CSIRO PUBLISHING

www.publish.csiro.au/journals/ijwf *International Journal of Wildland Fire*, 2003, **12**, 117–128

A review of prescribed burning effectiveness in fire hazard reduction

Paulo M. Fernandes[A,B] *and Hermínio S. Botelho*[A]

[A]Centro de Estudos de Gestão de Ecossistemas/Departamento Florestal,
Universidade de Trás-os-Montes e Alto Douro, Quinta de Prados, 5000–911 Vila Real, Portugal.
[B]Corresponding author. Telephone: +351 259 350236; fax: +351 259 350480; e-mail: pfern@utad.pt

Abstract. Wildfire hazard abatement is one of the major reasons to use prescribed burning. Computer simulation, case studies, and analysis of the fire regime in the presence of active prescribed burning programs in forest and shrubland generally indicate that this fuel management tool facilitates fire suppression efforts by reducing the intensity, size and damage of wildfires. However, the conclusions that can be drawn from the above approaches are limited, highlighting the need for more properly designed experiments addressing this question. Fuel accumulation rate frequently limits prescribed fire effectiveness to a short post-treatment period (2–4 years). Optimisation of the spatial pattern of fire application is critical but has been poorly addressed by research, and practical management guidelines are lacking to initiate this. Furthermore, adequate treatment efforts in terms of fire protection are constrained by operational, social and ecological issues. The best results of prescribed fire application are likely to be attained in heterogeneous landscapes and in climates where the likelihood of extreme weather conditions is low. Conclusive statements concerning the hazard-reduction potential of prescribed fire are not easily generalised, and will ultimately depend on the overall efficiency of the entire fire management process.

Additional keywords: fuel management; fire management; forest protection.

Introduction

Prescribed burning is the deliberate application of fire to forest fuels under specified conditions such that well-defined management goals are attained (Wade and Lunsford 1989). A wide spectrum of objectives can be accomplished by prescribed fire, including site preparation for tree regeneration, silvicultural improvements, range and wildlife habitat management, control of weeds, insects and diseases, and biodiversity maintenance (Kilgore and Curtis 1987; Wade and Lunsford 1989). It is the reduction of wildfire hazard in protecting forests, wildland resources and infrastructures at the urban interface, which ultimately affects human safety, that remains the main motivation for prescribed burning, in spite of its growing importance as an ecosystem management tool (Haines *et al.* 1998).

The rationale for hazard-reduction burning is clear-cut. Once a fire is ignited, its behaviour is determined by weather, topography and fuels, but management actions to mitigate its negative consequences are restricted to fuels. Current fire fighting technology fails when faced with multiple-fire events, and is not able to cope with wildfires burning under severe weather conditions. According to the review of Hirsch and Martell (1996), it is generally accepted that the suppression capability of ground forces has an upper fireline intensity limit of 3000–4000 kW m^{-1}, and that fire fighting actions are futile beyond 10 000 kW m^{-1}.

Fire intensity is essentially a function of rate of fire spread and the amount of available fuel for combustion (Byram 1959). Prescribed fire decreases the intensity of a subsequent wildfire primarily by reducing fuel loads, especially of the finer elements in the more aerated fuel layers that govern fire spread (Rothermel 1972), but also by disrupting the horizontal and vertical continuity of the fuel complex. Fuel modification from a prescribed-burning treatment is expected to improve directly the probability of successful fire control by reducing fire intensity. In ecosystems where high-intensity fire is not acceptable, the routine use of prescribed fire should change the wildfire regime such that it will be characterised by smaller and less severe fires from both the ecological and economic perspective.

Relationships between fuel accumulation and wildfire activity have been reported in Europe, for both the Mediterranean basin (Rego 1991) and the boreal forest (Schimmel and Granström 1997). Logical reasoning, model simulation and observation all indicate that fire exclusion from the conifer ecosystems of the western USA has led to unnatural fuel accumulations conducive to uncontrollable and highly-damaging wildfires (Van Wagtendonk 1985; Arno and Brown 1989; Keane *et al.* 1990; Brown *et al.* 1994). The so-called fuel/age paradigm (Zedler and Seiger 2000) states that previous fire history controls the spatial pattern of fires in vegetation types with a time-dependent, fuel-driven,

 10.1071/WF02042 1049-8001/03/020117

non-random fire regime. For example, fire size in California chaparral is limited by fuel age patchiness (Minnich 1983; Minnich and Chou 1997), and fuel contiguity influences the spatial distribution of fire (Chou *et al.* 1990). Natural prescribed fire programs in conifer forests of the Yellowstone (Sweaney 1985) and Yosemite (van Wagtendonk 1995) National Parks have generated fuel mosaics where previous fires act as effective containment lines. Similar patterns occur naturally in the boreal forest of Canada (Amiro *et al.* 2001).

The efficiency of prescribed fire in reducing wildfire hazard is frequently mentioned as a matter of fact, but the basic premise is seldom questioned. However, uncertainty about the protective advantages brought by prescribed burning has been identified by fire managers as an obstacle, albeit minor, to expansion of its use (Haines *et al.* 2001). The meaningful quantification of the impact of fuels on fire regimes is regarded by Schmoldt *et al.* (1999) as a major research priority. Even though fuel effects are accounted for by current fire behaviour models used in fire management applications, proper quantification of such effects has not been attempted for high-intensity fires burning under extreme weather conditions (Cheney 1996).

Fuel breaks, whose efficiency has been discussed by Agee *et al.* (2000), and prescribed fire are part of complementary strategies, aiming respectively at wildfire containment by fuel isolation and fire behaviour modification by fuel reduction (Pyne *et al.* 1996). It is the purpose of this paper to analyse, as objectively as possible, the premise that prescribed fire is a valuable tool for forest protection and wildfire mitigation, on the basis of a literature review covering different vegetation types and fire environments from North America, Australia and Europe. The economic aspects of prescribed burning have been reviewed by Hesseln (2000) and will not be addressed here.

Fuel reduction assessment at the management level

The effectiveness of prescribed burning at the management level can be determined by effective monitoring, where a systematic process of data collection is used to establish a basis to evaluate and adjust the practice (Van Wagtendonk *et al.* 1982). Evaluation by fire management agencies of the effectiveness of prescribed fire in hazard reduction generally concentrates on its effect on fuels. Burning plans usually specify how much and what categories of fuels should be removed, which requires pre- and post-burn assessments.

Several alternative methods can be used to determine pre-burn fuel quantities, including the assignment of standard (Anderson 1982) or custom (e.g. Fernandes and Pereira 1993) fuel models, photo series illustrating known fuel loads (e.g. Weise *et al.* 1997) or fuel hazard classifications (McCarthy *et al.* 1998) that are compared with the current fuel situation being monitored in the field. Indirect procedures to estimate fuel loads resort to descriptors such as vegetation height, cover and litter depth (e.g. Sneeuwjagt 1973; Armand *et al.* 1993; Finney and Martin 1993), which are frequently measured using line intercept sampling techniques (Van Wagner 1968; Brown 1974). Direct evaluation by destructive sampling methods (e.g. Brown *et al.* 1982) is seldom used by fire managers.

Fuel consumption achievement by hazard-reduction burning can be described or quantified by destructive sampling of the remaining fuel, visual estimates (usually expressed as a percentage of the pre-burn loading), specific photos series for fuel reduction (Scholl and Waldrop 1999), or measurement of post-burn variables such as charred surface percentage, depth of burn, diameter reduction of large woody fuels, and diameter of the remaining shrubs and twigs. Depth of burn, widely used in Canada (e.g. McRae *et al.* 1979), is especially relevant when the forest floor is predominant in the fuel complex. Ryan and Noste (1985) conceived a practical and broadly applicable method using flame length and char depth classes to assess prescribed fire severity that can be used to qualify forest floor consumption. Prescribed fire users in France and Portugal are simultaneously asked for quantitative and qualitative evaluations of fuel consumption during the monitoring process of the practice (Rigolot and Gaulier 2000).

