ELSEVIER

Journal of Environmental Management 70 (2004) 15–26

Journal of Environmental Management

www.elsevier.com/locate/jenvman

# Analysis of the prescribed burning practice in the pine forest of northwestern Portugal

P. Fernandes*, H. Botelho

*Departamento Florestal, Centro de Estudos em Gestão de Ecossistemas, Universidade de Trás-os-Montes e Alto Douro, 5000-911 Vila Real, Portugal*

Received 9 April 2003; revised 3 October 2003; accepted 28 October 2003

## Abstract

The ignition of low-intensity fires in the dormant season in the pine stands of north-western Portugal seeks to reduce the existing fuel hazard without compromising site quality. The purpose of this study is to characterise this practice and assess its effectiveness, based on information resulting from the normal monitoring process at the management level, and using operational guidelines, fire behaviour models and a newly developed method to classify prescribed fire severity.

Although the region's humid climate strongly constrains the activity of prescribed fire, 87% of the fires analysed were undertaken under acceptable meteorological and fuel moisture conditions. In fact, most operations achieved satisfactory results. On average, prescribed fire reduces by 96% the potential intensity of a wildfire occurring under extreme weather conditions, but 36% of the treated sites would still require heavy fire fighting resources to suppress such fire, and 17% would still carry it in the tree canopy. Only 10% of the prescribed burns have an excessive impact on trees or the forest floor, while 89% (normal fire weather) or 59% (extreme fire weather) comply with both ecological integrity maintenance and wildfire protection needs. Improved planning and monitoring procedures are recommended in order to overcome the current deficiencies.

*Keywords:* Prescribed fire; Fuel management; Fire behaviour; Fire severity; *Pinus pinaster*; Portugal

## 1. Introduction

Wildfires burn each year 700,000–1,000,000 ha of wildlands in the Mediterranean Basin, as a direct or indirect consequence of modifications in the intensity and type of land use that progressively took place since the mid-20th century (Velez, 2000). The highly flammable Mediterranean pine forests are among the most affected vegetation types (Pausas and Vallejo, 1999), and are expected to suffer a pronounced decline in the long-term, since they lack the resilience traits that would allow them to withstand the frequency and severity of the current fire regime (Pausas, 1999).

A huge afforestation program essentially based on maritime pine (*Pinus pinaster*) was initiated in the 1930s by the state Forestry Services on communal lands of the mountainous northern and central Portugal (Brower, 1993). As a result, the traditional fine-grained mosaic of grazed shrubland and cultivated fields was replaced over thousands of hectares by continuous, dense and even-aged pine plantations, whose wildfire hazard potential soon became apparent (Silva, 1993). Even though its climate departs from the typical mediterranean conditions, the north-western Iberian Peninsula has the highest fire frequency in Europe, possibly reflecting the favourable conditions for plant growth (Vázquez et al., 2002). In fact, fuel accumulation in the maritime pine stands of the region is unparalleled by pine forests in temperate climates elsewhere (Vega, 2001).

Many *Pinus* species have the ability to resist low-intensity fires without damage, making them obvious candidates to prescribed burning programs (de Ronde et al., 1990). A prescribed fire seeks well-defined effects that will fulfil one or more management goals, which are attained by burning in a specific fire environment (the prescription) and following specific operational procedures (the burn plan) (Pyne et al., 1996). Fire hazard reduction frequently is the main reason to use prescribed burning (Haines et al., 2001), and this was also the case with its

---

* Corresponding author. Tel.: +351-259-350236; fax: +351-259-350480.

*E-mail address:* pfern@utad.pt (P. Fernandes).

0301-4797/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jenvman.2003.10.001

introduction in Portugal in the mid 1970s, but benefits to soil properties and the diversity and nutritive value of understorey vegetation were also expected (Silva, 1987a). The genesis and history of prescribed burning in north-western Portugal is thoroughly described by Silva (1997). More than adopted, the technique has been adapted to the region specifically, and its operational implementation by the Forestry Services went hand in hand with research studies focused on its ecological effects (Rego, 1986; Botelho et al., 1998a; Moreira et al., 2003).

The basic principles guiding the pioneer pine underburning practice in Portugal were extensively disseminated to European foresters via technical literature (Silva, 1987a, 1988). The burning activity takes place in the dormant season, during periods when weather and moisture conditions are conducive to low rates of heat release and selective biomass elimination. The burn blocks are delimited by pre-existing barriers, usually forest roads and fuel-breaks, complemented by the establishment of control lines. The fires are started by line ignition (rarely exceeding a length of 200 m) and are conducted as back fires, i.e. against the wind and down slope. When fuel moisture is too high for sustained back fire propagation, head firing (up slope and upwind) is used, ordinarily as a succession of fire lines separated by short distances. The burning crew is composed of a technical supervisor and 4–10 persons that rely solely on hand tools for fire containment.

The success of a prescribed fire program depends of adequate planning (Fischer, 1978), which clearly distinguishes prescribed burning from the traditional use of fire (Pyne et al., 1996). A systematic monitoring and documentation of pre-fire, fire and post-fire variables is a crucial activity to determine whether the pursued objectives have been met. It also is used to assess the operational effectiveness of prescribed fire and provides a sound basis to adjust and refine the practice in the future (Van Wagtendonk et al., 1982). However, the outcomes of the monitoring and evaluation activities carried out by management agencies are rarely reported to a wider audience. Literature on the subject (Czuhai and Cushwa, 1968; Burrows, 1987; Keifer, 1998; James, 1999) is, consequently, very scarce and often sketchy, in spite of the decisive contribution that such information could give to the contemporary debates focused on the relevance of prescribed burning as a land management tool (Morrison et al., 1996; Bradstock et al., 1998; Baeza et al., 2002; Keeley, 2002).

Documentation of the prescribed burning operations conducted by the Forestry Services in Portugal is based on a simple field form, conceived to be easily filled in by trained forest rangers, yet complete enough to address all subjects the evaluation of prescribed fire should consider, i.e. the environmental burning conditions, the behaviour and accomplishment of the fire, costs incurred, and observations (Fischer, 1978). This paper analyses the information provided by this data source, with the purpose of characterising and evaluating the results of management-ignited fires in the pine forest of the Entre Douro e Minho region of north-western Portugal.

## 2. Methods

### 2.1. Available and estimated variables

From prescribed fires 493 field forms from prescribed fires conducted in the years of 1979–2001 were retrieved from the Forestry Services and translated into a database This sample is representative of prescribed fire activity in the pine stands of north-western Portugal. Based on an estimate extrapolated from figures in Silva (1987b), it represents no more than one seventh to one fifth of the total number of burn operations during the study period.

The prescribed fire form contains both qualitative and easily assessed quantitative elements that describe the burn unit and the behaviour and effects of the fire. Information on sampling intensity is not available, but it is assumed to be a function of treated area. A few important variables were derived from the information contained in the form, in order to fully characterise, understand and evaluate the practice; for this purpose we used regional equations whenever they were available. The treatment unit is identified, and its location and date of the prescribed fire are reported. Physiographic elements are provided on terrain slope, aspect, elevation, and parent soil material. Stand age and the dominant tree species are indicated, and stand structure is described by tree density (no. ha$^{-1}$), height, height to live crown base, and diameter at breast height (DBH). These variables were assessed by standard forest inventory procedures.

Pre-burn fuel characteristics are succintly described in the form by litter depth, measured to the nearest millimeter, and by understorey height (in decimetres) and cover percentage by species, determined along a linear transect. Each species height was weighted by its cover to calculate a mean height value for the overall understorey. Potential heat release is directly proportional to fuel load, i.e. the amount of biomass available to burn (Byram, 1959), and this variable is therefore a fundamental input to fire behaviour prediction models and systems (Rothermel, 1972). Prescribed burning priorities are commonly assigned on the basis of a fuel hazard classification scheme driven by fuel load (McCarthy et al., 1998), whose pre-burn and post-burn estimates allow objective evaluations of the burn success in meeting management goals (Brown et al., 1991).

