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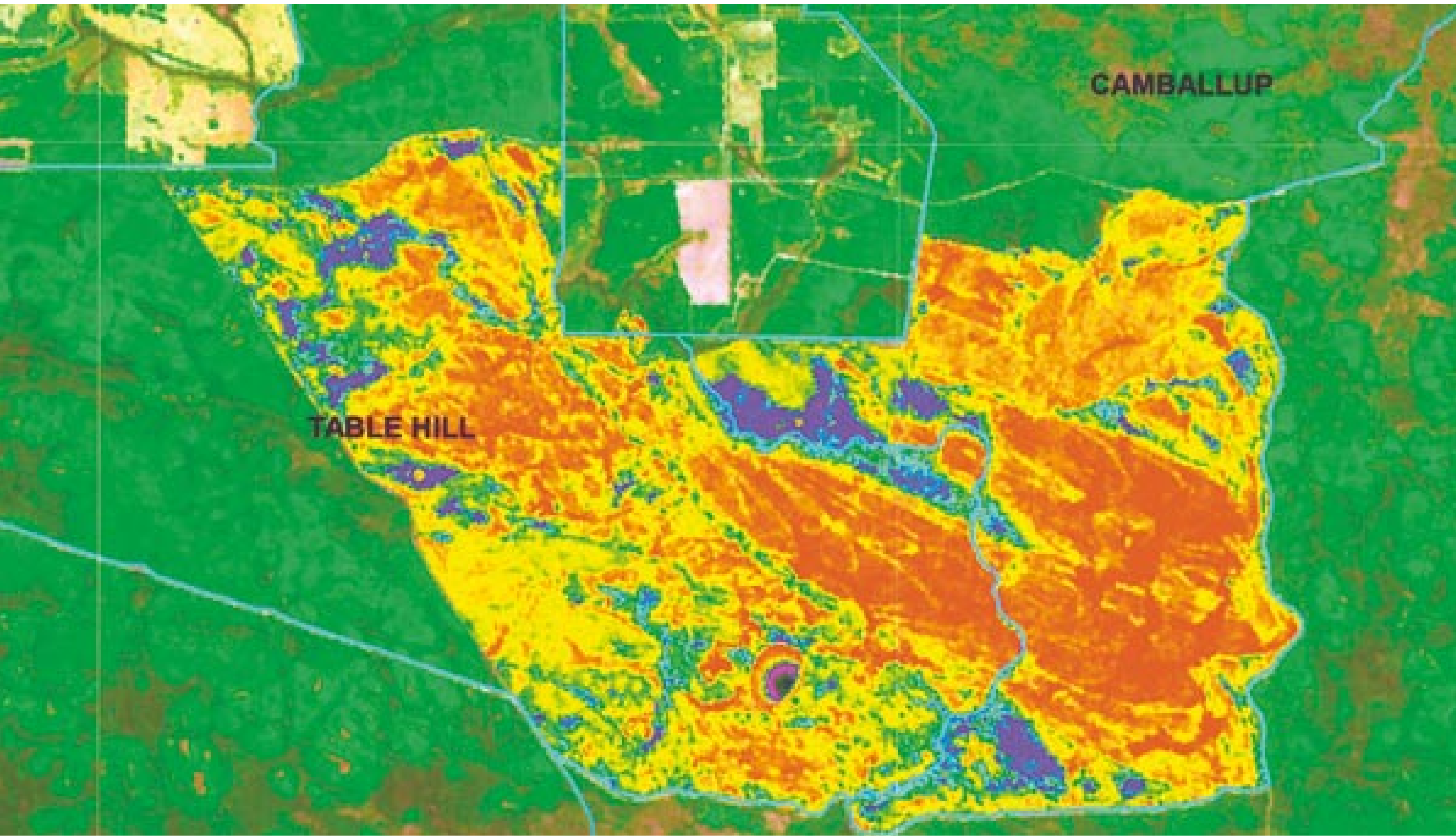
A review of the relationship between fireline intensity and the ecological and economic effects of fire

and methods currently used to collect fire data



Research report no. 67

Victoria
The Place To Be

A review of the relationship between fireline intensity and the ecological and economic effects of fire, and methods currently used to collect fire data

Research Report No. 67

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Forest Science Centre

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Cover photograph: Landsat-TM image analysed to indicate fire severity classes
(Image courtesy Dept Conservation and Land Management, W.A.)

