}), where IV is the product of shrub canopy cover and mean height (Fernandes et al., 2002a). Bracken fern (*Pteridium aquilinum*) in NW Iberia often dominates the maritime pine understory where site quality is higher, but hazard implications are minor, since it generally represents less than 3 t ha^{-1} and its peak flammability occurs in the autumn after curing.

Detailed studies of tree biomass are available for maritime pine, e.g. Ritson and Sochacki (2003), but not of its characterization as a fire fuel. Crown branches and their attached needles significantly increase fire hazard if left on-site after thinning and pruning. Vega et al. (1993b) indicate a mean value of 16 t ha^{-1} for the addition of maritime pine slash to the surface fuel complex after tree felling and exploitation in NW Spain. Fernandes et al. (2002a) studied the amount (around 0.4 kg m^{-3} of crown volume) and vertical distribution of foliar biomass in young trees of maritime pine, which has allowed estimation of canopy bulk density (0.19–0.24 kg m^{-3}) in a 28-year-old stand (Fernandes et al., 2004). Quantitative knowledge about ladder and crown fuels of the species is clearly quite deficient.

Inventoried fuel data can be organized and synthesized in fuel models (Burgan and Rothermel, 1984). A fuel model quantifies the surface fuel complex as an input to the semi-physical fire spread model of Rothermel (1972). Custom fuel models for maritime pine have been developed to describe regional fuel conditions in Portugal, e.g. Fernandes et al. (1991), and the hazard-reduction benefits of fuel management, e.g. Fernandes and Botelho (2004). Fuel modeling is however likely to be a futile exercise if not validated with real-world fire observations. Table 2 displays a set of fuel models – previously used to simulate landscape fire growth (Loureiro et al., 2002) – which depict fuel dynamics after prescribed burning in the maritime pine stands of NW Portugal. The parameters of these fuel models reflect calibration against experimental fire data (Fernandes et al., 2002b) and consequently should provide fire behaviour estimates that are adequate to management purposes.

Cohen et al. (2002) developed a methodology to model the spatial distribution of fuel – species, layers and densities of biomass – with a cellular automata for a physical fire behavior model (Morvan and Dupuy, 2001). Results of the application to specific maritime pine stands are found in Vigy et al. (2005).

The first studies of fire behavior in maritime pine litter took place in the south west of Australia, by Ward (1971) in the laboratory, and by Peet et al. (1971) in the field. The Forest Fire Behaviour Tables for Western Australia (Sneeuwjagt and Peet, 1985) allow for the prediction of rate of fire spread in maritime pine plantations by adjustment of the estimates obtained for eucalypt dry forest. In fact, and from a practical viewpoint, fires in pine and eucalyptus stands do not differ significantly in their

Table 2
Fuel models for NW Portugal maritime pine stands used in Loureiro et al. (2002)

Time (years)	Fuel load (t ha^{-1})				1 h SVR (m^{-1})	Fuel bed depth (m)	Heat content (J g^{-1})	
	1 h	10 h	100 h	Live woody			Dead	Live
1	2.63	1.00	0.50	2.64	4717	0.05	20,756	20,203
2	4.99	1.00	0.50	4.29	4784	0.10	20,828	20,369
3	6.68	1.00	0.50	5.76	4812	0.16	20,846	20,442
4	8.06	2.00	1.00	6.93	4851	0.22	20,831	20,435
5	9.21	2.01	1.00	7.83	4891	0.28	20,830	20,461
6	10.20	2.03	1.00	8.53	4930	0.34	20,827	20,477
7	11.07	2.05	1.00	9.06	4968	0.40	20,822	20,488
8	11.85	2.08	1.00	9.45	5003	0.45	20,817	20,495
9	12.56	2.14	1.00	9.71	5035	0.50	20,811	20,500
10	13.22	2.21	1.00	9.89	5065	0.54	20,806	20,503

Time: time since prescribed fire. 1, 10 and 100 h denote size classes for dead fuels in the forest floor and understorey vegetation, corresponding to diameters <6, 6–25, and 25–75 mm, respectively (Rothermel, 1972). Live woody respects to shrub biomass <6 mm in diameter. SVR: surface area to volume ratio. Constant parameters: live herbaceous load: 0.33 t ha^{-1}; live woody SVR: 5800 m^{-1}; live herbaceous SVR: 8500 cm^{-1}; dead fuel moisture of extinction: 40%.

Table 3
Inputs required by the models available to predict surface fire behavior in maritime pine stands

Reference	Inputs		
	Wind	Fuel moisture (f.m.)	Fuel
Andrews et al. (2004)	Midflame windspeed	Dead f.m. by size class Live woody f.m. Live herbs f.m.	Fuel model
Forestry Canada Fire Danger Group (1992)	10 m open windspeed	FFMC BUI	–
Sneeuwjagt and Peet (1985)	1–2 m forest windspeed	SMC PMC	Fuel loading
Fernandes et al. (2002b)	1.7 m forest windspeed	Fine dead f.m.	Understorey vegetation cover Understorey vegetation height Fuel loading

FFMC: fine fuel moisture code, represents the moisture content of surface (the top 10 mm, approximately) litter; BUI: buildup index, indicator of the total fuel available for spreading the fire; SMC: moisture content of the surface (top 10 mm) litter; PMC: moisture content of the profile litter, i.e. the entire litter above mineral soil.

behavior, except when spotting has a relevant role in fire propagation (Alexander, 1998).

European laboratorial studies of fire behavior frequently resort to fuel beds of maritime pine needles, e.g. Dupuy (1995) and Mendes-Lopes et al. (2003). On the contrary, field experimentation in maritime pine stands is scarce (Vega et al., 1993b; Botelho et al., 1994; Cruz and Viegas, 2001), although prescribed burning studies often document fire characteristics. The most extensive study was conducted in northern Portugal, resulting in equations that classify the likelihood of sustained fire propagation and quantify the rate of spread, flame properties and intensity of surface fires (Fernandes et al., 2002b).

In maritime pine as in other wildland ecosystems, the tools developed by the US Forest Service – with Rothermel's model at their core – such as Behave Plus (Andrews et al., 2004), are a flexible solution to predict fire behavior, and offer a valuable framework for fire risk analysis and mapping. The complete process of fuel modeling and validation is nonetheless cumbersome. If available, empirical fire behavior models such as those in Fernandes et al. (2002b) should be preferred, provided they are robust and their use is limited to the range of environmental conditions within which they were developed (Marsden-Smedley and Catchpole, 1995). This is especially true when operational circumstances call for more accurate, reliable and easily obtainable estimates.

Table 3 summarizes the models available to predict fire characteristics – rate of spread, flame length or height, fire intensity – in maritime pine stands, as well as their input requirements. The Canadian Forest Fire Behaviour Prediction System (CFFBPS) (Forestry Canada Fire Danger Group, 1992) is included because its C-6 fuel type (conifer plantation) describes pine litter with physical properties (Van Wagner, 1968) similar to maritime pine. All systems can account for the effect of slope on fire spread. Comparison between the estimates of the four options is complicated by the fact that equivalence between the input variables is not straightforward.