The above-mentioned structural characteristics of the fuel-complex were coupled with models in Fernandes et al. (2002a) to generate mean fuel loads (t ha$^{-1}$) for each burn unit. The following fuel categories were considered: (i) surface litter, the forest floor top horizon composed of freshly cast needles; (ii) lower litter or upper duff, the decomposing needles and woody material; (iii) understorey elevated fuel, comprehending shrubs, forbs, herbs and ferns.

Duff refers to the fermentation and humus layers. Classes (i) and (iii) are designated surface fuel, and appraisal of their weights was limited to the finer size class (thickness $<6$ mm), which governs fire propagation (Rothermel, 1972) and consequently is the main target of hazard-reduction burning.

Weather data for the duration of the fire includes ambient temperature and relative humidity measured in-forest at 1.7 m height with a psychometer, wind direction, and wind velocity measured with a cup anamometer or classified according to the Beaufort scale. Each wind class in the Beaufort scale has an equivalent range of wind speed (at 6 m height in open terrain), whose central value was assumed and converted to surface (1.7 m) wind speed ($\mathrm{km\,h^{-1}}$), using adjustment factors (Rothermel, 1983) consistent with the stand structure of each burn unit.

The behaviour and effects of a fire are strongly conditioned by fuel moisture, a variable that profoundly affects ease of ignition, combustion velocity, fuel consumption and flame temperature (Nelson, 2001). Such importance is even more noteworthy in understorey prescribed burning, where the ignition pattern is usually designed to cancel the dynamic influences of wind and slope. Moisture content of the fine surface dead fuels was estimated from ambient temperature, relative humidity and time since rainfall (Fernandes et al., 2002b), and then corrected for the amount of solar radiation according to Rothermel (1983).

Operational information comprises fire characteristics (times of initiation and termination, ignition pattern, area, fire behaviour, and fuel impact) and the assigned human resources. Burn duration and size were combined to yield the treatment rate ($\mathrm{ha\,h^{-1}}$). The forms provide the spread rate ($\mathrm{m\,h^{-1}}$) and vertical extent (flame height, m) of the flaming front, estimated visually against reference points of known size. Flame length and fire intensity ($\mathrm{kW\,m^{-1}}$) are equally important descriptors of fire behaviour and were derived from flame height (Fernandes et al., 2002c).

Post-burn fuel assessment is limited to depth of burn—the removed forest floor thickness (mm), measured in spikes driven into the soil before the fire—and to the terminal diameter of the residual woody shrub biomass ($d_t$, mm). Burn depth was translated into fuel consumption by using bulk density values of 2.2 and $4.8\ \mathrm{t\,ha^{-1}\,cm^{-1}}$, respectively, for surface litter and upper duff (Fernandes et al., 2002a). Estimates of shrub consumption ($\mathrm{t\,ha^{-1}}$) were obtained by multiplying the pre-burn load by $[1-\exp(-0.762d_t)]$ (Fernandes, 2002a). A constant fuel consumption of 90% was assumed for non-woody species (Fernandes, 2002a).

Tree injury is expressed by crown scorch height, but only 6% of the forms assess this variable, probably because it is not immediately apparent and requires inspection two to three weeks after the fire; a semi-empirical model (Fernandes, 2002a) whose output depends of flame length, ambient temperature and wind speed generated estimates for the remaining cases. Crown scorch ratio reveals the severity of foliar damage and was calculated as the scorched crown length in proportion of total crown length (Wyant et al., 1986). The non-existence of mid-term or long-term monitoring of prescribed burnt units precludes tree mortality evaluation. A probability of tree mortality was calculated from crown scorch ratio following Botelho et al. (1998a).

The form contains also a section for observations, where qualitative statements on fuel moisture and other environmental factors are made, operational constraints and problems are reported, and the achievement of treatment objectives is classified.

The prescribed fires evaluation took into account the problems reported in the forms, the weather conditions under which the fires were lit, and their hazard-reduction effect and impact on-site. We classified the fires according to their compliance with the general weather prescription for prescribed burning in pine stands (Fernandes et al., 2002b). A given burn was declared optimal, acceptable or unacceptable (out of prescription) regarding ambient temperature, wind speed and dead fuel moisture content; relative humidity is a surrogate for fuel moisture and was not considered.

### 2.2. Hazard-reduction evaluation

The hazard-reduction effect of a burn was evaluated in terms of fuel modifications, and by comparing potential wildfire characteristics before and after the treatment. The BEHAVE Plus Fire Modelling System (Andrews et al., 2003) was used to simulate surface fire behaviour for two summer weather scenarios as determined from historical climate data for the study region (INMG, 1990). Dead fuel moisture contents of 12 and 9%, and in-stand surface wind speeds of 5 and 15 $\mathrm{km\,h^{-1}}$, respectively, define the normal and extreme situations. On average, extreme fire weather is expected for 5% of the summer days, but it can extend to 10–15% of the days in severe years. The hierarchical and agglomerative cluster analysis method of Ward (Johnson and Wichern, 1982) was employed to identify similar pre- and post-burn fuel situations, and the characteristic fuel properties of each group was assigned a fuel model (Burgan and Rothermel, 1984) for use in the BEHAVE system. Post-burn needle fall from crown scorch (NF, $\mathrm{t\,ha^{-1}}$) was added to the residual surface fuel after estimation with an equation in Fernandes et al. (2002a)

$$\mathrm{NF} = 0.217\mathrm{DBH}^{1.243}\exp[2.349(\mathrm{SH}-1)/\mathrm{SH}]\mathrm{TD}/1000$$

where DBH is the mean tree diameter at breast height (cm); SH, the crown scorch height (m); TD is the density of trees (no. $\mathrm{ha^{-1}}$).

Surface fire intensities associated to the untreated and treated fuel conditions followed Alexander (1994) and interpreted in terms of fire fighting resources requirements. The simulated fire intensity was also combined with canopy base height, such that a given fire could be categorised as either a surface or a crown fire, after the widely used theory of Van Wagner (1977); the post-treatment calculation changed crown base height to crown scorch height to account for abscission of injured foliage. Direct suppression actions were judged ineffective when crown fire events were predicted (Alexander, 1987). The fuel hazard reduction resulting from a prescribed burn was considered fully effective if the post-treatment fire behaviour level indicated maximum assistance with the suppression of a subsequent wildfire on the site, i.e. the heat release potential of such fire was below 500 kW m$^{-1}$ and was within the control capability of crews equipped with hand-tools.

### 2.3. Fire severity evaluation

Ryan and Noste (1985) define fire severity as the immediate effect of fire on the ecosystem, and present a general severity rating method based on flame length and depth of burn. These variables indicate the upward and downward heat pulses, respectively, and are combined in a two-dimensional classification matrix. We embrace Ryan and Noste's concept and approach as a starting point in the development of a specific method to evaluate the ecological severity of prescribed fire in maritime pine stands.

The potential of flame length (or fire intensity) as a component of a fire severity appraisal scheme is somewhat limited, because the post-fire survival and recovery of trees is linked to their morphology. It seems therefore advisable to replace flame length with a variable related to tissue damage, such as crown scorch ratio (RCs). Damage to needles and buds is the prevalent cause of mortality in *Pinus* species (Van Wagner, 1973); duff moisture conditions during prescribed burning preclude root injury, and stem injury is unlikely in maritime pine, because the cambium tissue is effectively protected by a relatively thick bark acquired at an early age (Ryan et al., 1994).