The full series of Fire Research Reports can be found on:
www.dse.vic.gov.au/fires (fire management; fire research)

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Background

For each wildfire attended by the Department of Sustainability and Environment or reported on public land, Section 2.4.9 of the Code of Practice for Fire Management on Public Land (CNR 1995) requires the Department to maintain records which include the origin and size of the fire, vegetation types burned, an estimate of the damage caused on public land and a map of the area of public land burned – including indicators of fire intensity. Other records to be maintained include estimates of annual fire damage and other economic or ecological consequences (Section 2.2.6 of the Code). With an average of 235 000 ha of forest burned by about 500 wildfires and 1000 prescribed fires each year in Victoria (1984–1992)[1], this is a large task. Current methods of collecting the relevant information include ground surveys and aerial photography. These methods do not provide comprehensive or uniform records and the formats in which they are collected are not easily incorporated into Geographic Information Systems (GIS).

The aims of this report are to:

- review the relationship between fireline intensity and economic and ecological effects of fire, with the intention of eventually developing a system that will enable the routine mapping and recording of indicators of fire intensity within all fires
- examine the methods currently used to collect such fire data throughout the world.

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[1] Statistics retrieved from FIRES – the Department of Sustainability and Environment's Fire Information Resource and Equipment System database.

Review

Fireline intensity and economic and ecological effects of fire

Fireline intensity (commonly referred to as fire intensity) was defined by Byram (1959) as the rate of heat output per length of fireline (*I*), expressed as kilowatts per metre of fire edge, as shown in Equation 1.

$$I = H\,w\,R \qquad \textbf{\textit{Equation 1}}$$

where:

I = fireline intensity (kW m^{-1})

H = heat yield of the fuel consumed (kJ kg^{-1})

w = amount of fuel consumed (kg m^{-2})

R = forward rate of spread of the fire (m s^{-1})

Fire intensity is sometimes used to describe (Cheney 1981; Burrows 1995) or compare fires. However, fire intensity should only be used to compare fires in similar fuel types (Pyne et al. 1996; Cheney & Sullivan 1998). As Pyne et al. (1996) demonstrated in their Figure 2.18 (reproduced in Figure 1 below), fires of equal intensity may, in fact, be produced in quite different types of fuel and with different forward rates of spread. Average fire intensity around the perimeter of a fire also varies by a factor of up to 10 (Catchpole et al. 1992), indicating that the amount of damage caused by a fire will depend on what part of the fire's perimeter (i.e. head fire, flank fire, backing fire) burnt that particular area. As fire intensity varies around the perimeter of a fire, so does the percentage of area burned at a particular intensity

If fire intensity is calculated for only one part of a fire, actual fire intensity at other times or at other parts of the fire may be over- or underestimated. Fire intensity can also be overestimated where rates of spread are fast—here, less fuel is burned in the flaming front because only partial combustion is achieved—than in a slower-moving fire, where more fuel is consumed in the flaming front (Burrows 1994). In fluctuating winds, fire intensity may be over- or underestimated for the flank fires, as flank fires alternate between backing and head fires depending on wind direction (Cheney 1990; Cheney & Sullivan 1998).