The ability to predict crown fire initiation and behavior in maritime pine stands is currently limited. Illustrative figures can be obtained with the CFFBPS or other empirical models developed for North-American conifer forests (Cruz et al., 2004, 2005). The CFFBPS is based on the Forest Fire Weather Index (FWI) System (Van Wagner, 1987), which has been shown useful to classify fire danger and thus assess the general fire behavior potential in New Zealand pine plantations (Pearce and Alexander, 1994) and maritime pine stands in Portugal (Palheiro et al., 2006).

4. Management for fire hazard reduction

Minimization of pine stands losses to wildfire calls for prompt and effective fire detection and fire fighting deployment and action. Fire danger rating systems and forecasts of potential fire behavior are useful to define the level of preparedness and resource requirements for initial attack, e.g. Sneeuwjagt and Peet (1985). Firebreaks are expected to help fire suppression via isolation from the outside and compartmentalization of the stands, even if they cannot be relied on to stop or significantly slow down high-intensity fires in maritime pine stands (Burrows et al., 2000; Ferreira and Galante, 2003; Sevilla, 2005).

The probability of failure of a strategy based on a fast response to fire occurrence increases with fire weather severity, especially in steep terrain and when fire-fighting resources are made scarce by multiple ignitions. Case studies and fire reports from Australia (McArthur et al., 1966; Billings, 1980; Burrows et al., 1988, 2000) and Portugal (Macedo and Sardinha, 1987; Ferreira and Galante, 2003; Fernandes et al., 2004) provide evidence that maritime pine plantations without proper fuel management are prone to high-intensity crown fires—even under relatively mild weather. To be effective, pre-suppression and suppression activities should therefore be balanced with proactive hazard reduction by fuel management and silvicultural operations.

Stand management against wildfire – the so-called preventive silviculture in southern Europe – should obviously target the surface fuel complex, but also aim at a vertically and horizontally discontinuous structure. The following operational sequence is advisable in dry conifer forests (Rigolot, 2002a; Graham et al., 2004; Agee and Skinner, 2005):

1. Decrease surface fuel accumulation or modify its structure, in order to limit the potential fire intensity, and so tree injury and the difficulty of fire suppression.
2. Prune the trees and remove ladder fuels, raising the canopy base and minimizing with the previous procedure the likelihood of torching, i.e. vertical fire development.
3. Thin the stand to decrease foliage density, hampering fire transmission between adjacent tree crowns. Thinning alone increases wind movement and fuel drying and will aggravate surface fire behavior.

Several techniques to manage surface fuels are available, singly or in combination, including a variety of mechanical treatments with different physical effects, herbicides, and controlled grazing (Valette et al., 1993; Etienne et al., 1994). However, the treatment of choice in pine stands is prescribed burning: it provides the most complete impact on the fuel complex (Graham et al., 2004), and from the practical (de Ronde et al., 1990) and economical (Rego, 1993) points of view it is the sole way of reducing the fuel build-up that characterizes pine plantations. Reports exist of wildfire behavior, severity or suppression difficulty amelioration in previously prescribed burnt stands of maritime pine (Silva, 1997; Burrows et al., 2000; Fernandes et al., 2005). Treatment with prescribed fire 2 and 3 years before turned a crown fire into a surface thinning fire during an experimental burn conducted under very high fire danger conditions in a 28-year-old plantation (Fernandes et al., 2004).

Prescribed fire in maritime pine should take place in the dormant season, when weather and moisture conditions (Table 4) are conducive to acceptable burn severity levels, as defined by the extents of crown scorch and forest floor consumption (Fernandes and Botelho, 2004). Several European studies in maritime pine stands have tackled the effects of prescribed burning on soil properties and ecosystem components other than trees, e.g. Rego et al. (1991), Fontúrbel et al. (1995), Gillon et al. (1995), and Moreira et al. (2003). The impact, either negative or positive, is generally negligible and short-lived, but a minimum 5-year fire return interval is advisable to maintain biodiversity and site quality in the stands of NW Iberia (Fernandes, 2002b). Fernandes and Botelho (2004) analyzed prescribed burning operations in the same region and found a generally strong impact on surface fine fuels, with a mean fuel load reduction of 89%; negative effects on trees or soil were present in 10% of the total number of burns and would be easily avoided with improved planning procedures.

Maritime pine underburning is rarely used in Europe, despite the species tolerance to low-intensity fire and the existence of expertise. European forestry has traditionally seen wildland fire solely as an element of destruction, disregarding its ecological role and potential as a management tool (Leone et al., 1999). On the contrary, prescribed fire is a widespread and routine practice in the highly valued plantations of SW Australia. Based on study cases of wildfires, and instead of the common practice of burning compartments in a mosaic pattern, Burrows et al. (2000) recommend wide (500–1000 m) and long buffers at 3 km intervals, burnt every 2–3 years to maintain fuel loads below 6 t ha^{-1}.

Prescribed fire is also potentially interesting in the pre-commercial thinning of maritime pine, modifying the structure of naturally regenerated dense stands such that silvicultural and fire resistance objectives are simultaneously met. Experiments conducted in SE France (Rigolot, 2000) and NW Portugal (Fernandes et al., 2005) suggest that the desired level of thermal thinning can be attained by carefully choosing the season of burn, weather conditions and ignition pattern. Four years after treating a 14-year-old stand, trees were normally distributed by diameter class, and tree density, basal area, dominant height, fine fuel load and canopy base height were respectively 58%, 116%, 108%, 45% and 123% of the adjacent untreated area, which had an inverse-*J* diameter distribution (Fernandes et al., 2005).

Treating surface fuels in conifer stands can be insufficient to prevent fires from crowning, and in this respect the critical importance of decreasing the vertical and horizontal continuity of the canopy is well documented, e.g. McArthur et al. (1966), Billings (1980) and Agee and Skinner (2005). During the extensive South Australia wildfires of February 1983, old

Table 4
Conditions recommended for maritime pine underburning

Variable	Portugal[a] (Fernandes et al., 2002c)	Western Australia (Sneeuwjagt and Peet, 1985)
Air temperature (°C)	<20 (6–13)	<20
Relative humidity (%)	>23 (31–78)	50–70
Surface litter moisture (%)	>12 (15–21[b]; 22–30[c])	20–30
Decomposing litter moisture (%)	>100 (>150)	–
Profile litter moisture (%)	–	>60
1–2 m forest wind speed (km h^{-1})	<12 (3–6)	2–6
FFMC (fine fuel moisture code)	<91 (86–89[b]; 81–85[c])	–
DMC (duff moisture code)	<30 (<15)	–
SDI (soil dryness index)	–	<250

[a] Brackets indicate the optimum range.
[b] Back firing.
[c] Strip-head firing.

multi-thinned pine plantations generally escaped crown fire, except where pine regeneration was well developed (Keeves and Douglas, 1983). The following three examples from maritime pine plantations in SW Australia offer good evidence on the worth of silviculture to avoid crown fire. In spite of a moderate surface fuel accumulation of 12 t ha^{-1}, an unthinned and unpruned stand suffered periods of severe crowning under relatively mild weather (Burrows et al., 1988). In the Gnangara fire analyzed by Burrows et al. (2000) crown fire runs were associated to stand densities near 600 stems ha^{-1}, but were absent from the prevailing open stand structures, regardless of surface fuel load. Smith (1992) reports – in a mature stand pruned and thinned to 100–300 trees ha^{-1} – a high intensity surface fire that did not develop into a crown fire. In Andalucía, southern Spain, open maritime pine stands are not prone to crowning, and consequently tend to experience lower fire severity than closed stands (Gallegos et al., 2003). Fire rate of spread and intensity can however be similar in thinned and unthinned pine stands if slash fuel remains on site (Billings, 1980; Keeves and Douglas, 1983; pers. observ.).