Higher levels of crown scorch are parallel with growth decreases in *Pinus* species, but most studies agree that pines can sustain one third (Ryan, 1982; Wright and Bailey, 1982) to two thirds (Wade and Lundsford, 1989; de Ronde et al., 1990) of foliage loss without noteworthy detrimental effects on growth. In mature maritime pine stands, prescribed fire does not reduce tree vigour or growth when crown scorch is absent or minimal (Peet and McCormick, 1971; Vega et al., 1983; Rego, 1986), but growth loss can be important if more than half of the crown is scorched in length (McCormick, 1976) or volume (de Ronde, 1983). In maritime pine stands younger than 20 years in northern Portugal, artificially heat-injured trees showed significant growth improvements for RCs = 0.25, and similar decreases for RCs = 0.50 and 0.75 (Botelho, 1996). Botelho et al. (1998b) report similar results after experimental fires: negative effects on tree growth were not revealed for RCs < 0.75 and growth increased when RCs < 0.25.

The above information, coupled with mortality models for individual maritime pine trees (Botelho et al., 1998a), suggests the following classes to rate fire severity in terms of crown scorch ratio:

1. $0 \le$ RCs $< 0.25$. Tree growth is not affected or increases slightly, and tree mortality is negligible.
2. $0.25 \le$ RCs $< 0.75$. Growth tends to diminish, especially in mature stands. Mortality as a direct consequence of the fire is unlikely (unless pre-burn tree vigour is weak), but the trees can attract or become more susceptible to Scolytidae bark beetles (Bradley and Tueller, 2001).
3. $0.75 \le$ RCs $< 0.90$. Tree growth is greatly impacted and the occurrence of mortality is probable.
4. $0.90 \le$ RCs $\le 1$. Extensive tree mortality.

The burn depth classes of Ryan and Noste (1985) cover the entire wildland fire severity spectrum, which makes them too broad for classifying the effects of relatively mild burns. Furthermore, their assignment is based on the visual characteristics of ground char, and therefore is prone to subjectivity. Forest floor has an important role in soil fertility and stability, and although the desired amount of residual duff can vary by burn objective, the necessity of moderating the organic layer removal and minimise humus consumption is widely recognised (de Ronde et al., 1990; DeBano, 1991; Hungerford et al., 1991). Hence, and given the position of upper duff (between surface fuels and the humus horizon), we use its consumption (RFc) to describe the downward component of fire severity. Similarly to RCs, we express RFc as a ratio, positioning the impact of fire in relation to the minimum and maximum modifications that are physically possible. The following RFc classes are favoured after examining and crossing the information contained in Vega et al. (2000) and Fernandes (2002a)

1. $0 \le$ RFc $< 0.25$. The upper duff remains intact or is slightly removed.
2. $0.25 \le$ RFc $< 0.50$. The fermentation layer is moderately consumed.
3. $0.50 \le$ RFc $< 0.75$. Excessive reduction of the upper duff, some humus is eliminated.
4. $0.75 \le$ RFc $\le 1$. Consumption of the upper duff is nearly total. A considerable amount of the humus layer will be available to burn. Plant structures below the ground surface can experience lethal heating, depending on their location and duration of the combustion.

The RFc classification is essentially dividing Ryan and Noste's Low and Moderate classes into two Low and two Moderate classes. The combination of the first and second RCs classes with the first and second RFc classes defines a region of acceptable fire severity.

## 3. Results and discussion

### 3.1. Characteristics of the prescribed fires

Ten different Communal Forests within the Entre Douro e Minho region had prescribed fire activity during the study period (Fig. 1). Overall, those units amount to 74,280 ha, or 55% of the total communal wildland area in north-western Portugal.

Slope and elevation in the burned units range from zero to 68% and from 150 to 1000 m, averaging 22% and 520 m. Soils are derived from schist or granite. Table 1 displays numerical information concerning vegetation, weather-related variables, and fire behaviour and effects in the treated plots.

The vast majority of the burns is conducted in maritime pine (*P. pinaster*) stands, either pure (90.9% of the total number of fires) or dominated by the species (3.0%), but Scots pine (*Pinus sylvestris*) plantations are also prescribed burnt (5.3%); a few (0.8% of the total) trials were attempted in Monterey pine (*Pinus radiata*). Distribution of the treated area by cover type is 86.4% (pure *P. pinaster*), 7.9% (dominated by *P. pinaster*), 5.3% (*P. sylvestris*), and 0.4% (*P. radiata*).

The prescribed burning program firstly emphasised pine stands older than 20 years, where fire use was deemed easier by the presence of taller trees and suppressed understorey. Subsequent tree mortality caused by Scolytidae insects, especially in dense stands with more than 30 years of age (Silva, 1997), motivated a shift towards younger age classes (Fig. 2), and after 1995 there are no records of fires in stands older than 25 years. The remaining descriptors of prescribed fire activity lack temporal patterns.

The stands subjected to prescribed fire are diverse in structure but carry in general a well-developed understorey layer, composed of evergreen sclerophylous shrubs of the Calluno-Ulicetea class (Rivas-Martinez, 1979). Gorse species (*Ulex europaeus*, *Ulex minor*)-favoured by the oceanic character of the climate and frequently in association with bracken-fern (*Pteridium aquilinum*)-dominate or co-dominate the community in 71% of the stands and account for more than half of total understorey cover in 57% of the cases. Dry sites and inland locations are dominated by the legume *Chamaespartium tridentatum* and by ericaceous species.

Fig. 3 depicts the burns distribution by classes of air temperature and relative humidity. Mean values for these variables during the burns varied between 9.2 °C in December to 13.6 °C in November, and from 63.1% in April to 74.2% in November. Similar mild weather is prescribed for fuel reduction burning in the pine plantations of south-eastern USA (Wright and Bailey, 1982) and Australia (Woodman and Rawson, 1982; Sneeuwjagt and Peet, 1985), which is consistent with the need to minimise tree injury in forests primarily managed for their wood resources.

A fire intensity upper limit in the 250–700 kW m$^{-1}$ range is often recommended for prescribed burning under tree canopies (Cheney, 1981; Wade and Lunsford, 1989; de Ronde et al., 1990). Estimated fire intensity exceeds 250 kW m$^{-1}$ for 11% of the data base fires, despite the already mentioned conservative prescription for weather. This highlights the role of fuel in fire behaviour. Average understorey height exceeds one meter in 25% of the sites, and the shrub canopy—well aerated, dense, comprised of fine elements with an important dead

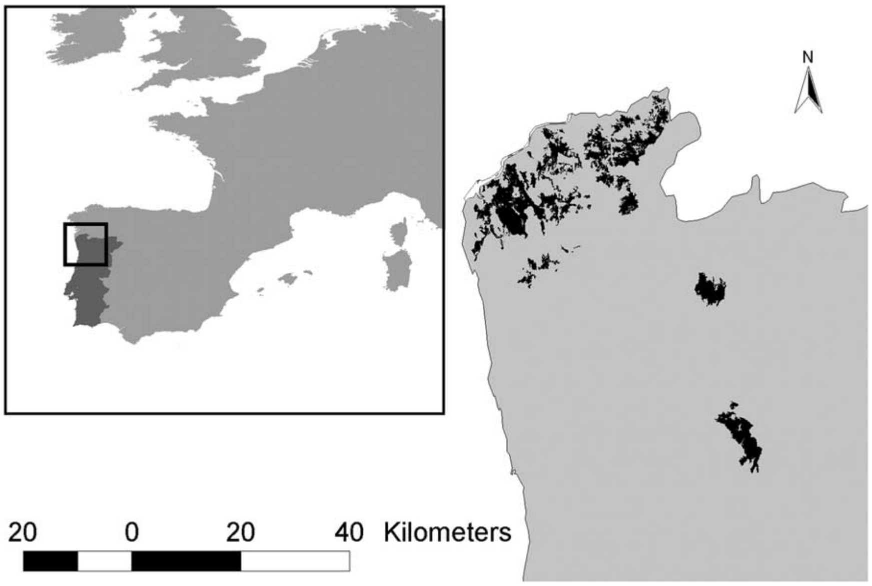

Fig. 1. Study region location. The Communal Forests with prescribed fire activity in the 1979–2001 period appear in dark grey.