Few examples exist where quantitative information on fuel reduction is translated into classifications of effectiveness, probably because of the natural variability in fuel conditions. In *Eucalyptus* woodland in the Blue Mountains of south-eastern Australia, James (1999) considers that a burn is effective when fine fuel reduction surpasses 50% of the pre-burn quantity and proposes a methodology based on visual estimates of both reduced and created fuel to verify if fuel management objectives are met. Buckley and Corkish (1991) also propose a visual method of rating fuel reduction in thinning slash of *Eucalyptus sieberi* (Table 1). More objective classifications of fuel reduction effectiveness based on post-burn fuel information are feasible and can be developed with the aid of fire behaviour simulators (see next section).

Fuel consumption by prescribed fire is weather dependent, introducing an additional element of variability into the outcomes of fuel management (Omi and Kalabokidis 1998). For example, even though the average surface fuels reduction during an experimental burning program in *Pinus pinaster*

Table 1. Classification of prescribed fire effectiveness based on visual estimates of fine fuel reduction percentages
Adapted from Buckley and Corkish (1991)

Effectiveness class	Reduction (%)		
	Litter	Slash	Shrub
Very good	>50	>75	>75
Good	25–50	>75	25–75
Fair	<25	25–75	<25
Poor	Unburned	<25	Unburned

stands was 90%, a variation of 9–100% was observed between fires (Fernandes *et al.* 2000*a*). Proper prescribed burning planning can optimise fuel reduction through the use of predictive models that use fuel moisture content and pre-burn fuel loading as inputs (e.g. McRae 1980; Sandberg 1980; Harrington 1987; Brown *et al.* 1991). However, variability in fuel consumption within a site is unavoidable and can be large (e.g. Robichaud and Miller 1999), which means the burn goal may not be achieved in some areas of the overall burn.

Fire managers should also appraise fuel reduction based on area treated, especially when aerial ignition is used to apply fire across a large landscape. According to Wade and Lunsford (1989), it is sufficient to have fuels reduced on 75–80% of a given area, while Wilson (1992) indicates a range from 50% to 90%, depending on fire protection priorities. The target for hazard reduction in Tasmanian moorland is a 70% fuel consumption over 70% of the area being treated (Marsden-Smedley *et al.* 1999).

Computer simulation of prescribed fire effectiveness

The changes induced on the fuel complex structure by a fuel treatment are measurable, and can be quantified in terms of changes in fire behaviour by computer simulation. The BEHAVE fire behaviour prediction system (Andrews 1986) based upon the spread model of Rothermel (1972) is frequently used to predict and compare fuel treatment effects on potential fire hazard, using customised fuel modelling (Burgan and Rothermel 1984) to emulate the modifications undergone by the fuel complex. Users of this approach should be aware of the subjectivity in quantifying post-burn shrub and downed woody fuels depths for the purpose of building a fuel model.

Anderson and Brown (1987) characterise fire behaviour in managed (not specifying the method of treatment) and untreated fuels of common western United States vegetation types. Their BEHAVE simulations for extreme fire weather show post-treatment reductions in fireline intensity between 80% and 96%. Similar figures in the range 80–98% were obtained for southern European pine stands after experimental prescribed fires (Rego *et al.* 1987; Vega *et al.* 1994; Fernandes *et al.* 2000*b*). When evaluating an actual prescribed fire management program, Fernandes *et al.* (1999) found an average fireline intensity reduction of 98% of the pre-treatment values, allowing wildfire suppression to be undertaken by direct attack with hand tools (Andrews and Rothermel 1982). However, the estimated decrease in fire behaviour can be as low as 10% (Omi and Kalabokidis 1998) due to insufficient impact on the fuel complex because of excessive fuel moisture. These previous results concern the immediate effects of prescribed fire. However, the effect of time since burning can be simulated by dynamic fuel models. For example, in the pine forests found on Florida's coastal plain, difficulty of wildfire control would be moderate to high 5 years after treatment (Brose and Wade 2002).

Empirical Australian models and guides for fire spread in eucalypt forest, derived from experimental fires under relatively mild weather, use a directly proportional relationship between rate of fire spread and fuel load (McArthur 1962, 1967; Sneeuwjagt and Peet 1985). Consequently, they predict that a 50% reduction in fuel load will halve the rate of spread but reduce fireline intensity fourfold.

The benefits of extending the simulations from the plot/stand scale to a landscape scale are obvious. Outputs from the BEHAVE system, combined with crown-fire initiation thresholds, indicate significant decreases in fire hazard at both the stand and landscape levels from the joint application of prescribed fire and thinning in late-successional forests of the north-western United States (Wilson and Baker 1998).

The association of GIS technology with fire behaviour models makes detailed predictions possible at the landscape level. FARSITE (Finney 1998) is a spatial fire growth model that integrates spatial (fuels and topography) and temporal (weather, fuel moisture) data, allowing analysis of the implications of fuel changes under specified ignition and weather scenarios.

Van Wagtendonk (1996) used FARSITE to examine fire behaviour modifications due to fuel-breaks and alternative management practices of surface fuels and crown fuels in the Sierra Nevada of California. Prescribed fire was the most effective technique, and under severe weather conditions reduced the average fireline intensity of a wildfire by 76% and its burned area by 37%, avoiding manifestations of severe fire behaviour. Stephens (1998) compared the effects of 12 different fuel and silvicultural treatments using FARSITE where prescribed burning alone, or in combination with thinning, was the most effective method to reduce fireline intensity.

The most complete example of FARSITE capabilities comes from Finney *et al.* (in press). Two scenarios were tested: no-treatment, and a combination of prescribed burning with tree pruning and thinning. Fire fighting effectiveness was simulated for both cases, and their fire suppression, fuel management, property damage and post-burn rehabilitation costs were estimated. According to the simulation, fuel management did slow fire growth and allowed for quicker fire containment. Estimated costs and net value change of the no-treatment option were estimated to be seven times higher.

Any fire behaviour simulation should consider the effect of prescribed fire that leads to a decrease in wildfire intensity, and consequently to easier suppression and less damage. The passive effect of prescribed burning on wildfire propagation, which assumes that the fuel complex becomes non-flammable, thus preventing fire ignition and spread, can also be explored. After formulation by Gill and Bradstock (1998), this approach has been attempted by Bradstock *et al.* (1998*a*) on a simulated landscape, relying on a simple spatial model based on percolation theory. The authors conclude that prescribed burning diminishes the average size of wildfires burning during extreme weather conditions only when the rates of wildfire occurrence are low, and stress the importance of preventing ignitions.

Observed effects of prescribed burning on wildfire behaviour, severity and suppression

Well-documented case studies concerning the fate of wildfires that run into fuel managed areas are useful to fulfil the objectives of this review. A number of examples are available and testify to both the virtues and limitations of hazard-reduction burning.

Tree damage resulting from wildfire occurrence is one of the most used descriptors of the prescribed fire effect. Reductions in tree mortality and crown scorch have been found for *Pinus ponderosa* stands that were treated by prescribed burning 1 year (Wagle and Eakle 1979), 5 years (Pollet and Omi 2002) and 6 years (Martin *et al.* 1988) before the wildfire, when compared with adjacent untreated stands. Weatherspoon and Skinner (1995) showed the importance of previous stand conditions, and indirectly, fuel management activities in the reduction of tree crown injury after extensive wildfires in California conifer forests: all stands with untreated fuels were severely damaged.

Wildfires burning under extreme drought conditions swept across 10 000 ha of the Osceola National Forest in Florida, despite the existence of a regular prescribed fire program (Outcalt and Wade 2000). Nevertheless, pine mortality in recently burned areas (up to 1.5 years) was restricted to 15% in natural stands and 5% in plantations, while it reached 44% and 52% in the same stands, respectively with a fuel age of 2 years or more.

California chaparral burned sites of 12–20 ha in size were successful in containing 11 wildfires at temperatures above 32°C, relative humidities below 20%, and wind speeds higher than 30 km h^{-1} (Franklin 1988). Regelbrugge (2000) also described how a prescribed burned area in chaparral contributed in protecting a community from wildfire in a wildland–urban interface.