Minimizing the likelihood of crown fire implies thinning treatments that for most species are conducive to understocking and loss of stand growth (Keyes and O'Hara, 2002). This conflict between wildfire damage mitigation and the ultimate goal of management is obvious for maritime pine in Europe and is not easily resolved. However, simulations for NW Spain show that low-density maritime pine stands yielding high-value timber are economically more appealing than the traditional silvicultural alternatives whose goal is stand volume maximization (Rodríguez et al., 2000). Chambonnet (2005) indicate demonstration sites in southern France where surface fuel treatment and early thinning to densities of 400 trees ha^{-1} and less are expected to enhance protection from fire and add to tree growth and wood quality. The classical alternative, yet less effective than area-wide treatments, is quite used in Mediterranean France (Rigolot, 2002b). Up to 20% of the landscape is allocated to strategically placed wide strips where surface fuels are modified and the overstory is high pruned and greatly reduced in density, named crown fire free zones (Cheney and Richmond, 1980) or shaded fuel breaks (Agee et al., 2000).

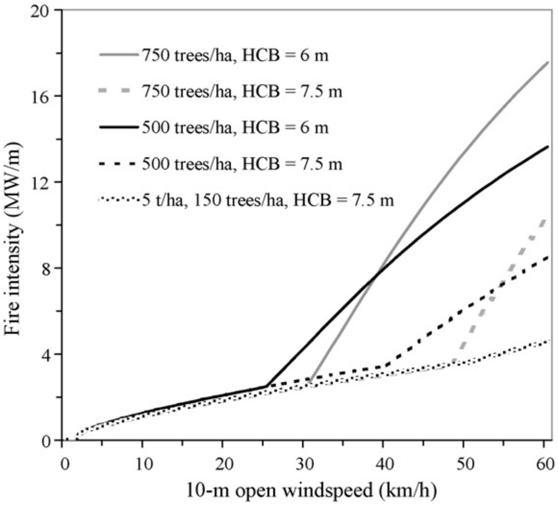

Fig. 3. Fire intensity in maritime pine stands exemplified for five scenarios of fuel management and stand structure in NW Portugal. Transition from surface to crown fire occurs when a curve inflects. The simulation combines models in Fernandes et al. (2002b) and Forestry Canada Fire Danger Group (1992) for flat terrain and extreme summer drought conditions. HCB = height to live crown base. Surface fuel load = 10 t ha^{-1}, except where noted.

Quantitative, scientifically based guidelines for stand management against wildfire are quite scarce, especially in regards to thinning. Development of treatment prescriptions that are effective under extreme fire weather requires fire behavior evaluation, the link between formulation of the desired degree of structural resistance to fire and the corresponding fuel management operations. Nonetheless, the current knowledge gaps on crown fire behavior are not an obstacle to the application of basic principles that can guide stand structure manipulation to reduce fire vulnerability according to objective criteria (Keyes and O'Hara, 2002; Graham et al., 2004; Agee and Skinner, 2005). Fig. 3 illustrates how the use of fire behaviour models can inform fuel and stand management. Fire intensity and the onset of crowning are represented as a function of wind speed for five hypothetical but typical scenarios of modified stand structure, including a crown fire free zone.

5. Conclusion

Maritime pine has evolutionary adaptations that help perpetuation in fire-prone environments. Intra-specific variation in morphology and reproductive behavior, seemingly shaped by past fire regimes, determines disparate fire-persistence abilities between the various populations and provenances in the western Mediterranean Basin. Afforestation initiatives could take advantage of this variability for the sake of a more ecologically and functionally resilient forest. However, it is important to note that the species can simultaneously exhibit fire resistance and fire evasion traits that are sufficiently developed to cope with a variable fire regime, a flexibility seldom found in the *Pinus* genus.

Maritime pine plantations are inherently susceptible to fire. Regardless of the natural capacity of the species to regenerate after stand-replacing fire – which occurs whenever the interaction of fuel, weather and topographical conditions allow – the occurrence of wildfires of such severity defeats the purpose of establishing a plantation. Fuel management decreases the ecological impact of fire, including tree injury and mortality, and enhances the effectiveness of fire suppression operations and the salvage value of timber. Consequently, it should be mandatory and a key part of maritime pine management where the likelihood of damaging fires is high. Unsurprisingly, the required treatment efforts may raise fire protection expenditures to unreasonable levels that severely limit or even cancel incomes, especially where the fire environment is more hostile and site quality is poorer.

The development of a fire-adapted silviculture is at its infancy. The current understanding of the effects of fuel and stand management on fire behavior is limited, particularly under critical weather conditions, because it rests essentially on case studies and simulation with fire models and has been poorly addressed by experimentation. Objective guidelines for planning hazard management in maritime pine stands would benefit from enhanced models of crown fire behavior and improved information on fuel dynamics in relation to stand age and silvicultural practices.

Lower density stands composed of larger high-pruned trees are obviously more resistant to fire and less susceptible to crowning. However, and since open canopies promote development of the understory vegetation and alter the microclimate, a commitment to periodic surface fuel management is necessary. The generally moderate to high bark thickness of maritime pine makes the species amenable to treatment by prescribed underburning, usually in the form of low-intensity fires that maintain light surface fuel loads. Higher-intensity burns, yet to explore, could be employed to modify stand structure, such as to obtain a strong thinning effect in a high-density naturally regenerated stand or to advance evolution towards a shaded fuel break. Studies addressing the cumulative effects of a prescribed fire regime on soils and biodiversity are lacking.

The maintenance of maritime pine stands to satisfy societal needs is not possible without an adequate fire regime. Management of maritime pine in fire-prone landscapes must recognize the inevitability of trade-offs between protection from destructive wildfires and yield of wood products, and should integrate the active use of fire, rather than attempting to exclude it. This issue will be even more critical in the future, because climate change scenarios predict drier conditions that will decrease the resiliency of maritime pine ecosystems, and significant increases in fire risk with the potential to reduce the area occupied by the species in Portugal (Pereira et al., 2002).

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References

Agee, J.K., 1998. Fire and pine ecosystems. In: Richardson, D.M. (Ed.), Ecology and Biogeography of *Pinus*. Cambridge University Press, Cambridge, pp. 193–218.