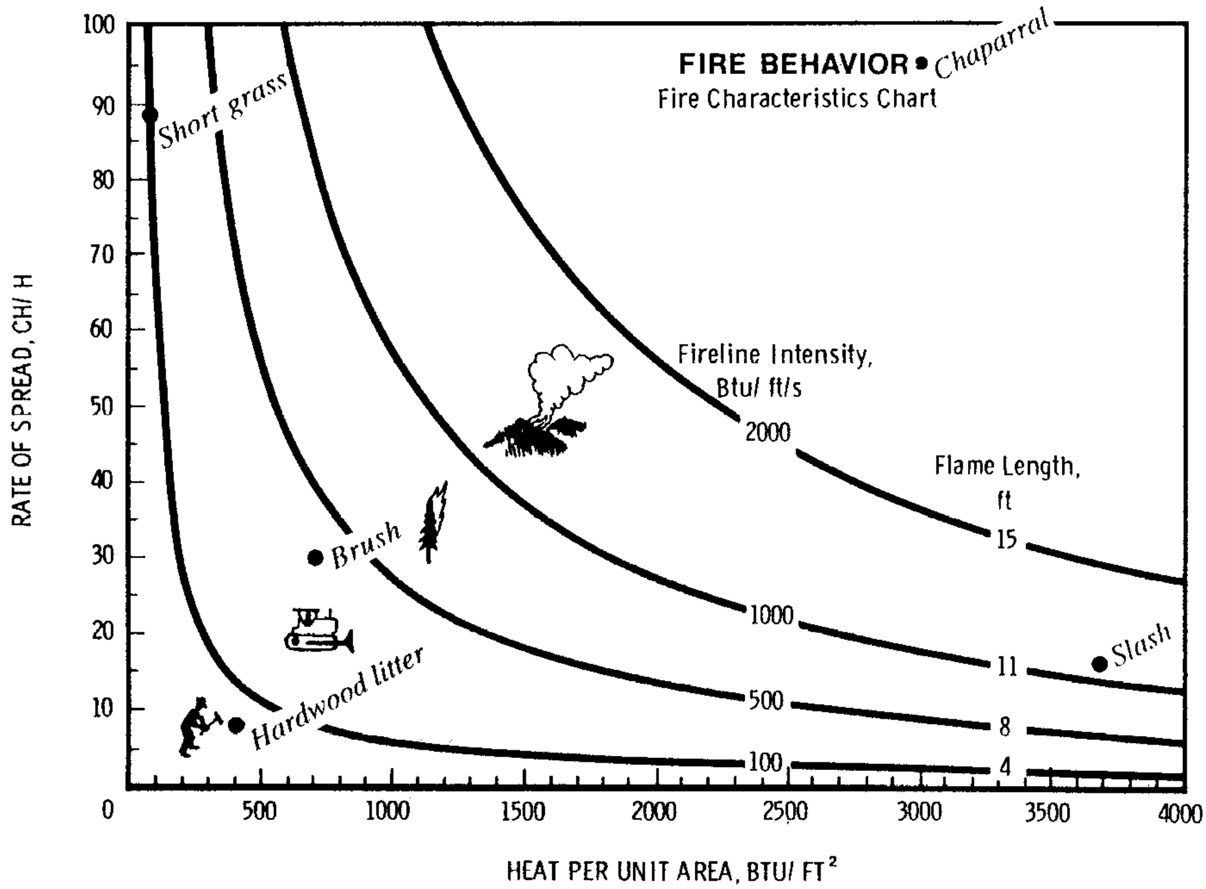

Figure 1 Potential fire characteristics for any given rate of spread and intensity
Reproduced from Figure 2.18 of Pyne et al. (1996)

Further, the energy released from a fire is not confined to its edge. Rather, it comes from the entire area of combustion until all available fuel is burnt out. The full range of fuels, from the surface fine fuels (i.e. the fuel covering the mineral soil) to the heavy fuels, contributes to the energy released (Cheney 1981). Gill (1981) indicated that the effects of fire on plants and animals depend on the characteristics of the fire along the perimeter. Therefore, measures of the intensity along all points of a fire's perimeter (Catchpole et al. 1982), and not just certain parts of the fire (e.g. the head fire area only), would be useful when trying to predict the ecological effects of forest fires.

McArthur (1962) noted that fire damage was closely related to fire intensity. Thus a reduction in the destructiveness of wildfires can generally be achieved by broadscale prescribed burning—where the primary objective is to reduce the accumulation of fuel over a wide area. Such broadscale reduction in fuel should result in significantly decreased rates of spread and intensities of a wildfire, which should in turn assist suppression forces in controlling the fire (McArthur 1962). This is the rationale behind the extensive prescribed burning programs carried out for fuel reduction purposes across public land in Victoria. An additional objective of prescribed burning is to minimise the possible damage to forests and other environmental values by a wildfire.