Table 1
Descriptors of the fire environment, the fire behaviour and the fire impact in the prescribed burns

| Variable | Mean | Median | Range |
|---|---|---|---|
| *Stand descriptors* | | | |
| Age, years | 22 | 18 | 7–52 |
| Tree density, no. $ha^{-1}$ | 1101 | 1000 | 200–3695 |
| Diameter at breast height, cm | 18 | 15 | 5–35 |
| Height, m | 12.4 | 12 | 4–20 |
| Height to live crown base, m | 3.2 | 2 | 0.2–15 |
| *Fuel descriptors* | | | |
| Litter depth, cm | 11.2 | 10 | 2–30 |
| Litter load, t $ha^{-1}$ | 35.1 | 31.3 | 6.3–93.8 |
| Understory vegetation (cover, %; height, m) | 68.9; 0.9 | 70.0; 0.8 | 0–100; 0.1–3.5 |
| Understory vegetation fine fuel load, t $ha^{-1}$ | 11.4 | 10.9 | 0–32.6 |
| Surface fine fuel load, t $ha^{-1}$ | 19.7 | 19.0 | 7.9–39.3 |
| *Weather-related descriptors* | | | |
| Ambient temperature, °C | 11.8 | 12.0 | 3.3–23.0 |
| Relative humidity, % | 70.8 | 69.0 | 15–100 |
| Wind speed, km $h^{-1}$ | 4 | 4 | 1–18 |
| Surface dead fine fuel moisture, % | 23 | 23 | 12–38 |
| *Fire behaviour (backfires and strip-head fires; headfires)* | | | |
| Rate of spread, m $h^{-1}$ | 28; 84 | 22; 63 | 3–150; 19–198 |
| Flame height, m | 0.6; 1.4 | 0.5; 1.1 | 0.1–4.0; 0.7–3.5 |
| Flame length, m | 0.7; 1.7 | 0.6; 1.3 | 0.2–4.8; 0.8–4.2 |
| Fire intensity, kW $m^{-1}$ | 111; 784 | 55; 348 | 8–3657; 139–3657 |
| *Fire impact descriptors* | | | |
| Litter depth reduction, % | 46.2 | 45 | 6–100 |
| Litter reduction, t $ha^{-1}$ | 13.2 | 10.3 | 1.0–61.0 |
| Lower litter reduction, % | 17 | 6 | 0–100 |
| Shrub terminal diameter, mm | 2.4 | 2.3 | 0.8–7.2 |
| Understorey reduction, t $ha^{-1}$ | 10.1 | 9.4 | 0.5–28.1 |
| Surface fuel load reduction, % | 87 | 89 | 25–100 |
| Tree crown scorch ratio | 0.30 | 0.23 | 0–1 |
| Probability of tree mortality | 0.07 | 0.00 | 0.00–0.90 |

component—will give rise to tall flames if fully involved in combustion; additionally, flames can be vertically transmitted to the ladder fuels (dead needles suspended in the lower branches of the trees) in unpruned stands. Fuel-complex structure and the elevated fuel quantity should therefore be the main causes for the unusual flame dimensions and fire intensity reported for some fires, even when back firing was the method of ignition.

Any prescribed fire program is strongly constrained by weather factors. The maritime influence that prevails over the study region attenuates diurnal oscillations in temperature and humidity, making fire behaviour more predictable and facilitating a burn operation. On the other hand, the vegetation growing period is lengthened by such moderating effects and curtails the potential season for prescribed fire. But rainfall poses the major climatic restriction to prescribed burning in the region, ranging annually from 1500 to 2500 mm (among the highest values in Europe) and occurring in more than 40% of the days (Ribeiro et al., 1987). The burn season is variable and can extend from November to April, but the frequency and quantity of autumn rain can preclude any burning activity until January. Most fires are conducted from December to February. Prescribed burning is concentrated in January. Forty-one percent of the fires and area burned occurred in this month, when favourable burning conditions coincide with cold dry weather associated with dominance of high pressure systems (Ribeiro et al., 1987).

Prescribed fire in the pine stands of north-western Portugal is clearly a small-scale practice. The average burn lasts for six hours approximately and attains 3.5 ha in size, with mean values by Communal Forest ranging from 0.6 to 7.5 ha. Only 20% of the fires have 5 ha or more (60 ha is the maximum recorded value) and 15% of the burns are smaller than 1 ha. The average burn is accomplished at a rate of 0.52 ha $h^{-1}$, which is two to five times faster than mechanical and chemical fuel management methods (Santos, 2000), but mean values by Communal Forest vary in the 0.12–1.03 ha $h^{-1}$ interval. At the end of the prescribed fire season, mean patch size-the average plot that results from adjacent treatment units burnt in different days—is 8.6 ha, with a variation by Communal Forest of 2.0–18.3 ha. Spatial patterns of prescribed burning programmes elsewhere are not comparable, since they include burn units larger by one or two orders of magnitude (McRae and Flannigan, 1990; Grant and Wouters, 1993; Alfonso et al., 2000; Finney, 2002).

Several factors are accountable for the small fire size, including the limited fire suppression capabilities of the burning crews, the heterogeneity and steepness of the terrain, and weather patterns that constrain fire spread rate and fire sustainability (and therefore the number of hours that are available to burn on each day). Fire duration explains 21% of the variation in fire size, with 25% of the fires being ignited after noon but only 10% finishing at 18:00 or later, but other variables were also found to be significantly correlated ($p < 0.05$) with the area of a burn (Table 2). Burn operations tend to be larger in older stands and stands with less abundant understorey vegetation, which might reflect the use of more conservative ignition patterns where trees are most at risk to suffer damage from fire. An increase in the size of the treated areas is advisable and would be achieved by enlarging the duration of the burns when possible, but especially by increasing the treatment rate through longer ignition lines; in less favourable topographies this would involve additional manpower and fire suppression equipment, i.e. vehicles equipped with water pumps.

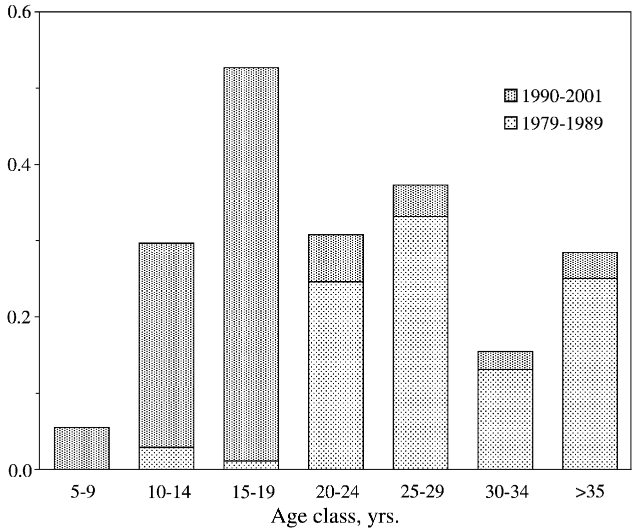

Fig. 2. Proportions of the total number of prescribed fires on each stand age class for the periods 1979–1989 and 1990–2001.

Table 2
Variables with a significant statistical effect ($p < 0.05$) on the area of a prescribed fire operation, increasing (+) or decreasing (−)

| Variable | $p$-Value | Variable | $p$-Value |
|---|---|---|---|
| Burn duration (+) | <0.0001 | Understorey vegetation height (−) | 0.0060 |
| Relative humidity (−) | 0.0304 | Stand age (+) | <0.0001 |
| Wind speed (+) | 0.0027 | Diameter at breast height (+) | 0.0114 |
| Understorey vegetation cover (−) | 0.0006 | | |

### 3.2. Evaluation of the prescribed fires

#### 3.2.1. Operational problems and prescription compliance

The section of the field form dedicated to observations is frequently empty and, when filled, its contents are usually poor. Operational difficulties are reported for 16.7% of the forms. Fires with problems can be divided in two major categories, the fires whose propagation was marginal due to excessive fuel moisture content (10.8%) and those that were suspended (5.9%). Four different reasons leading to the interruption of a burn are indicated, respectively, high fuel moisture (41.4% of the cases), fire behaviour causing unacceptable tree damage and/or fire control problems (31.0%), changes in wind speed or direction (20.7%), and unfavourable moisture and wind (6.9%).