Agee, J.K., Skinner, C.N., 2005. Basic principles of forest fuel reduction treatments. For. Ecol. Manage. 211, 83–96.

Agee, J.K., Bahro, B., Finney, M.A., Omi, P.N., Sapsis, D.B., Skinner, C.N., van Wagtendonk, J.W., Weatherspoon, C.P., 2000. The use of shaded fuel-breaks in landscape fire management. For. Ecol. Manage. 127, 55–66.

Alexander, M.E., 1998. Crown Fire Thresholds in Exotic Pine Plantations of Australasia. PhD Thesis. Australian National University, Canberra.

Alía, R., Martín, S., de Miguel, J., Galera, R., Agúndez, D., Gordo, J., Salvador, L., Catalán, G., Gil, L., 1996. Regiones de procedencia *Pinus pinaster* Aiton. Ministerio de Medio Ambiente, Organismo Autónomo Parques Nacionales, Madrid.

Alvarez, R., Valbuena, L., Calvo, L., 2005. Influence of tree age on seed germination response to environmental factors and inhibitory substances in *Pinus pinaster*. Int. J. Wildland Fire 14, 277–284.

Ana-Magán, F.J., 1982. Las hogueras en el monte y el ataque del hongo *Leptographium gallaeciae* sp. nv. sobre *P. pinaster* Ait. Bol. Serv. Plagas 8, 69–92.

Andrews, P., Bevins, C., Seli, R., 2004. BehavePlus Fire Modeling System, Version 3.0: User's Guide. USDA Forest Service RMRS-GTR-106WWW, Ogden.

Barbéro, M., Loisel, R., Quézel, P., Richardson, D.M., Romane, F., 1998. Pines of the Mediterranean Basin. In: Richardson, D.M. (Ed.), Ecology and Biogeography of *Pinus*. Cambridge University Press, Cambridge, pp. 153–170.

Bento, J.S., 1994. Oferta Sustentada de Material Lenhoso de Pinheiro Bravo, Uma Aplicação a Nível Nacional. PhD Thesis. UTAD, Vila Real.

Berbigier, P., Bonnefond, J.M., 1995. Measurement and modelling of radiation transmission within a stand of maritime pine (*Pinus pinaster* Ait). Ann. Sci. For. 52, 23–42.

Berg, B., Albrektson, A., Berg, M., Cortina, J., Johansson, J., Gallardo, A., Madeira, M., Pausas, J., Kratz, W., Vallejo, R., McClaugherty, C., 1999. Amounts of litter fall in some pine forests in a European transect, in particular Scots pine. Ann. For. Sci. 56, 625–639.

Billings, P., 1980. Some Aspects of the Behaviour of the Caroline Fire of February 1979. Res. Rep. No. 7. Department of Conservation and Environment, Victoria.

Botelho, H.S., 1996. Efeitos do Fogo Controlado em Árvores de Povoamentos Jovens de *Pinus pinaster* Ait. PhD Thesis. UTAD, Vila Real.

Botelho, H., Vega, J.A., Fernandes, P., Rego, F., 1994. Prescribed fire behavior and fine fuel consumption in Northern Portugal and Galiza maritime pine stands. In: Viegas, D.X. (Ed.), Proc. 2nd Int. Conf. Forest Fire Research, Universidade de Coimbra, pp. 343–353.

Botelho, H.S., Rego, F.C., Ryan, K.C., 1998a. Tree mortality models for *Pinus pinaster* of Northern Portugal. In: Proc. 13th Conf. Fire and Forest Meteorology, IAWF, pp. 235–240.

Botelho, H.S., Fernandes, P., Loureiro, C., 1998b. Growth response of maritime pine (*Pinus pinaster*) trees to high-intensity prescribed fires. In: Viegas, D.X. (Ed.), Proc. 3rd Int. Conf. Forest Fire Research and 14th Fire and Forest Meteorology Conf. ADAI, University of Coimbra, pp. 1863–1873.

Botelho, H., Fernandes, P., Ruas, L., 1998c. Modeling *Pinus pinaster* trees damage induced by up-slope wind-driven prescribed fires in Northern Portugal. In: Proc. 13th Conf. Fire and Forest Meteorology, IAWF, pp. 473–476.

Brown, J.K., 2000. Introduction and fire regimes. In: Brown, J.K., Kapler, J. (Eds.), Wildland Fire in Ecosystems: Effects of Fire on Flora, vol. 2. USDA Forest Service RMRS-GTR-42, Ogden, pp. 1–8.

Burgan, R., Rothermel, R., 1984. BEHAVE: Fire Behavior Prediction and Fuel Modeling System—FUEL Subsystem. USDA Forest Service GTR INT-167, Ogden.

Burrows, N., Ward, B., Robinson, A., 1988. Aspects of Fire Behaviour and Fire Suppression in a *Pinus pinaster* Plantation. Dept. of Conserv. and Land Manage. of West. Aust., Landnote 2/88, Perth.

Burrows, N., Ward, B., Robinson, A., 2000. Behaviour and some impacts of a large wildfire in the Gnangara maritime pine (*Pinus pinaster*) plantation, Western Australia. CALM Sci. 3, 251–260.

Carcaillet, C., Barakat, H.N., Panaiotis, C., Loisel, R., 1997. Fire and late-Holocene expansion of *Quercus ilex* and *Pinus pinaster* on Corsica. J. Veg. Sci. 8, 85–94.

Carrión, J.S., Navarro, C., Navarro, J., Munuera, M., 2000. The distribution of cluster pine (*Pinus pinaster*) in Spain as derived from palaeocological data: relationships with phytosociological classification. Holocene 10, 243–252.

Castro, J.F., Bento, J., Rego, F., 1990. Regeneration of *Pinus pinaster* forests after wildfire. In: Goldammer, J.G., Jenkins, M.J. (Eds.), Fire in Ecosystem Dynamics, Proc. 3rd Int. Symp. Fire Ecology, SPB Academic Publishing, The Hague, pp. 71–75.

Chambonnet, F., 2005. Prévention des feux de forêts et gestion des forêts privées en Ardèche. Forêt Méditerranéenne 26, 87–90.

Cheney, N.P., Richmond, R.R., 1980. The impact of intensive forest management on fire protection with special regard to plantation of eucalypts. In: Prepared for 11th Commonwealth Forestry Conference, CSIRO, Canberra.

Cohen, M., Etienne, M., Rigolot, E., 2002. Modelling fuel distribution with cellular-automata for fuel-break assessment. In: Viegas, D.X. (Ed.), Forest Fire Research and Wildland Fire Safety. Millpress, Rotherdam, CD-ROM.

Cohen, M., Cuiñas, P., Diez, C., Fernandes, P., Guijarro, M., Moro, C., 2003. Wildland Fuel Particles Characterization Database Content. Contract No. EVG1-CT-2001-00041, Fire Star: A Decision Support System for Fuel Management and Fire Hazard Reduction in Mediterranean Wildland—Urban Interfaces. Deliverable D6-03-A1.