Despite fire intensity being considered a good indicator of fire behaviour in general, fire intensity is difficult to measure accurately (Burrows 1995), especially over short periods of time. Often it is only estimated post-fire. A number of studies have been conducted to determine the relationships between fire intensity and other fire behaviour characteristics, such as flame dimensions (Byram 1959; Johnson 1982; Burrows 1995), scorch height (van Wagner 1973; Burrows 1995; Tolhurst 1995) and crowning potential (Catchpole et al. 1992). Flame length has been used to estimate fire intensity. However, flame length itself is not easy to estimate, as it is assessed either visually, using an apparent spatial average value per unit of time, or by photographic methods—which only give as estimation for a specific instant (Johnson 1982). And both methods only give an average value. Burrows (1995) found that by separating the fire into four impact zones—above flames, in flames, below flames and behind flames—he could adequately describe the impacts, heat outputs and factors affecting heat transfer of a fire and quantify the impacts. This framework did not rely on *knowing* the fire intensity. However as Burrows (1995) commented, '…it is important to identify and measure variables which are linked to the immediate impacts of fire'. Tolhurst (1995) suggested that fire severity rather than fire intensity, is the best measure of the effect of fire. Thus fire severity could be considered as a measure of the economic and/or ecological impact of the fire.

Cheney (1993) defined fire severity as the *degree to which a site has been altered or disrupted by fire; which is loosely a product of fire intensity and residence time.* More particularly, Burrows (1995) stated that fire severity 'will depend on the amount and rate of heat energy released and on the amount and rates of heat transfer to plants and the soil'. Therefore fire severity can be defined as a function of fire intensity, residence time and soil and plant dryness. However, it is a subjective term and must be measured in terms of the *value* being considered. For example, economic damage can be measured in dollars or lost volume, whereas ecological damage can be measured by the amount of scorch, death toll of plants and/or animals, changes in soil, nutrient loss and so on.

Abbott and Christensen (1994) commented that the unit of area burned differs each year, resulting in a mosaic of areas of variable magnitude and frequency of burn across the landscape. That is, the entire forest area is unlikely to be burned in the one season in the one year. Thus, fire creates environmental diversity at several scales. At the broad scale (i.e. across thousands of hectares) there is a mosaic of areas burned one, two, three, up to 50 or so years previously. At the local scale (i.e. across single hectares) spatial variation in fire intensities produces a patchiness in the resultant effects. These different fire intensities may have quite different effects on both economic and ecological values, and the effects themselves may have both beneficial and detrimental outcomes for both ecological and economic values.

Effects on ecological values

The intensity of a fire influences the heat output per metre of fireline that the flora and/or fauna are subjected to. This, in turn, affects their rate of survival. Survival of fauna immediately after a fire depends on the direct effects of the fire on the individual animals. Suckling and Macfarlane (1984) commented that the rate of survival (during a fire) of mammals is a function of fire intensity. However, longer-term recovery also depends on the recovery of habitat (i.e. shelter, food, breeding sites), in both composition and structure, which may be quite rapid or may take 20 to 40 years for complete recovery (ibid.). Suckling and Macfarlane (1984) also found that predation and starvation caused a high rate of mortality in fauna after high intensity fires. Whether a faunal species is completely eliminated from a site, however, would depend on the home range of the species and the size and intensity of the fire.

In the case of fauna, both Campbell and Tanton (1981) and Suckling and Macfarlane (1984) noted that the effects of fire varied greatly depending on the time of year that the fire occurred (such as during the breeding or lactating period). This meant that the season of the fire was a more critical determinant than fire intensity. Accordingly, both frequency and season of fire are more important in determining community survival than fire intensity alone. However, fire intensity still plays an important role in species abundance and regeneration in the short term (Chesterfield 1984; Suckling & Macfarlane 1984). The creation of mosaics, especially by low-intensity fires, tends to produce greater variation in vegetation (Suckling & Macfarlane 1984). Chesterfield (1984) noted that crown fires can cause a temporary reduction in site occupancy by the dominant eucalypt species, and this in turn assists the growth of the understorey species. However, he also noted that annual fires could cause a decline in understorey species, as can long periods without fire—which could possibly cause a decline in overall vegetation composition and vitality.