Table 3 shows the proportion of fires by prescription interval (i.e. optimum, acceptable and out of prescription) for the variables ambient temperature, wind speed and dead fuel moisture content. Thirteen percent of the fires are conducted under unacceptable conditions, but wind speed is practically the sole variable responsible for that percentage. Control problems can arise from an excessively strong wind, while lack of wind, a more common situation, complicates the conduction of the burn and increases tree canopy scorch. Winter dry periods in the study region are often calm, especially when determined by an Iberian high-pressure system (Ribeiro et al., 1987). Depending on stand structure and topographical position, wind speed inside a forest is 2–10 times lower than wind speed in the open (Rothermel, 1983).

Overall, and because the preferred range of the prescription is rarely observed by the three variables concurrently, only 8% of the fires qualify as optimal. The sub-optimal burns (79% of the total) tend to occur under warmer, calmer, and moister conditions than the ‘ideal’, a deviation that should increase tree crown scorch and decrease fuel reduction. Since two thirds of the fires were conducted with dead fuel moisture contents in excess of

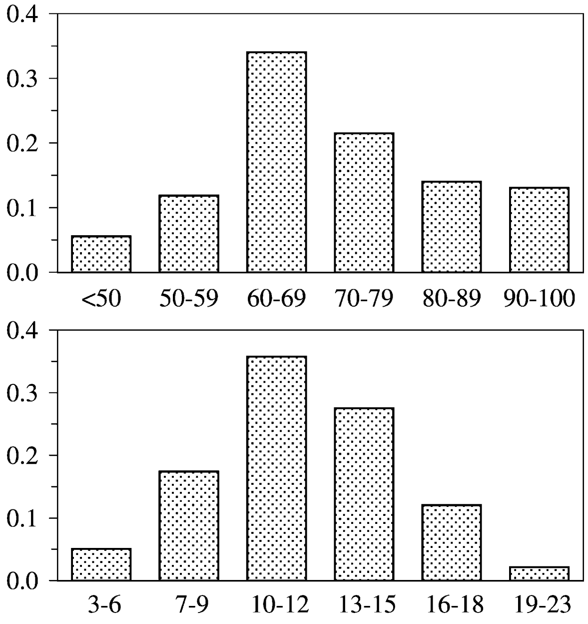

Fig. 3. Proportions of prescribed fires by classes of relative humidity (%, top) and ambient temperature (°C, bottom).

Table 3
Distribution (%) of the prescribed fires by prescription interval (within parentheses)

| Variable | Optimum | Acceptable | Out of prescription |
|---|---|---|---|
| Ambient temperature | 58.0 (<13 °C) | 41.8 (14–20 °C) | 0.2 (>20 °C) |
| Wind speed | 56.3 (3–6 $\mathrm{km\,h^{-1}}$) | 25.6 (1–2 $\mathrm{km\,h^{-1}}$)<br>4.2 (7–12 $\mathrm{km\,h^{-1}}$) | 8.0 (no wind)<br>5.9 (>12 $\mathrm{km\,h^{-1}}$) |
| Surface dead fine fuel moisture | 35.5 (15–21%) | 1.2 (12–14%)<br>63.3 (>21%) | 0.0 (<12%)<br>– |
| Combined result | 8.0 | 79.2 | 12.8 |

21%, fuel dampness is undoubtedly the major reason for marginal burning conditions.

### 3.2.2. Classification of the fires as a function of the results obtained

The cluster analysis of pre-treatment fuel conditions in the burn units has identified six consistent groups, which are sorted by hazard level in Table 4. Distinction between the clusters is essentially determined by the importance and structure of the understorey vegetation, rather than by the accumulation of litter. The shrub layer dominates the fuel-complex and hence has the prevailing role in fire behaviour in 75% of the burn units.

In addition to their descriptive value, the results in Table 4 are useful to appreciate the overall selection of the burn units. Silva (1987a) recommends the application of prescribed fire in maritime pine stands when the fine fuel load exceeds 8–10 t ha$^{-1}$, and the mean value for cluster 1 is 9 t ha$^{-1}$. Simulated fire intensity in 25% of the plots (clusters 1 and 2) is low enough ($<500$ kW m$^{-1}$) to assure effective fire suppression with minimum resources in a normal summer weather scenario, but the same fuel hazard levels require heavy ground equipment to contain wildfires burning under severe weather conditions. However, the scarcity of resources for fuel management and the common practice of prioritizing fuel treatments according to fire behaviour potential (Sneeuwjagt, 1998), would normally recommend the exclusion of prescribed fire from clusters 1 and 2.

A minor portion (2%, cluster 6 in Table 4) of the prescribed burns is conducted in stands where fine fuel accumulation (averaging 36 t ha$^{-1}$) and shrub height (2.2 m) are on the opposite end of the fuel spectrum. The task of achieving a balance between proper fuel consumption and acceptable tree damage is complex in this situation, advising the replacement of prescribed fire by a mechanical fuel treatment.

Table 4
Descriptors of pre-treatment surface fuel hazard and potential fire behaviour under two summer weather scenarios for each cluster of prescribed burnt plots

| Cluster no. (%) | Surface fine fuel load, t ha$^{-1}$ | | Vegetation height, m | Fire intensity[a], kW m$^{-1}$ | |
|---|---|---|---|---|---|
| | Litter | Vegetation | | N | E |
| 1 (1.4) | 7.83 | 1.28 | 0.4 | 234 | 985 |
| 2 (23.3) | 8.55 | 6.03 | 0.5 | 407 | 1657 |
| 3 (23.8) | 6.00 | 10.48 | 0.7 | 1377 | 5712 |
| 4 (33.6) | 9.46 | 11.92 | 0.9 | 2132 | 8795 |
| 5 (16.1) | 8.69 | 19.07 | 1.3 | 5832 | 23,748 |
| 6 (1.8) | 8.75 | 27.58 | 2.2 | 16,568 | 58,884 |

[a] Simulated for the mean slope of each cluster (18–41%) and for normal (N) and extreme (E) summer conditions: dead fuel moisture content = 12 and 9%; wind speed = 5 and 15 km h$^{-1}$, respectively.

The information in Table 1 indicates that prescribed fire in maritime pine stands generally has a strong impact on fine surface fuels, albeit some variation can be expected. The upper litter horizon, with a median consumption value of 100%, is partially removed on occasions only. The corresponding value for understorey vegetation is lower (86%, range of 37–100%), but the most flammable shrub components (foliage and very fine twigs) are usually removed by the fire: post-burn terminal diameter of shrubs' remains is less than 2 mm in only 24% of the burns. The difference in relative fuel reduction between the two surface fuel layers conforms to observations made in experimental studies (Botelho et al., 1994; Hernando and Guijarro, 1997; Vega, 2001). The porous and continuous *P. pinaster* litter is the main vector of fire propagation and its physical properties favour complete combustion (Dupuy, 1995).

The modified fuel conditions following the application of prescribed fire indicate an average reduction of 96% (with a variation of 59–100%) in the intensity of a wildfire, under extreme summer weather. This figure is similar to previous estimates based on experimental data, made for pine stands in Europe (Vega et al., 1994; Fernandes et al., 2000) and elsewhere (Anderson and Brown, 1987). Even though this relative reduction in fire potential illustrates the prescribed fire impact, it does not indicate how the control of a wildfire is affected by the treatment.