The south-east of Australia provides several examples of the prescribed burning effects on wildfires. McArthur *et al.* (1966) describe how a scrub area burned 1 year before hindered a fire from entering a pine plantation. Four case studies of wildfires burning under conditions of very high fire danger in *Eucalyptus* forest and heathland show that fuel reduction burns up to 10 years old can still influence fire behaviour, even if the best results occurred within 2 years after the treatment (Grant and Wouters 1993). Five case studies are reported by Billing (1981) where property losses were avoided or fireline intensity was diminished, thus making direct fire fighting attack possible. Rawson *et al.* (1985) found evidence of wildfires stopped or slowed by previous prescribed fires, improved fire control operations due to the existence of fuel-reduced areas, effective protection of assets, and less overall demand for fire fighting resources. These benefits extended through 5 years after the treatments.

McCarthy and Tolhurst (2001) present an in-depth assessment of the effectiveness of fuel reduction burning in public land across the state of Victoria in Australia. Suppression of 11% of the wildfires occurring in 1990–1997 was positively affected by the practice, with fuel hazard level (or time since last burn) and fire danger index being critical regarding the probability of a previous prescribed burn slowing a headfire. Obvious effects in wildfire propagation were observed in areas treated no more than 2–4 years before, but the assistance to fire suppression generally ceased after 10 years. Fire spread delays for a given fuel hazard level are also increasingly less likely as fire weather becomes more severe.

Valuable assistance to fire control is attributed to prescribed fire during the less severe phases (estimated fireline intensity in the 1000–7000 kW m^{-1} range) of the extensive Dwellingup fire of 1961 in the *Eucalyptus marginata* forest of south-western Australia (Peet and Williamson 1968). During the major run of the same fire, with a fireline intensity in excess of 15 000 kW m^{-1} (Peet and Williamson 1968), the fire dramatically changed its behaviour and did not affect the tree crowns as it crossed an area that was burned 2 years before (McArthur 1962). Underwood *et al.* (1985) describe nine selected wildfires in south-western Australia whose direct attack was not possible or failed, but that were only controlled after entering areas treated up to 4 years before. Previous prescribed fires affected the outcomes of a wildfire in a *Pinus pinaster* plantation in the same region (Burrows *et al.* 2000): intensity, difficulty of control, and tree damage were higher where fuel loading was greater. McCaw *et al.* (1992) report extensive fire propagation in 5-year-old shrubland in south-western Australia under conditions of extreme fire weather that generated fire intensities estimated at 20 000–40 000 kW m^{-1}; a delay in fire spread and actual vegetation patches remaining unburned were observed in 5-year-old fuels, but not in fuels older than 8 years.

In Europe, where prescribed fire programs are more recent and localised, available information is scarce. In *Pinus pinaster* stands in Portugal, Silva (1997) describes how three wildfires were affected by burned buffer zones established in the previous winter. Fire behaviour was visibly reduced by the treatments, allowing easy containment in one of the cases. Observations by the authors in *Pinus pinaster* stands in Portugal where prescribed fire had been carried out 4 years before include a stand-replacement fire that was turned into a non-lethal surface fire, and a crown fire that went through a pole-sized stand without any noticeable reduction of intensity.

Some well-documented case studies are available for southern France. Rigolot (1997) provides six examples of wildfires in the eastern Pyrenees that ran into shrubland areas that were prescribed burned between 1 month and 7 years before; the efficiency of the treatment was variable and seemed to be affected by wind speed, size of the wildfire, and available suppression forces. Lambert *et al.* (1999) assessed the efficiency of fuel-breaks, including those maintained by periodic burning in combination with grazing or mechanical treatments. The authors reported 10–100-fold reductions in fireline intensity for a wildfire crossing a fuel-break, and indicated a fuel loading of 1 t ha^{-1} as the upper threshold where a wildfire under extreme weather conditions (including wind speeds up to 90 km h^{-1}) will not be stopped by a fuel-break in the absence of suppression.

Effects of fuel reduction on the wildfire regime

Fire regime can be defined as the nature and severity of fire occurring over long periods (Brown 2000). The available examples relate essentially to the effects of prescribed fire on the size component of the fire regime, and come from parts of the United States and Australia with extended prescribed burning programs. Wright and Bailey (1982) refer to studies by several authors indicating reductions in the area burned by wildfires in the *Pinus ponderosa* forests of the western United States as a result of prescribed burning programs. Fires occurring in fuel-reduced areas also tend to be smaller, less damaging to trees, and lower in fire suppression expenditures.

Davis and Cooper (1963) found that the number, but especially the size, of wildfires in the coastal plains of the south-eastern United States increased with time since the last hazard-reduction burn: 7% of the total forested area with fuels older than 5 years burned each year, in contrast to a figure of 0.1% where fuel accumulation time had not reached 5 years. The effect of prescribed burning within the same region has been analysed by comparing wildfire activity in treated and non-treated areas (Martin 1988, cited by Koehler 1993): 91.5% of the area burned by wildfires larger than 40 ha occurred where prescribed fire had not been used during the previous 3 years, while the average size of a wildfire was 8.5 ha in areas treated within the last 3 years and increased to 25.2 ha in untreated areas. An estimate was made that prescribed burning saved more than 4500 ha of forest and decreased fireline intensity on 2385 ha.

Koehler (1993) analysed fire statistics in a portion of central Florida from 1981 to 1990. He concluded that prescribed fire programs that have been active for a sufficient time are reflected in less and smaller wildfires on average. Data also showed minor fluctuations in wildfire acreage from year to year, suggesting that prescribed fire attenuates the behaviour of subsequent fires that might occur under severe fire weather.

Mercer *et al.* (2000) examined the relationship between wildfire activity in counties of Florida during the particularly severe year of 1998 and the number of burn permits, a surrogate for prescribed fire activity. In contradiction with the above-mentioned studies, little statistical evidence was obtained that prescribed fire reduces wildfire area. Smaller and less numerous burn operations were associated to the occurrence of larger wildfires, but the authors have considered such result not conclusive, since a lower number of prescribed fire permits may be issued in severe wildfire years. The results were even less demonstrative of a prescribed fire effect when the approach was extended to the 1995–1999 period by Prestemon *et al.* (2002), who question the adequacy of the permits to describe the amount of prescribed burning and suggest a finer spatial scale of analysis.

According to Cheney (1996), prescribed fire has been so effective in reducing the wildfire threat to some regions of Australia that local inhabitants have developed a false sense of security. More than 90% of the wildfires in south-western Australia remain below 10 ha and large fires occur only under extreme weather situations. As a consequence of the emphasis that has been put in the prescribed burning practice since the early 1960s, most large wildfires occurred where the use of prescribed fire is less substantial (Sneeuwjagt 1994). A valid counter argument is that the two first-mentioned effects can be affected by efficient fire suppression resources, since early detection and rapid initial attack are common features of the fire management strategy in western Australia (Underwood *et al.* 1985).

In the opinion of Meredith (1996), prescribed fire is more effective in south-western than in south-eastern Australia. Nevertheless, the statistics for southern New South Wales in the period 1980–1992 are also favourable (Good 1996): the average size of a wildfire burning in treated areas with less than 3 years was 302 ha, against 584 ha outside treated areas, and only 15% of the wildfires occurring on prescribed fire areas had grown to more than 50 ha.

Limitations and constraints to prescribed fire effectiveness

Weather and fuel considerations

The previously mentioned study by McCarthy and Tolhurst (2001) is expressive of the limitations that extreme fire weather and fuel re-accumulation impose on the effectiveness of a prescribed burn program. A very small percentage of the total number of all wildfires accounts for the majority of the burned area (Strauss *et al.* 1989) and those fires are driven by synoptic-scale weather patterns (Schmoldt *et al.* 1999). Jasper (1999) states that 95% of the fires that destroyed property occurred on days when the fire danger was very high or extreme. Prescribed fire impacts the behaviour and effects of large wildfires, but it is unlikely that the fuel effect will override extreme weather conditions to the extent of actually inhibiting fire spread. However, the critical importance of weather can be easily underestimated when the emphasis of management is placed on fuel modification (Bradstock *et al.* 1998*a*).