In respect to the flora, fire intensity can have a marked effect on the extent of post-fire recovery and on the relative abundance of plant species regenerating from seeds or vegetatively (Christensen et al. 1981[2]; Lutze & Terrell 1998). Low-intensity fires (less than 500 kW m^{-1}) will result in a low overall death rate of trees because the amount of bark removed from and damage to the tree boles and of crown scorch are minimal. On the other hand, greater damage occurs to the boles and crowns of trees and more bark is consumed in high-intensity fires (greater than 500 kW m^{-1}) and higher plant mortality is likely. High-intensity fires are also more likely to affect the canopy cover of the overstorey, which may enable the better establishment of understorey species—Chesterfield (1984) noted that bracken increased in dominance under a eucalypt overstorey after a number of 'hot fires' decreased the canopy cover. Seed germination depends on the exposure of the seed to heat (Christensen et al. 1981), which in turn depends on the depth the seed is stored in the soil, the quantity of fuel burned and the degree of exposure of mineral soil. Recovery by seed therefore depends on the fire producing enough heat to initiate germination. Accordingly, seed germination would be expected to be more successful after high-intensity fires than after low-intensity ones. However, if a second fire occurs over the same area soon after the first, recovery after the second fire could be quite different from the recovery after the first one (Tolhurst & Oswin 1992).

McArthur (1962) noted that the genus *Eucalyptus* is remarkably resistant (in terms of overall survival of individual trees) to fires of low to moderate intensity. He also noted, however, that their resistance to fire depends on the intensity of the fire and the seasonal dryness as indicated by the Keetch-Byram Drought Index. Many adaptations in the genus also make them resistant to damage from high-intensity crown fires, as only a few species are likely to be killed outright in such fires.

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[2] Christensen et al. (1981) based their work on leguminous species only.

Both Cheney (1981) and Christensen et al. (1981) tried to quantify the relationship between fire intensity and the physical damage to the burnt eucalypt forests (Table 1). The characteristics identified by both as important for each fire intensity range are quite similar, although Christensen et al. (1981) goes to greater detail—particularly about the expected methods of regeneration on the site. However, the major flaw in their comments, particularly with the details provided by Christensen et al. (1981), is that the effects of fire on vegetation do not depend on fire intensity alone.

Table 1 Expected effects on eucalypt forests of fire of different intensities

Fire intensity (kW/m)	Remarks from Cheney (1981)	Remarks from Christensen et al. (1981) based on a community dominated by leguminous species
< 500	Low – maximum flame height of 1.5 m. Upper limit recommended for fuel reduction burning.	Little tree canopy scorch, but understorey species may be partially or wholly damaged; can expect vegetative regeneration, but little or no seed regeneration.
500 – 1700	Moderate – maximum flame height of 6.0 m. Scorch of complete crown in most forests.	Defoliation and death of most understorey species; damage to branchlets of overstorey and some fire scarring on boles of overstorey may occur. Would expect regeneration by both vegetative and seed means.
1700 – 3500	Moderate/High – flame height between 6.0 and 15.0 m. Scorch of complete crown in most forests, with crown fire in low forest types (<15.0 m high).	Significant physical damage to bole and crown of trees. Epicormic shoots generally stimulated.
3500 – 7000	High – maximum flame height of 15.0 m. Crown fires in low forests (<15.0 m high).	Crown fires in forests <15.0 m height, with tree canopies defoliated over large areas; understorey woody stems destroyed and mineral soil exposed. Vegetative regeneration may not occur due to outright death of plants.
7000 – 70 000	Very High – flame heights of greater than 15.0 m. Crown fire in most forest types, with firestorm conditions at the upper fire intensities.	Death of almost all above-ground foliage of most species; can cause uprooting and fracturing of trees.

Note: The effects are based on surface fine fuels only; not all fine fuels.

Abbott and Christensen (1994) noted that fire intensity depends largely on the time of the year (i.e. the dryness of the litter and the stage in the life cycle), prevailing weather conditions and the period since the last fire (i.e. the amount of fuel available). The recovery of vegetation also depends on the weather conditions following the fire (Chesterfield 1984) and the legacy left in the soil in the form of seeds, bulbs, corms, tubers and lignotubers (Abbott & Christensen 1994). The effects of a fire will also depend on the season, the species involved, the residence time of the fire, fire frequency and the dryness of the vegetation and soil. Therefore, indicators of fire severity may indeed be a more effective measure of the ecological effect of the fire than fire intensity indicators alone.

