

A review of prescribed burning effectiveness in fire hazard reduction

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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,

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 Wagtenonk 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 Schmoltdt *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 Wagtenonk *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.* 2000a). 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.* 2000b). 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 Wagtenonk (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.* (1998a) 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 fire-line 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 head-fire. 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.* 1998a).

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 Wagtenonk 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.* (1998b) 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.* 1998b). 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.* 1998c).

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.

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