Simulations of surface fireline intensity and crown fire initiation in western Canadian subalpine forests have attributed a relatively minor role to fuel in comparison to weather (Bessie and Johnson 1995). On the contrary, simulations for boreal mixedwood forest of eastern Canada, where weather is generally more moist and vegetation variability among stands is high, show that fuels are the driving force in fire behaviour (Hély *et al.* 2001). In opposition to a well-established belief (e.g. Rothermel and Philpot 1973; Sapsis and Martin 1994), it has been shown that large chaparral fires in southern California do not depend on the availability of old fuels for their propagation (Dunn 1989; Keeley *et al.* 1999) nor are they stopped by a landscape mosaic of different fuel ages (Zedler and Seiger 2000; Keeley and Fotheringham 2001). Similarly to chaparral, most subalpine (Bessie and Johnson 1995) and boreal forests (Johnson *et al.* 2001) in Canada are closed-canopied vegetation types characterised by a fire regime of large and inevitable stand-replacing crown fires induced by the vertical and horizontal fuel continuity and triggered by dry periods.

The previous paragraph leads to the conclusion that the fuel/age paradigm is a simplification, and that the hazard-reduction effectiveness of prescription burning will vary by ecosystem (or fuel type) and according to the relative impacts of fuels and weather on fire behaviour. Because fire behaviour increases in a non-linear fashion with the decrease of fuel moisture and the increase of wind speed, which additionally vary in a much wider range than fuel properties, the influence of these factors on fire behaviour will increasingly prevail over the effect of fuel characteristics in more severe weather scenarios. Prescribed burning will be less effective in regions that have higher likelihood of experiencing strong winds during drought periods, because such combination is conducive to extreme fire events in intensity and extension (Schmoldt *et al.* 1999).

Longevity of the prescribed fire effect is conditioned by the intrinsic nature of vegetation, sooner or later, regaining its former fuel loading and structure. Fuel dynamics knowledge is used to define the prescribed fire return interval and the burning effort required to reach a management objective (e.g. to maintain fuel loads below a given hazard threshold). However, post-treatment recovery can be so fast that fuel management may be futile or even counter-productive in some vegetation types (e.g. Fensham 1992). Fuel dynamics can be exacerbated by a number of factors, namely the amount of remaining fuel and newly created fuel (i.e. conversion of live vegetation to dead fuel, post-burn litter fall), changes in vegetation composition such that it becomes more flammable (e.g. invasion by grass or weed species), and post-burn reduction of the decomposition rate.

Litter hazard is commonly re-established within 2–5 years after prescribed fire (Sackett 1975; Van Wagtendonk and Sydoriak 1987; Fensham 1992). Nevertheless, the overall benefits of prescribed burning, namely in avoiding crown fire or substantially reducing the potential for its occurrence, should persist for longer periods, since the understory vegetation layer build-ups at a lower rate. Reduction in the amount of fibrous loose bark is important in some *Eucalyptus* species to preclude the development of crown fires and reduce airborne firebrands lofted ahead of the fire front (McArthur 1967); the effects of prescribed fire on this fuel component can be of long duration (Tolhurst *et al.* 1992).

Fireline intensity will undoubtedly be decreased by prescribed burning compared to a no-treatment scenario so long as fuel loads remain below the pre-treatment values. However, early claims that rate of spread increases with fuel load (e.g. McArthur 1962), are not supported by more recent studies (Gould 1991; Cheney *et al.* 1993; McAlpine 1995; Burrows 1999), which points to a short-lived effect of prescribed burning on this fire parameter, probably disappearing as soon as the fuel complex regains its pre-burn structure. Experimental studies (Cheney *et al.* 1998) designed to clarify the effect of time since last fire and fuel loading on fire behaviour under an extended range of burning conditions are being undertaken in dry eucalypt forest in south-western Australia.

Spatial considerations

The size, shape and spatial arrangement of the treatment units, including their location in relation to fuel breaks (Agee *et al.* 2000), can strongly affect the efficiency of the prescribed fire treatment at the landscape scale. The hazard reduction effect brought by discrete fuel treatments to specific stands may be too small and/or too fragmented to have any impact on large fires (Omi and Kalabokidis 1998).

The spatial pattern of hazard reduction burning can be quite varied, comprising treatments dispersed in the landscape, extensive application to large areas, or strategic and more intensive use in order to link or expand discontinuities such as fuel breaks and non-flammable areas. In the western United States (Finney 2002) and in Canada (McRae and Flannigan 1990), prescribed fire is commonly applied in units of 100s to 1000s of hectares. Maximum size of the burn units can reach 8000 ha in Australian eucalypt forest (Grant and Wouters 1993), 300 ha in southern France shrubland (Rigolot 1997), or 30 ha in pine stands of Portugal (Fernandes *et al.* 1999).

The hazard-reduction advantages of large-scale prescribed burning are not proven and some authors are of the opinion that burning in strategic small areas creates more effective barriers because the percentage of area burned is higher and the amount of residual fuel is lower (Grant and Wouters 1993; Rawson *et al.* 1985). For vegetation types dominated by crown-fire regimes, Keeley (2002) suggests intensively managed buffer zones (including prescribed burned areas) in strategic locations, especially in the wildland–urban interface. However, in fuel types prone to long-distance spotting, the benefits of prescribed fire on a broad area basis are apparent: sufficiently large treatment units will provide landing spots for most firebrands, reducing their ignition potential and the likelihood of developing into intense fire fronts, as well as reducing production and lofting of firebrands when the main fire front actually propagates in the treated area. Simulations with FARSITE suggest that disperse and small treated areas are preferable to network-type treatments, because shorter distances will result between individual fuel-reduced areas thus limiting wildfire growth more effectively (Finney *et al.* 1997). According to Loureiro *et al.* (2000), maximum landscape fragmentation (a surrogate for fuel discontinuity) is achieved by a compromise between the number and the size of prescribed fire units.

Selection of treatment areas currently relies on combined functions of several factors, such as values at risk, ignition potential, suppression capability and fire behaviour potential (Sneeuwjagt 1998). Other constraints are listed in the next section. According to Finney (2001), such approaches will likely originate arbitrary or random spatial patterns with a poor influence on wildfire growth. Based on fire shape and relative fire spread in treated and untreated areas, Finney (2001) gives a set of equations to optimise the width and length of a rectangular treatment unit such that it maximises the delay in the propagation of a wildfire. After extending the same reasoning to a landscape level, the author concludes that feasible and effective spatial arrangements of prescribed burning should result in treatment units that partially overlap in the direction of fire spread. A promising automated method to optimise fuel treatment patterns in real landscapes is under development (Finney 2002).

Operational, social and ecological constraints

Prescribed burning programs are strongly constrained by a number of factors, including inadequate funding. Bradstock *et al.* (1998*b*) mentions other constraints such as suitable weather for burning, and favourable landscape in terms of topography and vegetation continuity. Meredith (1996) stresses the importance of environmental heterogeneity and gives the example of western versus eastern Australia: drier and more predictable weather, milder topography, and relatively uniform forests in south-western Australia allow larger, safer, and more effective burns that can be conducted more times per year. Liability risks and the necessity to comply with environmental protection, smoke management and air quality regulations are nowadays an important restriction to prescribed fire activity in both the United States (Haines *et al.* 1998, 2001) and Australia (Underwood and Sneeuwjagt 1993).

The opportunities to carry out prescribed burning operations are greatly reduced by the above-mentioned restrictions, and thus can compromise hazard minimisation in fire-prone regions. For example, in the urban–wildland interface of Sydney, Australia, 27% of the area would require annual treatment if probability levels of uncontrollable fire were to be reduced to 10 days per year (Bradstock *et al.* 1998*b*). The number of available days for burning is quite variable from year to year (e.g. Gill *et al.* 1987); it can be increased by broadening the prescription to hotter and drier conditions, but several problems may arise, including higher probabilities of escaped fires and property damage. According to a survey conducted in western United States, weather is by far (39% of the respondents) the most important reason for cancelling prescribed fires, followed by smoke management and air pollution concerns (18%) (Barrett *et al.* 2000).