Cruz, M.G., Viegas, D.X., 2001. Caracterização do comportamento do fogo em complexos combustíveis comuns na região centro de Portugal. Silva Lusitana 9, 13–34.

Cruz, M., Alexander, M., Wakimoto, R.H., 2004. Modeling the likelihood of crown fire occurrence in conifer forest stands. For. Sci. 50, 640–658.

Cruz, M., Alexander, M., Wakimoto, R.H., 2005. Development and testing of models for predicting crown fire rate of spread in conifer forest stands. Can. J. For. Res. 35, 1626–1639.

Daligault, O., 1991. Caracteristiques Physiques des Aiguilles de Pin. INRA, Lab. Rech. Forest. Méditerran., PIF9112, Avignon.

de Ronde, C., 1982. The resistance of *Pinus* species to fire damage. S. Afr. For. J. 122, 22–25.

de Ronde, C., 1983. Controlled burning in pine stands in the Cape: the influence of crown scorch on tree growth and litterfall. S. Afr. For. J. 123, 39–41.

de Ronde, C., 1990. How to use forest floor characteristics to determine litter reduction priorities, rate of fire hazard and feasibility of controlled burning. In: Proc. Int. Conf. Forest Fire Research, B.01-1-10, University of Coimbra.

de Ronde, C., 1993. Spatial variation of forest floor loading in pine stands of the Tsitsikamma. S. Afr. For. J. 166, 1–7.

de Ronde, C., Goldammer, J.G., Wade, D., Soares, R.V., 1990. Prescribed fire in industrial pine plantations. In: Goldammer, J. (Ed.), Fire in the Tropical Biota: Ecosystem Processes and Global Challenges. Springer-Verlag, Berlin, pp. 216–272.

DGF, 2003. Incêndios Florestais—2003. Relatório provisório. DSVPF, Lisboa.

Duhoux, F., 1994. Sensibilités de Plusieurs Espèces Arborées Méditerraneennes aux Stress Thermiques et Prédiction de la Mortalité Après Incendie du Pin d'Alep et du Pin Pignon. Mémoire de Fin D'études. ETSIPA/INRA, Lab. Rech. Forest. Méditer., PIF, Avignon.

Dupuy, J.L., 1995. Slope and fuel load effects on fire behaviour: laboratory experiments in pine needles fuel beds. Int. J. Wildland Fire 5, 153–164.

Escudero, A., Sanz, M.V., Pita, J.M., Pérez-García, F., 1999. Probability of germination after heat treatment of native Spanish pines. Ann. For. Sci. 56, 511–520.

Escudero, A., Núñez, Y., Pérez-García, F., 2000. Is fire a selective force of seed size in pine species? Acta Oecol. 21, 245–256.

Etienne, M., Mas, I., Rigolot, E., 1994. Combining techniques of fuel reduction for fuel-break maintenance in the French Mediterranean region. In: Viegas, D.X. (Ed.), Proc. 2nd Int. Conf. Forest Fire Research, Universidade de Coimbra, pp. 713–721.

Fahnestock, G.R., Hare, R.C., 1964. Heating of tree trunks in surface fires. J. For. 62, 799–805.

Fernandes, P., 2002a. Desenvolvimento de Relações Preditivas Para Uso no Planeamento de Fogo Controlado em Povoamentos de *Pinus pinaster* Ait. PhD Thesis. UTAD, Vila Real.

Fernandes, P., 2002b. Prescribed fire: strategies and management. In: Pardini, G., Pintó, J. (Eds.), Fire, Landscape and Biodiversity: An Appraisal of the Effects and Effectiveness, Diversitas 29. Universitat de Girona, Institut de Medi Ambient, Girona, pp. 187–200.

Fernandes, P., Botelho, H.S., 2004. Analysis of the prescribed burning practice in the pine forest of northwestern Portugal. J. Environ. Manage. 70, 15–26.

Fernandes, P., Rego, F., 1998. A new method to estimate fuel surface area-to-volume ratio using water immersion. Int. J. Wildland Fire 8, 121–128.

Fernandes, P., Botelho, H., Rego, F., 1991. Modelos de combustível em povoamentos de *Pinus pinaster* Ait. In: Comunicações Encontro sobre Pinhal Bravo, Material Lenhoso e Resina. ESAC, Coimbra, pp. 183–191.

Fernandes, P., Loureiro, C., Botelho, H., Ferreira, A., Fernandes, M., 2002a. Avaliação indirecta da carga de combustível em pinhal bravo. Silva Lusitana 10, 73–90.

Fernandes, P., Botelho, H., Loureiro, C., 2002b. Models for the sustained ignition and behavior of low-to-moderately intense fires in maritime pine stands. In: Viegas, D.X. (Ed.), Forest Fire Research and Wildland Fire Safety. Millpress, Rotherdam (CD-ROM).

Fernandes, P., Botelho, H., Loureiro, C., 2002c. Manual de Formação Para a Técnica do Fogo Controlado. UTAD, Vila Real.

Fernandes, P., Loureiro, C., Botelho, H.S., 2004. Fire behaviour and severity in a maritime pine stand under differing fuel conditions. Ann. For. Sci. 61, 537–544.

Fernandes, P., Loureiro, C., Botelho, H., 2005. Alterações estruturais num pinhal bravo de regeneração natural submetido a desbaste térmico. In: Silva, R., Páscoa, F. (Eds.), Actas Com. 5° Congr. Florestal Nacional. SPCF, Lisboa (CD-ROM).

Ferreira, O., Galante, M., 2003. Mata Nacional de Leiria—2 e 3 de Agosto de 2003, Relatório de Ocorrência. DGF, Lisboa.

Fontúrbel, M.T., Vega, J.A., Bara, S., Bernardez, I., 1995. Influence of prescribed burning of pine stands in NW Spain on soil microorganisms. Eur. J. Soil Biol. 31, 13–20.

Forestry Canada Fire Danger Group, 1992. Development and Structure of the Canadian Forest Fire Behavior Prediction System. For. Can. Inf. Rep., ST-X-3, Ottawa.

Freitas, H., 1995. Efeitos do Fogo Nos Processos Regenerativos do *Pinus pinaster*. Rel. Fin. de estágio da Lic. em Eng$^{\underline{a}}$ Florestal. UTAD, Vila Real.

Gallegos, V., Navarro, R., Fernández, P., Valle, G., 2003. Postfire regeneration in *Pinus pinea* L. and *Pinus pinaster* Aiton in Andalucia (Spain). Environ. Manage. 31, 86–99.

Gillon, D., Gomendy, V., Houssard, C., Marechal, J., Valette, J.C., 1995. Combustion and nutrient losses during laboratory burns. Int. J. Wildland Fire 5, 1–12.

Godinho-Ferreira, P., Azevedo, A., Rego, F., 2005. Carta da tipologia florestal de Portugal continental. Silva Lusitana 13, 1–34.

Graham, R., McCaffrey, S., Jain, T. (Tech. Eds.), 2004. Science Basis for Changing Forest Structure to Modify Wildfire Behavior and Severity. USDA Forest Service RMRS-GTR-120, Fort Collins.