Post-burn fuel conditions are described by ten fuel models. This finer resolution (in comparison with the pre-treatment fuel analysis) was advisable to better classify the efficiency of the burns. The corresponding fire behaviour simulations were crossed with those made for the pre-treatment fuel environment (Table 4), leading to the classification of the type (surface versus crown), intensity, and suppression difficulty of a wildfire occurring before and after the treatment (Table 5). Depending on the weather scenario (normal or extreme) under consideration, high-intensity fire behaviour with tree canopy involvement is predicted for 66 or 94% of the plots prior to the application of prescribed fire, a percentage that drops to 3 and 17% after the treatment. Regardless of weather conditions, 45% of the plots will not support fire propagation after a prescribed burn. It is interesting to note that fire intensity rarely falls within the 2000–4000 kW m$^{-1}$ range, either before or after the treatment, thus reducing the opportunities of efficient aircraft use in wildfire suppression. Finally, prescribed fire was successful, i.e. a post-treatment wildfire would be handled by a suppression crew with minimum equipment, in 97% (normal summer weather) or 64% (extreme summer weather) of the cases.

### 3.2.3. Ecological severity of the fires

Fire severity indicators for the typical prescribed fire indicate minimal impacts on the ecosystem, even if a broad range of variation is possible (Table 1). Duff removal is

Table 5
Wildfire classification and suppression interpretation before and after prescribed burning for the two summer weather scenarios (N: normal; E: extreme)

| Fire type and intensity, kW $m^{-1}$ | | Minimum resources required to contain the head of a fire | Before, % | | After, % | |
|---|---|---|---|---|---|---|
| | | | N | E | N | E |
| Surface | $< 10$ | Fire not sustained | 0.0 | 0.0 | 45.0 | 45.0 |
| | 10–500 | Ground crews with hand tools | 23.8 | 0.0 | 52.1 | 18.7 |
| | 500–2000 | Water under pressure, bulldozer | 7.9 | 5.1 | 0.0 | 19.6 |
| | 2000–4000 | Aircraft, retardants | 1.9 | 0.0 | 0.0 | 0.0 |
| | $>4000$ | Head fire attack probably not effective | 0.0 | 0.9 | 0.0 | 0.0 |
| Crown | | | 66.4 | 94.0 | 2.9 | 16.7 |

slight, and thus the downward heat pulse is expected to be highly correlated with surface fuel consumption, implying minimal smoke production and the absence of negative effects in the soil and root system of the trees. Pine canopy scorch is restricted to its lower third, and the average tree in a stand will not experience a decrease in growth rate and will survive the immediate effect of the treatment. The upward component of fire severity is therefore more prominent than its downward equivalent, given the generally high fuel accumulation and low tree crown base, the previously mentioned tendency to burn under calmer and warmer weather than the optimum, and because rainless periods are sufficiently brief to prevent deep duff drying.

Table 6 crosses the previously defined classes of crown scorch and upper duff consumption and shows the prescribed fires distribution among them. Seventy-nine percent of the fires are within the boundaries of the acceptable impact region, but this classification can be deemed excessively conservative. The association of RFc class 3 with RCs classes 1 and 2 might as well be considered acceptable (or at least tolerable) and will further increase to 90% of the total the number of prescribed fire operations that are ecologically sound. As expected from previous findings, burns with severe canopy impacts (RCs $\geq 0.75$) are comparatively more frequent (8.1% of the total) than burns with severe forest floor effects (RFc $\geq 0.75$, 1.5% of the total only). Fires combining both severity extremes were not present in the database.

We are aware of the limitations of the indicators used to classify the ecological severity of prescribed fire. RFc and RCs express the immediate and direct impacts of the fire, the so-called first-order fire effects (Reinhardt et al., 2001). The overall impact of a prescribed fire program has to consider the second-order fire effects, which are indirect outcomes of the fire that interact with other processes, and, on a longer temporal scale, the fire regime. The frequency component of the fire regime is expected to play an important role in the biodiversity of maritime pine stands. Consecutive burns at interval less than 5 years on a given site are not desirable (Fernandes, 2002b; Moreira et al., 2003).

An overall assessment of the prescribed fire program impact is not possible without merging the results in Tables 5 and 6. A simple procedure was adopted in order to reclassify them according to their joint ecological and fuel hazard reduction effect. Fires were deemed either severe or non-severe and efficient or inefficient (Table 7). The severity of 89% of the operations is mild while achieving a fuel-complex modification that provides adequate protection against a wildfire under normal summer weather, but under extreme meteorological conditions such figure is decreased to 59%.

Table 6
Prescribed fires distribution (%) by fire severity class, defined by the combination of crown scorch ratio (RCs) and the ratio of upper duff consumption (RFc)

| RFc | RCs | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| 1 | 31.4 | 31.4 | 2.8 | 3.8 |
| 2 | 8.9 | 7.0 | 0.5 | 0.5 |
| 3 | 8.9 | 2.8 | 0.0 | 0.5 |
| 4 | 1.0 | 0.5 | 0.0 | 0.0 |

Table 7
Distribution (%) of the prescribed fires according to their ecological severity and wildfire hazard-reduction effect, for the two summer weather scenarios (normal/extreme)

| Fire severity level | Hazard-reduction effect | |
|---|---|---|
| | Inefficient[a] | Efficient[b] |
| Acceptable[c] | 1.4/31.9 | 89.4/58.9 |
| Unacceptable[d] | 1.0/4.3 | 8.2/4.8 |

[a] Post-treatment fire intensity $\geq 500$ kW $m^{-1}$.
[b] Post-treatment fire intensity $< 500$ kW $m^{-1}$.
[c] RFc $< 0.75$ and RCs $< 0.75$.
[d] RFc $\geq 0.75$ or RCs $\geq 0.75$.

## 4. Conclusions

The dominance of sub-optimal environmental conditions—warmer, calmer and moister than the preferred prescription range—is an important determinant of the practice and achievements of pine underburning in the study region. Such deviations act to increase the ecological impact of the treatment (more scorch in the tree canopy) and decrease its effectiveness (less fuel consumption); in addition, the former effect can be exacerbated by fuel accumulation and ladder fuels when fire is used for the first time in a young stand. Two-stage burning can be recommended to improve the results, and it is sometimes used: a first fire conducted under poor burning conditions is followed by a burn under drier conditions. The occurrence of marginally high levels of moisture content in surface dead fuels is common in the prescribed fire season, due to high relative air humidity and the brevity of rainless periods. Moisture content is a especially constraining factor, and is a source of difficulty in achieving sustained fire propagation, as well as the main reported reason for cancelling a burn operation.

The selection of treatment units is generally well grounded from the perspective of pre-burn fuel hazard level and, despite the above mentioned environmental limitations, most prescribed fires are successful in achieving the stated objective of hazard reduction without harmful effects to the ecosystem. The structural modifications suffered by the fuel-complex dramatically reduce the post-treatment fire intensity potential, and practically exclude the likelihood of stand-replacement crown fire. Observations made during wildfires corroborate this, with prescribed burnt areas providing effective assistance to fire suppression (Silva, 1997). Fuel management is more relevant where the coincidence of extremely dry and windy conditions is unusual (Fernandes and Botelho, 2003), such as in north-western Portugal, but it is a matter of conjecture whether the current spatial pattern of prescribed fire application, i.e. in relatively small but strategically located strips, contributes to mitigate landscape fire spread in the region.

In this paper we have characterised hazard-reduction burning in the pine stands of northern Portugal, and attempted an objective analysis of its results at the operational scale (i.e. the treatment unit). Our findings support the practice, but the necessity of improvements is readily apparent. Operational planning and evaluation of the outcomes can and should be developed in the future, profiting from decision-support tools and more detailed and complete data collection, namely concerning the long-term monitoring of fire effects. The proposed method of fire severity rating is objective and user-friendly and could be a component of the process.