Prescribed fire planning often gives ecological considerations a secondary role, and the consequence is that fire managers can assume a successful fuel reduction operation as a burn that fulfills ecosystem management goals (Bennett and Kunzmann 1992). Conflicts between hazard-reduction burning and conservation values should be negligible in ecosystems with a recurrent history of low-intensity surface fires (e.g. Haase and Sackett 1998; Sackett and Haase 1998; Ward 1998; Barnett 1999), but not where a natural fire regime characterised by high-intensity fire is replaced by more frequent, smaller and less severe fires (Whelan and Muston 1991). Given the absence or scarcity of results from long-term studies on the ecological effects of prescribed fire regimes, methodologies based on biological indicators have been proposed to reconcile protection and conservation objectives (Gill and Bradstock 1994; Burrows and Friend 1998; Gill and McCarthy 1998), but such compromise is not always possible (e.g. Morrison *et al.* 1996; Bradstock *et al.* 1998*c*).

Conclusion

The hazard reduction benefits of prescribed fire are easily demonstrated by fire behaviour theory, through observation and measurement of post-treatment fuel changes in experimental or operational burns, and by computer simulation at the plot, stand, and landscape levels. Despite their limitations, the existing fire behaviour models, linked with fire effects and fuel dynamics models, provide a useful framework to predict and evaluate the outcomes of fuel management strategies, select alternative treatment methods, and plan the fuel treatments in time and space.

The operational effectiveness of prescribed fire inferred from case studies is largely anecdotal, and most of the examples of success that are available refer to recently (up to 4 years) treated areas. A wildfire is an unplanned event, which implies uncertainties regarding fuel characteristics, weather and fire behaviour, as well as the existence of interactive effects. Analysis of hazard reduction effectiveness based on well-documented case studies of wildfire behaviour, severity and suppression difficulty as modified by burned areas is thus limited in the conclusions that can be drawn. This stresses the need for replicated studies of high-intensity fire behaviour in field experiments.

Analysis of modifications in the fire regime induced by prescribed burning are currently the best way to evaluate the practice, even if they do not allow direct statistical confirmation. Positive changes brought by long-term prescribed fire programs are undeniable, but it is quite difficult, if not impossible, to isolate the protective effect of the treatment from the whole fire management process.

The amount of land that can be subjected to prescribed fire is greatly restricted by several operational and ecological issues, thus making a fire management approach difficult based solely or predominantly on prescribed burning. The higher incidences of unwanted ignitions are associated with areas where human pressure and residential development are also high, posing additional social constraints and operational difficulties on the use of fire. Nevertheless, rather than burning as much as possible, it is more important to carefully select the treatment locations. Simulations of fire growth or percolation in landscapes containing different fuel treatment configurations in terms of size, shape and spatial arrangement can give valuable insights into the delineation of more effective prescribed burning programs. Sound, well-established methods to design the spatial patterns of treatment application are still missing, and optimisation of the spatial arrangement of prescribed fire clearly requires further research.

Quantification of the influence of prescribed fire on large wildfires remains elusive, but the existing evidence supports the conclusion that recently treated areas do limit the spread of a fire and will result in a less homogeneous post-burn landscape. It is clear that prescribed fire moderates wildfire severity and can benefit wildfire control operations in various ways, by increasing the safety of the personnel involved in suppression, decreasing the quantity and type of fire fighting resources (e.g. ground crews instead of aircraft), changing the overall suppression strategy (e.g. direct attack instead of indirect attack), reducing the risk inherent to the burning-out operations that are used in indirect attack, lessening the amount of mopping-up, or simply providing better access and anchor points for suppression actions.

The best results of prescribed fire application (and indeed of other fuel management options) are likely to be achieved in regions less prone to experiencing extreme weather conditions, and where wildfire propagation is *a priori* constrained by landscape and land use diversity, and by natural or artificial obstacles. The spatial pattern of fuel treatment is also less critical in those situations. Since prescribed burning reduces but does not eliminate the threat posed by wildfires, mitigation of their undesired effects should rely on an integrated approach that combines prevention of human-caused fires, efficient fire detection and suppression, and adequate stand and fuel management practices.

Acknowledgements

This paper evolved from a deliverable of the research project FIRE TORCH Prescribed Burning as a Tool for the Mediterranean Region: a Management Approach (ENV4-CT98–0715), funded by the DG XII of the European Commission, in the framework of the Environment and Climate Program. The authors acknowledge the comments and suggestions made by two anonymous reviewers. Lachie McCaw (Western Australia Department of Conservation and Land Management) reviewed an early version of the paper and supplied additional literature.

References

Agee JK, Bahro B, Finney MA, Omi PN, Sapsis DB, Skinner CN, Van Wagtendonk JW, Weatherspoon CP (2000) The use of shaded fuelbreaks in landscape fire management. *Forest Ecology and Management* **127**, 55–66.

Amiro BD, Stocks BJ, Alexander ME, Flannigan MD, Wotton BM (2001) Fire, climate change, carbon and fuel management in the Canadian boreal forest. *International Journal of Wildland Fire* **10**, 405–413.

Anderson HE (1982) Aids to determining fuel models for estimating fire behaviour. USDA Forest Service, Intermountain Forest and Range Experiment Station General Technical Report INT–122. Ogden, UT. 22 pp.

Anderson HE, Brown JK (1987) Fuel characteristics and fire behavior considerations in the wildlands. In 'Symposium and workshop on protecting people and homes from wildfire in the Interior West'. pp. 124–130. USDA Forest Service, Intermountain Forest and Range Experiment Station General Technical Report INT-GTR–251. Ogden UT.

Andrews PL (1986) BEHAVE: fire behavior prediction and fuel modeling system–BURN subsystem, Part I. USDA Forest Service, Intermountain Research Station General Technical Report INT–194. Ogden, UT. 130 pp.

Andrews PL, Rothermel RC (1982) Charts for interpreting wildland fire behavior characteristics. USDA Forest Service, Intermountain Forest and Range Experiment Station General Technical Report INT–131. Ogden, UT. 21 pp.

Armand D, Etienne M, Legrand C, Marechal J, Valette JC (1993) Phytovolume, phytomass et relations structurales chez quelques arbustes méditerranéens. *Annales Sciences Forestières* **50**, 79–89.

Arno SF, Brown JK (1989) Managing fire in our forests–time for a new initiative. *Journal of Forestry* **87**, 44–46.

Barnett JP (1999) Longleaf pine ecosystem restoration: the role of fire. *Journal of Sustainable Forestry* **9**, 89–96.

Barrett TM, Jones JG, Wakimoto RH (2000) Forest Service spatial information use for planning prescribed fires. *Western Journal of Applied Forestry* **15**, 200–207.

Bennett PS, Kunzmann MR (1992) The applicability of generalized fire prescriptions to burning of Madrean evergreen forest and woodland. *Journal of the Arizona–Nevada Academy of Science* **24–25**, 79–84.

Bessie WC, Johnson EA (1995) The relative importance of fuels and weather on fire behavior in subalpine forests. *Ecology* **76**, 747–762.

Billing P (1981) The effectiveness of fuel-reduction burning: five case histories. Department of Conservation and Environment, Fire Management Branch, Research Report No. 10, Victoria.

Bradstock RA, Bedward M, Cohn JS (1998*a*) Weather, ignition and fuel as determinants of fire regimes: investigation of limits to management using a simple, spatial modelling approach. In 'Proceedings of the 3rd international conference on forest fire research & 14th conference on fire and forest meteorology'. (Ed. DX Viegas) pp. 2365–2378. (ADAI: Coimbra)

Bradstock RA, Gill AM, Kenny BJ, Scott J (1998*b*) 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.

Bradstock RA, Bedward M, Kenny BJ, Scott J (1998*c*) Spatially-explicit simulation of the effect of prescribed burning on fire regimes and plant extinctions in shrublands typical of south-eastern Australia. *Biological Conservation* **86**, 83–95.