Guijarro, M., Hernando, C., Díez, C., Martínez, E., Madrigal, J., Lampin, C., Blanc, L., Colin, P.Y., Pérez-Gorostiaga, P., Vega, J.A., Fonturbel, M.T., 2002. Flammability of some fuel beds common in the South-European ecosystems. In: Viegas, D.X. (Ed.), Forest Fire Research and Wildland Fire Safety. Millpress, Rotherdam (CD-ROM).

Hengst, G.E., Dawson, J.O., 1994. Bark properties and fire resistance of selected tree species from the central hardwood region of North America. Can. J. For. Res. 24, 688–696.

Hernandez, I., Gallardo, J., Santa-Regina, I., 1992. Dynamics of organic matter in forests subject to a Mediterranean semi-arid climate in the Duero basin (Spain): litter production. Acta Oecol. 13, 55–65.

Hernando, C., Guijarro, M., Díez, C., 2000. Régimen térmico en troncos de *Pinus pinaster*: aplicación a las quemas prescritas. In: Vega, J.A., Vélez, R. (Eds.), Actas de la Reunión sobre Quemas Prescritas, Cuadernos de la Sociedade Española de Ciencias Forestales, 9. pp. 75–89.

Jackson, J.F., Adams, D.C., Jackson, U.B., 1999. Allometry of constitutive defense: a model and a comparative test with tree bark and fire regime. Am. Nat. 153, 614–632.

Keeley, J.E., Zedler, P.H., 1998. Evolution of life histories in *Pinus*. In: Richardson, D.M. (Ed.), Ecology and Biogeography of *Pinus*. Cambridge University Press, Cambridge, pp. 219–250.

Keeves, A., Douglas, D.R., 1983. Forest fires in South Australia on 16 February 1983 and consequent future forest management aims. Aust. For. 46, 148–162.

Keyes, C.R., O'Hara, K.L., 2002. Quantifying stand targets for silvicultural prevention of crown fires. West. J. Appl. For. 17, 101–109.

Landers, J.L., 1991. Disturbance influences on pine traits in the Southeastern United States. In: High Intensity Fire in Wildlands: Management Challenges and Options, Proc. 10th Tall Timbers Fire Ecology Conf, Tall Timbers Res. Stn., Tallahassee, pp. 61–97.

Le Maitre, D.C., 1998. Pines in cultivation: a global view. In: Richardson, D.M. (Ed.), Ecology and Biogeography of *Pinus*. Cambridge University Press, Cambridge, pp. 407–431.

Leone, V., Signorile, A., Gouma, V., Pangas, N., Cronopoulou-Sereli, A., 1999. Obstacles in prescribed fire use in Mediterranean countries: early remarks and results of the Firetorch project. In: Proc. Int. Symp. on Forest Fires: Needs and Innovations, Cinar S.A., Athens, pp. 132–136.

Loureiro, C., Fernandes, P., Botelho, H., 2002. Optimizing prescribed burning to reduce wildfire propagation at the landscape scale. In: Viegas, D.X.

(Ed.), Proc. IV Int. Conf. Forest Fire Research & 2002 Wildland Fire Safety Summit, Millpress Science Publishers, Rotterdam, CD-ROM.

Luis-Calabuig, E., Torres, O., Valbuena, L., Calvo, L., Marcos, E., 2002. Impact of large fires on a community of *Pinus pinaster*. In: Trabaud, L., Prodon, R. (Eds.), Fire and Biological Processes. Backhuys Publishers, Leiden, pp. 1–12.

Macedo, F.W., Sardinha, A.M., 1987. Fogos Florestais. Publicações Ciência e Vida, Lda, Lisboa.

Madrigal, J., Hernando, C., Martínez, E., Guijarro, M., Díez, C., 2005. Regeneración post-incendio de *Pinus pinaster* Ait. en la Sierra de Guadarrama (Sistema Central, España): modelos descriptivos de los factores influyentes en la densidad inicial y la supervivencia. Invest. Agrar.: Sist. Recur. For. 14, 36–51.

Marsden-Smedley, J.B., Catchpole, W.R., 1995. Fire behaviour modelling in Tasmanian buttongrass moorlands. II. Fire behaviour. Int. J. Wildland Fire 5, 215–228.

Martín, R.T., Gil, L., 2000. Adaptación reproductiva de las especies forestales ante el fuego. In: Velez, R. (Ed.), La Defensa Contra Incendios Forestales: Fundamentos y Experiencias. McGraw-Hill, Madrid, pp. 4.33–4.66.

Martínez, E., Madrigal, J., Hernando, C., Guijarro, M., Vega, J.A., Pérez-Gorostiaga, P., Fonturbel, M., Cuiñas, P., Alonso, M., Beloso, M., 2002. Effect of fire intensity on seed dispersal and early regeneration in a *Pinus pinaster* forest. In: Viegas, D.X. (Ed.), Proc. IV Int. Conf. Forest Fire Research & 2002 Wildland Fire Safety Summit, Millpress Science Publishers, Rotherdam, CD-ROM.

Martínez-Sánchez, J.J., Marín, A., Herranz, J.M., Ferrandis, P., Heras, J., 1995. Effects of high temperatures on germination of *Pinus halepensis* Mill. and *P. pinaster* Aiton subsp. *pinaster* seeds in southeast Spain. Vegetatio 116, 69–72.

Maugé, J.P., 1987. Le Pin Maritime Premier Résineux de France. Centre de Productivité & d'Action Forestière d'Aquitaine. Institut pour le Développement Forestier, Paris.

McArthur, A.G., Douglas, D.R., Mitchell, L.R., 1966. The Wandilo Fire, 5 April 1958, Fire Behaviour and associated Meteorological and Fuel Conditions. Forestry and Timber Bureau, Leaflet No. 98, For. Res. Inst., Canberra.

McCormick, J., 1973. Assessing Maritime Pine Fuel Quantity. Res. Paper No. 7, Forests Dpt. West. Austr., Perth.

McCormick, J., 1976. Recovery of Maritime Pine (*Pinus pinaster*) after Severe Crown Scorch. Res. Pap. No. 20, Forests Dept. West. Austr., Perth.

Mendes-Lopes, J., Ventura, J., Amaral, J., 2003. Flame characteristics, temperature–time curves, and rate of spread in fires propagating in a bed of *Pinus pinaster* needles. Int. J. Wildland Fire 12, 67–84.

Michaletz, S.T., Johnson, E.A., 2006. Foliage influences forced convection heat transfer in conifer branches and buds. New Phytologist 170, 87–98.

Moreira, F., Rego, F.C., Ferreira, P.G., 2001. Temporal (1958–1995) pattern of change in a cultural landscape of northwestern Portugal: implications for fire occurrence. Land. Ecol. 16, 557–567.

Moreira, F., Delgado, A., Ferreira, S., Borralho, R., Oliveira, N., Inácio, M., Silva, J.S., Rego, F., 2003. Effects of prescribed fire on vegetation structure and breeding birds in young *Pinus pinaster* stands of northern Portugal. For. Ecol. Manage. 184, 225–237.