## Acknowledgements

This study would not have been possible without the operational data provided by Paulo Mateus (DRAEDM Forestry Services). We acknowledge funding by the European Commission under contract ENV4-CT98-0715 (DG XII, Environment and Climate programme), and by JNICT (PRAXIS XXI program, contract 3/3.2/FLOR/2103/95). The prescribed fire severity rating method was supported by a FCT grant to P. Fernandes (SFRH/BD/3277/2000). Cartography supplied by Luís Reis (Direcção Geral das Florestas) enabled the preparation of Fig. 1 by Carlos Loureiro (Departamento Florestal, UTAD). Two anonymous reviewers gave valuable comments on the manuscript.

## References

Alexander, M.E., 1987. Help with making crown fire hazard assessments, Symposium and Workshop on Protecting People and Homes From Wildfire in the Interior West. General Technical Report INT-GTR-251, USDA Forest Service, Ogden, pp. 147–156.

Alexander, M.E., 1994. Proposed revision of fire danger class criteria for forest and rural areas in New Zealand, Circular 1994/2, National Rural Fire Authority, Wellington, 73 pp.

Alfonso, P., Andrade, M., Castro, F., Diez, J., Francisco, M., Gras, J., Herrera, E., Jiménez, V., López, P., Marchena, F., Minino, V., Padín, N., Recamán, R., Rincón, V., Sarabia, A., 2000. Planificación y ejecución de las quemas controladas en la provincia de Pontevedra. Cuadernos de la Sociedade Española de Ciencias Forestales 9, 235–241.

Anderson, H., Brown, J., 1987. Fuel characteristics and fire behaviour considerations in the wildlands, Symposium and Workshop on Protecting People and Homes from Wildfire in the Interior West. General Technical Report INT-GTR-251, USDA Forest Service, Ogden, pp. 124–130.

Andrews, P.L., Bevins, C.D., Seli, R.C., 2003. BehavePlus Fire Modeling System Version 2.0 User's Guide, General Technical Report RMRS-GTR-106WWW, USDA Forest Service, Ogden, 133 pp.

Baeza, M.J., De Luís, M., Raventós, J., Escarré, A., 2002. Factors influencing fire behaviour in shrublands of different stand ages and the implications for using prescribed burning to reduce wildfire risk. Journal of Environmental Management 65, 199–208.

Botelho, H.S., 1996. Efeitos do fogo controlado em árvores de povoamentos jovens de *Pinus pinaster* Ait. PhD Thesis. UTAD, Vila Real, 251 pp.

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.), Proceedings of the Second International Conference on Forest Fire Research, Universidade de Coimbra, Coimbra, pp. 343–353.

Botelho, H.S., Rego, F.C., Ryan, K.C., 1998a. Tree mortality models for *Pinus pinaster* of Northern Portugal, Proceedings of the 13th Conference on Fire and Forest Meteorology, International Association of Wildland Fire, 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.), Proceedings of the Third International Conference on Forest Fire Research and 14th Fire and Forest Meteorology Conference, ADAI, Coimbra, pp. 1863–1873.

Bradley, T., Tueller, P., 2001. Effects of fire on bark beetle presence on Jeffrey pine in the Lake Tahoe Basin. Forest Ecology and Management 142, 205–214.

Bradstock, R.A., Gill, A.M., Kenny, B.J., Scott, J., 1998. Bushfire risk at the urban interface estimated from historical weather records: consequences for the use of prescribed fire in the Sydney region of south-eastern Australia. Journal of Environmental Management 52, 259–271.

Brower, R., 1993. The Forestry Services and the Commons in Portugal. Forest and Conservation History 37, 160–168.

Brown, J.K., Reinhardt, E.D., Fischer, W.C., 1991. Predicting duff and woody fuel consumption in northern Idaho prescribed fires. Forest Science 37, 1550–1566.

Burgan, R., Rothermel, R., 1984. BEHAVE: fire behavior prediction and fuel modeling system—FUEL subsystem, Research Paper INT-167, USDA Forest Service, Ogden, 126 pp.

Burrows, N.D., 1987. The soil dryness index for use in fire control in the south-west of Western Australia, Technical Report No. 17, Department of Conservation and Land Management, Perth, WA, 37 pp.

Byram, G.M., 1959. Combustion of forest fuels. In: Davis, K.P., (Ed.), Forest Fire Control and Use, McGraw-Hill, New York, pp. 61–89.

Cheney, N.P., 1981. Fire behaviour. In: Gill, A.M., Groves, R.H., Noble, I.R. (Eds.), Fire and the Australian Biota, Australian Academy of Science, Canberra, pp. 151–175.

Czuhai, E., Cushwa, C.T., 1968. A resumé of prescribed burnings on the Piedmont National Wildlife Refuge, Research Note SE-86, USDA Forest Service, Asheville, 4 pp.

DeBano, L.F., 1991. The effect of fire on soil properties. In: Harvey, A., Neuenschwander, L. (Eds.), Proceedings: Management and Productivity of Western-Montane Forest Soils, General Technical Report INT-280, USDA Forest Service, Ogden, pp. 151–156.

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

Fernandes, P., 2002. Desenvolvimento de relações preditivas para uso no planeamento de fogo controlado em povoamentos de fogo controlado em povoamentos de *Pinus pinaster* Ait. PhD Thesis. UTAD, Vila Real, 285 pp.

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, Universitat de Girona, Girona, pp. 187–200.

Fernandes, P., Botelho, H., 2003. A review of prescribed burning effectiveness in fire hazard reduction. International Journal of Wildland Fire 12, 117–128.

Fernandes, P., Botelho, H., Loureiro, C., 2000. Fire hazard implications of alternative fuel management techniques-case studies from northern Portugal. In: Neuenschwander, L., Ryan, K. (Eds.), Proceedings From the Joint Fire Science Conference and Workshop, vol. II. University of Idaho, Moscow, pp. 268–270.

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. Manual de Formação Para a técnica do Fogo Controlado, UTAD, Vila Real, 139 pp.

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

Finney, M.A., 2002. Use of graph theory and a genetic algorithm for finding optimal fuel treatment locations. In: Viegas, D.X., (Ed.), Forest Fire Research and Wildland Fire Safety, Millpress, Rotherdam.

Fischer, W.C., 1978. Planning and evaluating prescribed fires-a standard procedure, General Technical Report INT-43, USDA Forest Service, Ogden, 19 pp.

Grant, S.R., Wouters, M.A., 1993. The effect of fuel reduction burning on the suppression of four wildfires in Western Victoria, Research Report No. 41, Department of Conservation and Environment, Fire Management Branch, Victoria, 18 pp.

Haines, T.K., Busby, R.L., Cleaves, D.A., 2001. Prescribed burning in the South: trends, purpose, and barriers. Southern Journal of Applied Forestry 25, 149–153.

Hernando, C., Guijarro, M., 1997. Uso del fuego prescrito para la prevención de incendios forestales en masas de *Pinus pinaster* Ait. In: Puertas, F., Rivas, M. (Eds.), Libro de Actas-congresso Forestal Hispano Luso and II Congresso Forestal Espanol, Gobierno de Navarra, Pamplona, pp. 190–196.

Hungerford, R.D., Harrington, M.G., Frandsen, W.H., Ryan, K.C., Niehoff, G.J., 1991. Influence of fire on factors that affect site productivity. In: Harvey, A., Neuenschwander, L. (Eds.), Proceedings: Management and Productivity of Western-Montane Forest Soils, General Technical Report INT-280, USDA Forest Service, Ogden, pp. 32–50.

INMG, 1990. Normais climatológicas da região de Entre Douro e Minho e Beira Litoral correspondentes a 1951–1980. O clima de Portugal, 14. Lisboa. 38 pp.

James, S.G., 1999. Evaluation of the effectiveness of prescribed burning: a simple methodology for post-burn assessment of the achievement of fire management objectives. In: Lunt, I., Green, D.G. (Eds.), Proceedings of the Australian Bushfire 99 Conference, School of Environmental and Information Sciences, Charles Stunt University, Albury (http://life.csu.edu.au/bushfire99/papers).

Johnson, R.A., Wichern, D.W., 1982. Applied Multivariate Statistical Analysis. Prentice-Hall, New Jersey, 594 pp.