Brose P, Wade D (2002) Potential fire behavior in pine flatwood forests following three different fuel reduction techniques. *Forest Ecology and Management* **163**, 71–84.
Brown JK (1974) Handbook for inventorying downed woody material. USDA Forest Service, Intermountain Forest and Range Experiment Station General Technical Report INT–16. Ogden, UT. 24 pp.
Brown JK (2000) Introduction and fire regimes. In 'Wildland fire in ecosystems, effects of fire on flora'. (Eds JK Brown and JK Smith) pp. 1–7. USDA Forest Service General Technical Report RMRS-GTR–42-Vol. 2. Ogden, UT.
Brown JK, Arno SF, Barrett SW, Menakis JP (1994) Comparing the prescribed natural fire program with presettlement fires in the Selway-Bitterroot wilderness. *International Journal of Wildland Fire* **4**, 157–168.
Brown JK, Oberheu RD, Johnston CM (1982) Handbook for inventorying surface fuels and biomass in the interior west. USDA Forest Service General Technical Report INT–129. Ogden, UT.
Brown JK, Reinhardt ED, Fischer WC (1991) Predicting duff and woody fuel consumption in northern Idaho prescribed fires. *Forest Science* **37**, 1550–1566.
Buckley AJ, Corkish NJ (1991) Fire hazard and prescribed burning of thinning slash in eucalypt regrowth forest. Department of Conservation and Environment, Fire Management Branch, Research Report No. 29, Victoria.
Burgan R, Rothermel R (1984) BEHAVE: fire behavior prediction and fuel modeling system–FUEL subsystem. USDA Forest Service General Technical Report INT–167. Ogden, UT.
Burrows ND (1999) Fire behaviour in jarrah forest fuels: 2. Field experiments. *CALMScience* **3**, 57–84.
Burrows ND, Friend G (1998) Biological indicators of appropriate fire regimes in southwest Australian ecosystems. In 'Fire in ecosystem management: shifting the paradigm from suppression to prescription'. Tall Timbers Fire Ecology Conference Proceedings No. 20. (Eds TL Pruden and LA Brennan) pp. 413–421. (Tall Timbers Research Station: Tallahassee)
Burrows ND, Ward B, Robinson AD (2000) Behaviour and some impacts of a large wildfire in the Gnangara maritime pine (*Pinus pinaster*) plantation, Western Australia. *CALMScience* **3**, 251–260.
Byram GM (1959) Combustion of forest fuels. In 'Forest fire control and use'. (Ed. KP Davis) pp. 61–89 (McGraw-Hill: New York)
Cheney P (1996) The effectiveness of fuel reduction burning for fire management. In 'Fire and biodiversity: the effects and effectiveness of fire management'. Paper No. 8, pp. 7–16 (Department of the Environment, Sport and Territories: Canberra)
Cheney NP, Gould JS, Catchpole WR (1993) The influence of fuel, weather and fire shape variables on fire-spread in grasslands. *International Journal of Wildland Fire* **3**, 31–44.
Cheney NP, Gould JS, McCaw L (1998) Project Vesta: research initiative into the effects of fuel structure and fuel load on behaviour of wildfires in dry eucalypt forest. In 'Proceedings of the 13th fire and forest meteorology conference'. pp. 375–378 (International Association of Wildland Fire)
Chou Y, Minnich R, Salazar L, Power J, Dezzani R (1990) Spatial autocorrelation of wildfire distribution in the Idyllwild Quadrangle, San Jacinto Mountain, California. *Photogrammetric Engineering and Remote Sensing* **56**, 1507–1513.
Davis LS, Cooper RW (1963) How prescribed fire affects wildfire occurrence. *Journal of Forestry* **61**, 915–917.
Dunn AT (1989) The effects of prescribed burning on fire hazard in the chaparral: toward a new conceptual synthesis. In 'Proceedings of the symposium on fire and watershed management'. pp. 23–29. USDA Forest Service General Technical Report PSW–109.
Fensham RJ (1992) The management implications of fine fuel dynamics in bushlands surrounding Hobart, Tasmania. *Journal of Environmental Management* **36**, 301–320.
Fernandes P, Botelho H, Bento J (1999) Prescribed fire to reduce wildfire hazard: an analysis of management burns in Portuguese pine stands. In 'Proceedings of the DELFI international symposium on forest fires: needs and innovations'. pp. 360–364 (CINAR: Athens)
Fernandes P, Botelho H, Loureiro C (2000*a*) 'Modelling the links between environmental conditions, fire behaviour and fire effects important for prescribed burning operational purposes.' Fire Torch Project Contract No. ENV4-CT98–0715, Deliverable F1.
Fernandes P, Botelho H, Loureiro C (2000*b*) Fire hazard implications of alternative fuel management techniques—case studies from northern Portugal. In 'Proceedings from the joint fire science conference and workshop'. (Eds LF Neuenschwander and KC Ryan). Vol. II, pp. 268–270 (University of Idaho: Moscow, ID)
Fernandes PM, Pereira JP (1993) Caracterização de combustíveis na serra da Arrábida. *Silva Lusitana* **1**, 237–260.
Finney MA (1998) FARSITE: Fire Area Simulator—model development and evaluation. USDA Forest Service Research Paper RMRS-RP-4. Ogden, UT.
Finney MA (2001) Design of regular landscape fuel treatment patterns for modifying fire growth and behaviour. *Forest Science* **47**, 219–228.
Finney MA (2002) Use of graph theory and a genetic algorithm for finding optimal fuel treatment locations. In 'Forest fire research and wildland fire safety'. (Ed. DX Viegas). (Millpress: Rotherdam)
Finney MA, Martin RE (1993) Fuel loading, bulk density and depth of forest floor in coast redwood stands. *Forest Science* **39**, 617–622.
Finney MA, Sapsis DB, Bahro B (in press) Use of FARSITE for simulating fire suppression and analyzing fuel treatment economics. In 'Proceedings of the symposium on fire in California ecosystems: integrating ecology, prevention, and management'.
Franklin SE (1988) LACFD weeds out dangerous fuels with vegetation management program. *American Fire Journal*, January, 24–25.
Gill AM, Bradstock RA (1994) The prescribed burning debate in temperate Australian forests: towards a resolution. In 'Proceedings of the 2nd international conference on forest fire research'. (Ed. DX Viegas) pp. 703–712 (ADAI: Coimbra)
Gill AM, Bradstock RA (1998) Prescribed burning: patterns and strategies. In 'Proceedings of the 13th fire and forest meteorology conference'. pp. 3–6 (International Association of Wildland Fire)
Gill AM, Christian KR, Moore PH (1987) Bushfire incidence, fire hazard and fuel reduction burning. *Australian Journal of Ecology* **12**, 299–306.
Gill AM, McCarthy MA (1998) Intervals between prescribed fires in Australia: what intrinsic variation should apply? *Biological Conservation* **85**, 161–169.
Good RB (1996) Fuel dynamics, PrePlan and future research needs. In 'Fire and biodiversity: the effects and effectiveness of fire management'. Paper No. 8, pp. 7–16. (Department of the Environment, Sport and Territories: Canberra)
Gould JS (1991) Validation of the Rothermel fire spread model and related fuel parameters in grassland fuels. In 'Proceedings of the conference on bushfire modelling and fire danger rating systems'. (Eds NP Cheney and AM Gill) pp. 51–64. (CSIRO: Canberra)
Grant SR, Wouters MA (1993) The effect of fuel reduction burning on the suppression of four wildfires in Western Victoria. Department of Conservation and Environment, Fire Management Branch, Research Report No. 41, Victoria.
Haase SM, Sackett SM (1998) Effects of prescribed fire in giant sequoia–mixed conifer stands in Sequoia and Kings Canyon National Parks. In 'Fire in ecosystem management: shifting the paradigm from suppression to prescription. Tall Timbers fire ecology conference

proceedings No. 20'. (Eds TL Pruden and LA Brennan) pp. 236–243. (Tall Timbers Research Station: Tallahassee)

Haines TK, Martinez J, Cleaves DA (1998) Influences on prescribed burning activity in the United States national forest system. *International Forest Fire News* **19**, 43–46.

Haines TK, Busby RL, Cleaves DA (2001) Prescribed burning in the South: trends, purpose, and barriers. *Southern Journal of Applied Forestry* **25**, 149–153.

Harrington MG (1987) 'Predicting reduction of natural fuels by prescribed burning under ponderosa pine in southeastern Arizona.' USDA Forest Service Research Note RM–472. Fort Collins, CO.