Morvan, D., Dupuy, J.L., 2001. Modeling of fire spread through a forest fuel bed using a multiphase formulation. Combust. Flame 127, 1981–1994.

Muir, P.S., Lotan, J.E., 1985. Disturbance history and serotiny of *Pinus contorta* in Western Montana. Ecology 66, 1658–1668.

Nicolas, A., Gandullo, J.M., 1967. Ecologia de los Pinares Españoles. 1. *Pinus pinaster* Ait. Ministerio de Agricultura, Instituto Forestal de Investigaciones y Experiencias, Madrid.

Nunes, M., Vasconcelos, M., Pereira, J.C., Dasgupta, N., Alldredge, R., Rego, F., 2005. Land cover type and fire in Portugal: do fires burn land cover selectively? Land Ecol. 20, 661–673.

Oliveira, A.C., Pereira, J.S., Correia, A.V., 2000. A Silvicultura do Pinheiro Bravo. Centro Pinus, Porto.

Palheiro, P.M., Fernandes, P., Cruz, M.G., 2006. A fire behaviour-based fire danger classification for maritime pine stands: comparison of two approaches. In: Proc. V Int. Conf. Forest Fire Research.

Pausas, J.G., 1999. Response of plant functional types to changes in the fire regime in Mediterranean ecosystems: a simulation approach. J. Veg. Sci. 10, 717–722.

Pausas, J.G., Vallejo, V.R., 1999. The role of fire in European Mediterranean ecosystems. In: Chuvieco, E. (Ed.), Remote Sensing of Large Wildfires in the European Mediterranean Basis. Springler-Verlag, Berlin, pp. 3–16.

Pearce, H.G., Alexander, M.E., 1994. Fire danger ratings associated with New Zealand's major pine plantation wildfires. In: Proc. 12th Conf. Fire and Forest Meteorology, SAF Pub. 94-02, Soc. Am. For., Bethesda, pp. 534–544.

Peet, G.B., McCormick, J., 1971. Short-term Responses from Controlled Burning and Intense Fires in the Forests of Western Australia. For. Dept. West. Austr. Bull. No. 79, Perth.

Peet, G., McCormick, J., Sneeuwjagt, R., 1971. A Controlled Burning Guide for Maritime Pine Plantations. In: Underwood, R., Peet, G. (Eds.), Forest Notes, Special Issue on Forest Fire Control in Western Australia, Perth.

Pereira, J.M.C., Santos, M.T., 2003. Áreas Queimadas e Risco de Incêndio em Portugal. DGF, MADRP, Lisboa.

Pereira, J.S., Correia, A.V., Correia, A.P., Branco, M., Bugalho, M., Caldeira, M., Cruz, C., Freitas, H., Oliveira, A., Pereira, J.M.C., Reis, R., Vasconcelos, M., 2002. In: Santos, F.D., Forbes, K., Moita, R. (Eds.), Climate Change in Portugal Scenarios, Impacts and Adaptation Measures. 10. Forests and Biodiversity. Gradiva, Lisboa, pp. 363–413.

Pereira, J.M.C., Carreiras, J.M., Silva, J.M., Vasconcelos, M.J., 2006. Alguns conceitos básicos sobre os fogos rurais em Portugal. In: Pereira, J.S., Pereira, J.M.C., Rego, F.C., Silva, J., Silva, T. (Eds.), Incêndios Florestais em Portugal Caracterização, Impactes e Prevenção. ISAPress, Lisboa, pp. 133–161.

Peterson, D.L., 1985. Crown scorch volume and scorch height: estimates of postfire tree condition. Can. J. For. Res. 15, 596–598.

Peterson, D.L., Ryan, K.C., 1986. Modeling postfire conifer mortality for long range planning. Environ. Manage. 10, 797–808.

Rego, F.C., 1986. Effects of Prescribed Fire on Vegetation and Soil Properties in *Pinus pinaster* Forests of Northern Portugal. PhD Thesis. University of Idaho, Moscow.

Rego, F.C., 1992. Land use changes and wildfires. In: Teller, A., Mathy, P., Jeffers, J. (Eds.), Response of Forest Ecosystems to Environmental Changes. Elsevier, London, pp. 367–373.

Rego, F.C., 1993. Algumas considerações sobre a silvicultura do pinheiro bravo em relação com o fogo. Revista Florestal 6, 81–93.

Rego, F.C., Rigolot, E., 1990. Heat transfer through bark—a simple predictive model. In: Goldammer, J.G., Jenkins, M.J. (Eds.), Fire in Ecosystem Dynamics, Proc. 3rd Int. Symp. Fire Ecology, SPB Academic Publishing, The Hague, pp. 157–161.

Rego, F.C., Bunting, S.C., Silva, J.M., 1991. Changes in understory vegetation following prescribed fire in maritime pine forests. For. Ecol. Manage. 41, 21–31.

Reyes, O., Casal, M., 2001. The influence of seed age on germinative response to the effects of fire in *Pinus pinaster*, *P. radiata* and *Eucalyptus globulus*. Ann. For. Sci. 58, 439–447.

Reyes, O., Casal, M., 2002. Effect of high temperatures on cone opening and on the release and viability of *Pinus pinaster* and *P. radiata* seeds in NW Spain. Ann. For. Sci. 59, 327–334.

Rigolot, E., 2000. Le brûlage dirigé en France: outil de gestion et recherches associées. In: Vega, J.A., Vélez, R. (Eds.), Actas de la Reunión sobre Quemas Prescritas, Cuadernos de la Sociedade Española de Ciencias Forestales, vol. 9. pp. 165–178.

Rigolot, E. (Ed.), 2002a. Du Plan Départemental à la Coupure de Combustible. Guide Méthodologique et Pratique. Réseau Coupures de Combustible. Éd. de la Cardère, Morières.

Rigolot, E., 2002b. Fuel-break assessment with an expert appraisement approach. In: Viegas, D.X. (Ed.), Forest Fire Research & Wildland Fire Safety. Millpress, Rotherdam (CD-ROM).

Rigolot, E., 2004. Predicting postfire mortality of *Pinus halepensis* Mill. and *Pinus pinea* L. Plant Ecol. 171, 139–151.

Ritson, P., Sochacki, S., 2003. Measurement and prediction of biomass and carbon content of *Pinus pinaster* trees in farm forestry plantations, south-western Australia. For. Ecol. Manage. 175, 103–117.

Rodríguez, R., Álvarez, J., Schröderb, J., 2000. Simulation and comparison of silvicultural alternatives for even-aged *Pinus pinaster* Ait stands in Galicia (Northwestern Spain). Ann. For. Sci. 57, 747–754.

Rodríguez-Trejo, D., Fulé, P., 2003. Fire ecology of Mexican pines and a fire management proposal. Int. J. Wildland Fire 12, 23–57.