Keeley, J.E., 2002. Fire management of California shrubland landscapes. Environmental Management 29, 395–408.

Keifer, M., 1998. Fuel load and tree density changes following prescribed fire in the giant sequoia-mixed conifer forest: the first 14 years of fire effects monitoring. In: Brennan, L., Pruden, T. (Eds.), Fire in Ecosystem Management: Shifting the Paradigm from Suppression to Prescription, Proceedings of the Tall Timbers Fire Ecology Conference, No. 20, Tall Timbers Research Station, Tallahassee, pp. 306–309.

McCarthy, G.J., Tolhurst, K.G., Chatto, K., 1998. Overall fuel hazard guide, Fire Management Branch Research Report No. 47, Department of Natural Resources and Environment, Victoria, 33 pp.

McCormick, J., 1976. Recovery of maritime pine (*Pinus pinaster*) after severe crown scorch, Research Paper No. 20, Forests Department of Western Australia, Perth.

McRae, D.J., Flannigan, M.D., 1990. Development of large vortices on prescribed fires. Canadian Journal of Forest Research 20, 1878–1887.

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

Morrison, D.A., Buckney, R.T., Bewick, B.J., 1996. Conservation conflicts over burning bush in south-eastern Australia. Biological Conservation 76, 167–175.

Nelson, R.M., 2001. Water relations of forest fuels. In: Johnson, E.A., Miyanishi, K. (Eds.), Forest Fires Behavior and Ecological Effects, Academic Press, San Diego, pp. 79–149.

Pausas, J.G., 1999. Response of plant functional types to changes in the fire regime in Mediterranean ecosystems: a simulation approach. Journal of Vegetation Science 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, Berlin, pp. 3–16.

Peet, G.B., McCormick, J., 1971. Short-term responses from controlled burning and intense fires in the forests of Western Australia, Bulletin No. 79, Forests Department, Perth, WA, 21 pp.

Pyne, S.J., Andrews, P.L., Laven, R.D., 1996. Introduction to Wildland Fire, second ed., Wiley, New York, 769 pp.

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, 108 pp.

Reinhardt, E.D., Keane, R.E., Brown, J.K., 2001. Modeling fire effects. International Journal of Wildland Fire 10, 373–380.

Ribeiro, O., Lautensach, H., Daveau, S., 1987. Geografia de Portugal, vol. II. O Ritmo Climático e a Paisagem. Edições João Sá da Costa, Lisboa, 623 pp.

Rivas-Martinez, S., 1979. Brezales y jarales de Europa Occidental. Lazaroa 1, 5–128.

de Ronde, C., 1983. Controlled burning in pine stands in the Cape: the influence of crown scorch on tree growth and litterfall. South Africa Forestry Journal 123, 39–41.

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, Berlin, pp. 216–272.

Rothermel, R.C., 1972. A mathematical model for predicting fire spread in wildland fuels, Research Paper INT-115, USDA Forest Service, Ogden, 40 pp.

Rothermel, R.C., 1983. How to predict the spread and intensity of forest and range fires, General Technical Report INT-143, USDA Forest Service, Ogden, 111 pp.

Ryan, K.C., 1982. Evaluating potential tree mortality from prescribed burning. In: Baumgartner, D.M., (Ed.), Proceedings of the Symposium on Site Preparation and Fuels Management on Steep Terrain, Wasington State University, Pullman, pp. 167–179.

Ryan, K.C., Noste, N.V., 1985. Evaluating prescribed fires. In: Lotan, J., Kilgore, B., Fischer, W., Mutch, R. (Eds.), Proceedings of the Symposium and Workshop on Wilderness Fire, General Technical Report INT-182, USDA Forest Service, Ogden, pp. 230–238.

Ryan, K.C., Rigolot, E., Botelho, H., 1994. Comparative analysis of fire resistance and survival of Mediterranean and North-American conifers, Proceedings of the 12th Conference on Fire and Forest Meteorology. SAF Publication 94-02, Society of American Foresters, Bethesda, pp. 701–708.

Santos, F., 2000. Controlo de matos com meios mecânicos e químicos, Equipamentos e Práticas Culturais na Pequena Exploração Florestal, Associação Florestal do Vale do Douro Norte, Murça, 12 pp.

Silva, J.M., 1987a. Methodes sylvicoles propres a reduire les risques d'incendie, Seminar on Methods and Equipments for the Prevention of Forest Fires. FAO/ECE/ILO Committee on Forest Working Techniques and Training of Forest Workers, ICONA, Madrid, pp. 130–131.

Silva, J.M., 1987b. Fogo controlado. Boletim da Sociedade de Geografia de Lisboa 103, 95–105.

Silva, J.M., 1988. La stratégie de l'utilisation du feu dans la lutte contre les incendies forestiers. Forêt Méditerranéenne 10, 194–195.

Silva, J.M., 1993. Prevenção de incêndios florestais. Sociedade e Território 19, 71–79.

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

Sneeuwjagt, R.J., 1998. Application of wildfire threat analysis in southwestern forest of western Australia. In: Viegas, D.X., (Ed.), Proceedings of the Third International Conference on Forest Fire Research and 14th Conference on Fire and Forest Meteorology, ADAI, Coimbra, pp. 2155–2176.

Sneeuwjagt, R.J., Peet, G.B., 1985. Forest Fire Behaviour Tables for Western Australia, third ed., Department of Conservation and Land Management, Perth, WA, 59 pp.

Van Wagner, C.E., 1973. Height of crown scorch in forest fires. Canadian Journal of Forest Research 3, 373–378.

Van Wagner, C.E., 1977. Conditions for the start and spread of crown fire. Canadian Journal of Forest Research 7, 23–34.

Van Wagtendonk, J.W., Bancroft, L., Ferry, G., French, D., Hance, J., Hickman, J., McCleese, W., Mutch, R., Zontek, F., Butts, D., 1982. Prescribed Fire Monitoring and Evaluation Guide. NWCG, Washington, 16 pp.

Vázquez, A., Pérez, B., Fernández-González, F., Moreno, J., 2002. Recent fire regime characteristics and potential natural vegetation relationships in Spain. Journal of Vegetation Science 13, 663–676.

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, Escuela Técnica Superior de Ingenieros de Montes, Madrid, Cap. 1.

Vega, J.A., Bara, 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., Valette, J., Rego, F., Hernando, C., Gillon, D., Ventura, J., Bara, S., Gomendy, V., Botelho, H., Guijarro, M., Houssard, C., Ruas, L., Cuiñas, P., Marechal, J., Mendes-Lopes, J., Díez, R., Fernandes, P., Fontúrbel, M., Santos, J., Rozados, M., Beloso, M., 1994. Forest fire prevention through prescribed burning: an international cooperative project carried out in the European STEP program. In: Viegas, D.X., (Ed.), Proceedings of the Second International Conference on Forest Fire Research, University of Coimbra, Coimbra, pp. 75–84.

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. Cuadernos de la Sociedade Española de Ciencias Forestales 9, 189–198.

Vélez, R., 2000. Los Incendios Forestales en la Cuenca Mediterránea, La Defensa Contra Incendios Forestales: Fundamentos y Experiencias, McGraw-Hill, Madrid, pp. 3.1–3.31.

Wade, D., Lunsford, J.D., 1989. A guide for prescribed fire in southern forests, Technical Publication R8-TP 11, USDA Forest Service, Atlanta, 56 pp.

Woodman, M., Rawson, R., 1982. Fuel reduction burning in radiata pine plantations, Fire Management Branch Research Report no. 14, Department of Conservation and Natural Resources, Victoria.

Wright, H.A., Bailey, A.W., 1982. Fire Ecology, United States and Southern Canada, Wiley, New York, 501 pp.

Wyant, J.G., Omi, P.N., Laven, R.D., 1986. Fire induced tree mortality in a Colorado ponderosa pine/Douglas-fir stand. Forest Science 32, 49–59.