Hély C, Flannigan M, Bergeron Y, McRae D (2001) Role of vegetation and weather on fire behavior in the Canadian mixedwood boreal forest using two fire behavior prediction systems. *Canadian Journal of Forest Research* **31**, 430–441.

Hesseln H (2000) The economics of prescribed burning: a research review. *Forest Science* **46**, 322–334.

Hirsch KG, Martell DL (1996) A review of initial attack fire crew productivity and effectiveness. *International Journal of Wildland Fire* **6**, 199–215.

James SG (1999) Evaluation of the effectiveness of prescribed burning: a simple methodology for post-burn assessment of the achievement of fire management objectives. In 'Proceedings of the Australian Bushfire Conference'. (Eds I. Lunt and D.G. Green) [http://life.csu.edu.au/bushfire99/papers]

Jasper RG (1999) The changing direction of land managers in reducing the threat from major bushfires on the urban interface of Sydney. In 'Proceedings of the Australian Bushfire Conference'. (Eds I. Lunt and D.G. Green) [http://life.csu.edu.au/bushfire99/papers]

Johnson EA, Miyanishi H, Bridge SR (2001) Wildfire regime in the boreal forest and the idea of suppression and fuel buildup. *Conservation Biology* **15**, 1554–1557.

Keane RE, Arno SF, Brown JK (1990) Simulating cumulative fire effects in ponderosa pine/Douglas-fir forests. *Ecology* **71**, 189–203.

Keeley JE (2002) Fire management of California shrubland landscapes. *Environmental Management* **29**, 395–408.

Keeley JE, Fotheringham CJ (2001) Historic fire regime in Southern California shrublands. *Conservation Biology* **15**, 1536–1548.

Keeley JE, Fotheringham CJ, Morais M (1999) Reexamining fire suppression impacts on brushland fire regimes. *Science* **284**, 1829–1832.

Kilgore BM, Curtis GA (1987) Guide to understory burning in ponderosa pine–larch–fir forests in the Intermountain West. USDA Forest Service General Technical Report INT–233. Ogden, UT.

Koehler JT (1993) Prescribed burning: a wildfire prevention tool? *Fire Management Notes* **53–54**, 9–13.

Lambert B, Casteignau D, Costa M, Étienne M, Guiton J., Rigolot E (1999) 'Analyse aprés incendie de six coupures de combustible.' (Editions Cardère: Montfavet)

Loureiro C, Fernandes P, Rego F, Botelho H (2000) Optimização do fogo controlado na diminuição do potencial de propagação de incêndios à escala da paisagem. In 'Actas do congresso ibérico de fogos florestais'. pp. 167–176 (ESAC: Castelo Branco)

Marsden-Smedley JB, Rudman T, Pyrke A, Catchpole WR (1999) Buttongrass moorland fire-behaviour prediction and management. *Tasforests* **11**, 87–107.

Martin RE, Landsberg JD, Kauffman JB (1988) Effectiveness of prescribed burning as a fire prevention measure. In 'Proceedings of the international workshop on prescribed burning'. pp. 31–44 (INRA: Avignon)

McAlpine RS (1995) Testing the effect of fuel consumption on fire spread rate. *International Journal of Wildland Fire* **5**, 134–152.

McArthur AG (1962) 'Control burning in eucalypt forest.' Australian Forestry and Timber Bureau, Leaflet No. 80, Canberra.

McArthur AG (1967) 'Fire behaviour in eucalypt forest.' Australian Forestry and Timber Bureau, Leaflet No. 107, Canberra.

McArthur AG, Douglas DR, Mitchell LR (1966) 'The Wandiloo fire, 5 April 1958: fire behaviour and associated meteorological and fuel conditions.' Forest and Timber Bureau, Forest Research Institute, Leaflet No. 98, Canberra.

McCarthy GJ, Tolhurst KG (2001) 'Effectiveness of broadscale fuel reduction burning in assisting with wildfire control in parks and forests in Victoria.' Natural Resources and Environment, Fire Management Research Report No. 51, Victoria.

McCarthy GJ, Tolhurst KG, Chatto K (1998) 'Overall fuel hazard guide.' Department of Conservation and Environment, Fire Management Branch Research Report No. 47, Victoria.

McCaw L, Maher T, Gillen K (1992) 'Wildfires in the Fitzgerald River National Park, Western Australia, December 1989.' Western Australia Department of Conservation and Land Management, Technical Report No. 26, Perth.

McRae DJ (1980) 'Preliminary fuel consumption guidelines for prescribed burning in Ontario slash fuel complexes.' Department of the Environment, Canadian Forest Service, Report O-X–316, Sault Ste. Marie.

McRae DJ, Alexander ME, Stocks BJ (1979) 'Measurement and description of fuels and fire behavior on prescribed burns: a handbook.' Department of the Environment, Canadian Forest Service, Report O-X–287, Sault Ste. Marie.

McRae DJ, Flannigan MD (1990) Development of large vortices on prescribed fires. *Canadian Journal of Forest Research* **20**, 1878–1887.

Mercer DE, Pye JM, Prestemon JP, Butry DT, Holmes TP (2000) Economic effects of catastrophic wildfires: assessing the effectiveness of fuel reduction programs for reducing the economic impacts of catastrophic forest fire events. Southern Research Station., Research Triangle Park, Final Report Topic 8 of the Research Grant Ecological and Economical Consequences of the 1998 Florida wildfires, Joint Fire Science Program, SRS4851.

Meredith CW (1996) Is fire management effective? In 'Fire and Biodiversity: the effects and effectiveness of fire management'. Paper No. 8, pp. 227–231. (Department of the Environment, Sport and Territories: Canberra)

Minnich RA (1983) Fire mosaics in southern California and northern Baja California. *Science* **219**, 1287–1294.

Minnich RA, Chou YH (1997) Wildland fire patch dynamics in the chaparral of southern California and northern Baja California. *International Journal of Wildland Fire* **7**, 221–248.

Morrison DA, Buckney RT, Bewick BJ (1996) Conservation conflicts over burning bush in south-eastern Australia. *Biological Conservation* **76**, 167–175.

Omi PN, Kalabokidis KD (1998) Fuels modification to reduce large fire probability In 'Proceedings of the 3rd international conference on forest fire research & 14th conference on fire and forest meteorology'. (Ed. DX Viegas) pp. 2073–2088. (ADAI: Coimbra)

Outcalt KW, Wade DD (2000) The value of fuel management in reducing wildfire damage. In 'Crossing the millenium: integrating spatial technologies and ecological principles for a new age in fire management'. pp. 271–275 (University of Idaho/IAWF: Moscow, ID)

Peet GB, Williamson AJ (1968) An assessment of forest damage from the Dwellingup fires in Western Australia. In '5th conference of the institute of foresters of Australia' (Perth)

Pollet J, Omi PL (2002) Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. *International Journal of Wildland Fire* **11**, 1–10.

Prestemon JP, Pye JM, Butry DT, Holmes TP, Mercer DE (2002) Understanding broadscale wildfire risks in a human-dominated landscape. *Forest Science* **48**, 685–693.

Pyne SJ, Andrews PL, Laven RD (1996) 'Introduction to wildland fire (2nd edn).' (John Wiley and Sons: New York)

Rawson R, Billing P, Rees B (1985) Effectiveness of fuel-reduction burning. Department of Conservation and Environment, Fire Management Branch, Research Report No. 25, Victoria.

Regelbrugge JC (2000) Role of prescribed burning in the management of chaparral ecosystems in southern California. In '2nd interface between ecology and land development in California'. (Eds JE Keeley, M Baer-Keeley, and CJ Fotheringham) pp. 19–26. U.S. Geological Survey Open-File Report 00–62.

Rego FC (1991) Fuel management. In 'ECE/FAO/ILO seminar on forest fire prevention, land use and people'. pp. 209–221. (Ministry of Agriculture: Athens, Greece)

Rego FC, Silva JM, Botelho H (1987) Prescribed burning in the reduction of wildfire hazard in Northern Portugal. In 'Proceedings of the world congress on wildfire prevention'. (Athens)

Rigolot E (1997) 'Etude sur la caractérisation des effects causés aux écosystèmes forestières méditerranéens par les brulages dirigés et répétés, exercice 1996, Rapport final.' Ministère de l'Environment, Direction de la prévention et des risques, sous-direction de la prévention des risques majeurs.