Roig, S., del Rio, M., Cañellas, I., Montero, G., 2005. Litter fall in Mediterranean *Pinus pinaster* Ait. stands under different thinning regimes. For. Ecol. Manage. 206, 179–190.

Rothermel, R.C., 1972. A Mathematical Model for Predicting Fire spread in Wildland Fuels. USDA Forest Service RP INT-115, Ogden.

Ryan, K.C., 1998. Analysis of the relative value of morphological variables in predicting fire-caused tree mortality. In: Viegas, D.X. (Ed.), Proc. 3rd Int. Conf. Forest Fire Research and 14th Fire and Forest Meteorology Conf, ADAI, pp. 1511–1526.

Ryan, K.C., Rigolot, E., Botelho, H., 1994. Comparative analysis of fire resistance and survival of Mediterranean and North-American conifers. In: Proc. 12th Conf. Fire and Forest Meteorology, SAF Pub. 94-02, Soc. Am. For., Bethesda, pp. 701–708.

Schwilk, D.W., Ackerly, D.D., 2001. Serotiny and flammability as strategies: correlated evolution in pines. Oikos 94, 326–336.

Sevilla, F., 2005. Desarrollo de la Extinción en el Gran Incendio de 1998. Seminario de Restauración de Áreas Afectadas por Grandes Incendios: el Caso Particular de Teleno, Monografias del Centro para la Defensa contra el Fuego, Consejeria de Medio Ambiente, Junta de Castilla y León, León, pp. 73–87.

Silva, J.M., 1997. Historique des feux contrôlés au Portugal. Forêt Méditerranéenne 18, 299–310.

Smith, R., 1992. The Myalup Wildfire, April 1991—Observed Fire Behaviour and Damage. CALM, Fire Protection Branch, Bunbury.

Sneeuwjagt, R.J., Peet, G.B., 1985. Forest Fire Behaviour Tables for Western Australia, 3rd ed. West. Austr. Dept. Conserv. Land Manage., Perth.

Tapias, R., Gil, L., Fuentes-Utrilla, P., Pardos, J.A., 2001. Canopy seed banks in Mediterranean pines of South-eastern Spain: a comparison between *Pinus halepensis* Mill., *P. pinaster* Ait., *P. nigra* Arn., and *P. pinea* L. J. Ecol. 89, 629–638.

Tapias, R., Climent, J., Pardos, J., Gil, L., 2004. Life histories of Mediterranean pines. Plant Ecol. 171, 53–68.

Valbuena, L., Calvo, L., 1998. Seedling establishment after a wildfire in *Pinus pinaster* Ait. and *Pinus nigra* Arn. stands. In: Viegas, D.X. (Ed.), Proc. 3rd Int. Conf. Forest Fire Research and 14th Conf. Fire and Forest Meteorology, ADAI, pp. 1901–1911.

Valette, J.C., Rigolot, E., Etienne, M., 1993. Intégration des techniques de débroussaillement dans l'aménagement de défense de la forêt contre les incendies. Forêt Méditerranéenne 14, 141–154.

Van Wagner, C.E., 1968. Fire Behaviour Mechanisms in a Red Pine Plantation: Field and Laboratory Evidence. Can. Dep. For. Rur. Dev. Publ. No. 1229, Ottawa.

Van Wagner, C.E., 1977. Conditions for the, start and spread of crown fire. Can. J. For. Res. 3, 373–378.

Van Wagner, C.E., 1987. Development and Structure of the Canadian Forest Fire Weather Index System. Can. For. Serv., Forestry Tech. Rep. 35, Ottawa.

Vázquez, A., Moreno, J.M., 1998. Patterns of lightning-, and people-caused fires in Peninsular Spain. Int. J. Wildland Fire 8, 103–115.

Vázquez, A., Moreno, J.M., 2001. Spatial distribution of forest fires in Sierra de Gredos (Central Spain). For. Ecol. Manage. 147, 55–65.

Vega, J.A., 1978. Utilizacion del fuego controlado en las comunidades vegetales de Galicia. Bol. Estac. Central Ecol. 7, 3–19.

Vega, J.A., 2000. Resistencia vegetativa ante el fuego a través de la historia de los incendios. In: Vélez, R. (Ed.), La Defensa Contra Incendios Forestales: Fundamentos y Experiencias. McGraw-Hill, Madrid, pp. 4.66–4.85.

Vega, J.A., 2001. Efectos del Fuego Prescrito Sobre el Suelo en Pinares de *Pinus pinaster* Ait. de Galicia. PhD Thesis. Universidad Politécnica de Madrid, ETSIM, Madrid.

Vega, J.A., Bará, S., Gil, M.C., 1983. Prescribed burning in pine stands for fire prevention in the NW of Spain: some results and effects. Freiburger Waldschutz Abhandlungen 4, 49–74.

Vega, J.A., Bará, S., Gil, M.C., 1985. Algunos efectos a corto plazo del fuego prescrito en pinares de Galicia. In: Estudios sobre Prevención y Efectos Ecológicos de los Incendios Forestales. MAPA, ICONA, Madrid, pp. 103–145.

Vega, J.A., Cuiñas, P., Bará, S., Fontúrbel, M.T., Santos, J.A., Rozados, M.J., Alonso, M., Beloso, M.C., Calvo, E., 1993a. Forest Fire Prevention through Prescribed Burning: Experimental Study on Fire Effects on Litter and Soil, Informe Final, Contract No. CE/STEP-CT90-0087, CIF, Lourizãn.

Vega, J.A., Bará, S., Santos, J.A., Cuiñas, P., 1993b. Comportamento do lume en diferentes complexos de combustible forestal. In: Memoria 1993 Centro de Investigacións Forestais de Lourizan, Xunta de Galicia, Consellería de Agricultura, Gandería e Montes, pp. 115–127.

Vega, J.A., Pérez-Gorostiaga, P., Cuiñas, P., Alonso, M., Fontúrbel, M.T., Fernández, C., Rozados, M.J., 1998. Temperature spatial patterns at trunk and crown of *P. pinaster* during prescribed burning. In: Viegas, D.X. (Ed.), Proc. 3rd Int. Conf. Forest Fire Research and 14th Fire and Forest Meteorology Conf, ADAI, University of Coimbra, pp. 831–842.

Vega, J.A., Cuiñas, P., Fontúrbel, M.T., Fernández, C., 2000. Planificar la prescripción para reducir combustibles y disminuir el impacto sobre el suelo en las quemas prescritas. In: Vega, J.A., Vélez, R. (Eds.), Actas de la Reunión sobre Quemas Prescritas, Cuadernos de la Sociedade Española de Ciencias Forestales, vol. 9. pp. 189–198.

Vigy, O., Rigolot, E., Valette, J.C., 2005. Fire Star Wildland Fuel Structure: Model Results. FIRE STAR: A Decision Support System for Fuel Management and Fire Hazard Reduction in Mediterranean Wildland–Urban Interfaces, Deliverable D6-04, http://www.eufirestar.org.

Ward, D., 1971. A controlled experiment to study factors influencing fire rate of spread in *Pinus pinaster* litter. For. Notes 9, 39–47.