Rigolot E, Gaulier A (2000) 'Prescribed burning field forms.' Fire Torch Project Contract No. ENV4-CT98–0715, Deliverable B1.

Robichaud PR, Miller SM (1999) Spatial interpolation and simulation of post-burn duff thickness after prescribed fire. *International Journal of Wildland Fire* **9**, 137–143.

Rothermel RC (1972) A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service, Intermountain Forest and Range Experiment Station Research Paper INT–115. Ogden, UT. 40 pp.

Rothermel RC, Philpot CW (1973) Predicting changes in chaparral flammability. *Journal of Forestry* **71**, 640–643.

Ryan KC, Noste NV (1985) Evaluating prescribed fires. In 'Proceedings of the symposium and workshop on wilderness fire'. pp. 230–238. USDA Forest Service General Technical Report INT–182. Ogden, UT.

Sackett SS (1975) Scheduling prescribed burns for hazard reduction in the southeast. *Journal of Forestry* **73**, 143–147.

Sackett SS, Haase SM (1998) Two case histories for using prescribed fire to restore ponderosa pine ecosystems in northern Arizona. In 'Fire in ecosystem management: shifting the paradigm from suppression to prescription'. Tall Timbers Fire Ecology Conference Proceedings No. 20. (Eds TL Pruden and LA Brennan) pp. 380–389 (Tall Timbers Research Station: Tallahassee)

Sandberg D (1980) Duff reduction by prescribed underburning in Douglas-fir. USDA Forest Service Research Paper PNW–272. Portland, OR.

Sapsis DB, Martin RE (1994) Fire, the landscape, and diversity: a theoretical framework for managing wildlands. In 'Proceedings of the 12th conference on fire and forest meteorology'. pp. 270–278 (Society of American Foresters)

Schimmel J, Granström A (1997) Fuel succession and fire behaviour in the Swedish boreal forest. *Canadian Journal of Forest Research* **27**, 1207–1216.

Schmoldt DL, Peterson DL, Keane RE, Lenihan JM, McKenzie D, Weise DR, Sandberg DV (1999) Assessing the effects of fire disturbance on ecosystems: a scientific agenda for research and management. USDA Forest Service General Technical Report PNW-GTR–455. Portland, OR.

Scholl ER, Waldrop TA (1999) Photos for estimating fuel loadings before and after prescribed burning in the upper coastal plain of the southeast. USDA Forest Service General Technical Report SRS–26. Asheville, NC.

Silva JM (1997) Historique des feux contrôlés au Portugal. *Forêt Méditerranéenne* **18**, 299–310.

Sneeuwjagt R (1973) 'Measuring forest fuels.' Research Paper No. 9. (Forests Department of Western Australia: Perth)

Sneeuwjagt R (1994) Fighting fire with fire. *Landscope* **9**, 23–27.

Sneeuwjagt R (1998) Application of wildfire threat analysis in south-western forest of western Australia. In 'Proceedings of the 3rd international conference on forest fire research & 14th conference on fire and forest meteorology'. (Ed. DX Viegas) pp. 2155–2176. (ADAI: Coimbra)

Sneeuwjagt RJ, Peet GB (1985) 'Forest fire behaviour tables for Western Australia (3rd edn)' (Department of Conservation and Land Management: Perth)

Stephens SL (1998) Evaluation of the effects of silvicultural and fuels treatments on potential fire behaviour in Sierra Nevada mixed-conifer forests. *Forest Ecology and Management* **105**, 21–35.

Strauss D, Bednar L, Mees R (1989) Do one percent of forest fires cause ninety-nine percent of the damage? *Forest Science* **35**, 319–328.

Sweaney JN (1985) Old burns limit size of fires. In 'Proceedings of the symposium and workshop on wilderness fire'. USDA Forest Service General Technical Report INT–182, p. 389. Ogden, UT.

Tolhurst KG, Flinn DW, Loyn RH, Wilson AG, Foletta I (1992) Ecological effects of fuel reduction burning in a dry sclerophyll forest. Forest Research Centre, Department of Conservation and Environment. Melbourne.

Underwood RJ, Sneeuwjagt RJ (1993) Where there's fire, there's smoke. *Landscope* **8**, 10–16.

Underwood RJ, Sneeuwjagt RJ, Styles HG (1985) The contribution of prescribed burning to forest fire control in western Australia: case studies. In 'Fire ecology and management in western Australian ecosystems'. (Ed. JR Ford) pp. 153–170. WAIT Environmental Studies Group Report No. 14.

Van Wagner CE (1968) The line intersect method in forest fuel sampling. *Forest Science* **14**, 20–26.

Van Wagtendonk JW (1985) Fire suppression effects on fuels and succession in short-fire-interval wilderness ecosystems. In 'Proceedings–symposium and workshop on wilderness fire'. pp. 119–126. USDA Forest Service General Technical Report INT–182. Ogden, UT.

Van Wagtendonk JW (1995) Large fires in wilderness areas. In 'Proceedings of a symposium on fire in wilderness and park management'. pp. 113–116. USDA Forest Service General Technical Report INT–182. Ogden, UT.

Van Wagtendonk JW (1996) Use of a deterministic fire growth model to test fuel treatments. In 'Sierra Nevada ecosystem project: final report to Congress. Assessment and scientific basis for management options'. pp. 1155–1165 (University of California: Davis)

Van Wagtendonk JW, 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, Prescribed Fire and Fire Effects Working Team: Washington, D.C.)

Van Wagtendonk JW, Sydoriak CA (1987) Fuel accumulation rates after prescribed fires in Yosemite National Park. In 'Preprint volume 9th conference on fire and forest meteorology'. pp. 101–105. (American Meteorological Society: Boston)

Vega JA, Valette JC, Rego F, Lara 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, Fonturbel 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 'Proceedings of the 2nd international conference on forest fire research'. (Ed. DX Viegas) pp. 75–84 (ADAI: Coimbra)

Wade D, Lunsford JD (1989) 'A guide for prescribed fire in Southern forests.' USDA Forest Service Technical Publication R8-TP 11, Atlanta, GA.
Wagle RF, Eakle TW (1979) A controlled burn reduces the impact of a subsequent wildfire in a ponderosa pine vegetation type. *Forest Science* **25**, 123–129.
Ward D (1998) Reconstructing the fire history of the jarrah forest of south-western Australia. In 'Proceedings of the 13th conference on fire and forest meteorology'. pp. 245–249 (International Association of Wildland Fire)
Weatherspoon CP, Skinner CN (1995) An assessment of factors associated with damage to tree crowns from the 1987 wildfires in Northern California. *Forest Science* **41**, 430–451.
Weise, DR, Gelobter A, Haase SM, Sackett SS (1997) Photo series for quantifying fuels and assessing fire risk in giant sequoia groves. USDA Forest Service General Technical Report PSW-GTR–163. Albany, NY.
Whelan RJ, Muston RM (1991) Fire regimes and management in southeastern Australia. In 'Proceedings of the 17th Tall Timbers fire ecology conference. High intensity fire in woodlands: management challenges and options'. pp. 235–258 (Tall Timbers Research Station: Tallahassee)
Wilson AG (1992) 'Assessing fire hazard on public lands in Victoria: fire management needs, and practical research objectives.' Department of Conservation and Environment, Fire Management Branch, Research Report No. 31, Victoria.
Wilson JS, Baker PJ (1998) Mitigating fire risk to late-successional forest reserves on the east slope of the Washington Cascade Range, USA. *Forest Ecology and Management* **110**, 59–75.
Wright HA, Bailey AW (1982) 'Fire Ecology, United States and Southern Canada.' (John Wiley and Sons: New York)
Zedler PH, Seiger LA (2000) Age mosaics and fire size in chaparral: a simulation study. In '2nd interface between ecology and land development in California'. (Eds JE Keeley, M. Baer-Keeley and CJ Fotheringham), pp. 9–18, U.S. Geological Survey Open-File Report 00–62.