McArthur (1962) stated that ample research data and observations exist to indicate that damage to eucalypt forest resulting from low-intensity prescribed fire was negligible. However, he disclosed no examples of such data and/or observations.

It must also be remembered that pre- and post-fire seasonal conditions can have a more significant effect on vegetation recovery than fire intensity itself. Dry conditions may induce physiological stresses (Chesterfield 1984), as can browsing and grazing.

The effects of fire on soil depend on the temperature and the residence time of the fire as well as the soil moisture content. The greater the consumption of surface fine fuel, the more likely it is that the soil will be exposed. Flinn et al. (1984) commented that the degree of change in both the chemical and biological properties of soil was strongly linked with fire intensity; that is, the amount that the soil is exposed to heat. Exposure of the mineral soil may lead to loss of nutrients (Chesterfield 1984) and organic matter and possibly even significant erosion. Some of these events may be further aggravated by the weather conditions (like heavy rainfall) following the fire. Hatch (1960) noted that even under very hot logging slash fires, where heat penetration was considerable, any marked chemical changes that occurred in the surface soil were not permanent, with recovery to normal conditions generally being rapid.

In relation to water dynamics, Flinn et al. (1984) commented that variation in fire intensity on a site could affect the magnitude of the fire's effects on interception, evapotranspiration, overland flow, soil infiltration, field capacity, streamflow behaviour and stream water quantity.

Effects on the soil depend on the temperature and the residence time of the fire, and can be divided into three types: biological, chemical and physical. Biological effects are likely to be found when the temperature is less than 120 °C, chemical effects are likely to occur between 100 and 600+°C, and physical effects are likely to occur above 600 °C (Humphreys & Craig 1981). Effects on the soil also depend on the soil's moisture content and structure.

Effects on economic values

It is generally thought that the hotter the fire, or the more intense the fire, the more damage it will inflict on assets such as homes, farm buildings, fences and timber. Unfortunately, only a small amount of literature is available that discusses this assumption.

Fire intensity directly influences the cost of suppression, as the method of suppression depends on fire behaviour or, more generally, fire intensity. For low-intensity fires (i.e. less than 2000–3000 kW m^{-1}), direct attack methods may be used. For more intense fires, however, indirect attack methods are generally required, especially on the fire front.

Wilson (1984) stated that fire intensity is the most important determinant in whether a house survives a nearby wildfire, as compared to its construction material, the presence of flammable objects near the house and the presence of plants less than 5 m tall within 40 m of the house. Wilson and Ferguson (1984) studied houses that were affected (either destroyed or partially burned) in the fire at Mount Macedon on 16 February 1983. Fuel loads (including elevated and surface fine fuels, but not including the crown fuels) in the adjoining forest were up to 21 t ha^{-1}, forward rates of spread in the town were of the order of 3–4 km h^{-1} and the houses were exposed to fire intensities ranging between 500 and 60 000 kW m^{-1}. Of the total of 450 houses surveyed (of which 234 were destroyed), about 10% were exposed to crown fire in the adjacent forest canopy (crowning was infrequent once the fire entered the township) and 50% were exposed to surface fire intense enough to fully scorch surrounding trees. Almost 40% of houses were exposed to a less intense surface fire, but one that was nevertheless accompanied by strong winds and airborne embers. Wilson and Ferguson (1984) noted that houses exposed to high-intensity fires are subjected to severe thermal stresses, and sometimes the strong winds associated with high intensity fires can cause structural damage.

McArthur (1962) described, for prescribed fires, characteristic fire behaviours based on a series of fire intensity ranges. He implied that, to ensure that no unacceptable damage occurred in commercial (native) forests, all prescribed burning should be carried out with fire intensities less than 340 kW m^{-1} (or 100 BTU $ft^{-1}s^{-1}$). Gill et al. (1987) described the optimum prescribed burning days as those when fire intensities were between 60 and 250 kW m^{-1}. Luke and McArthur (1978) suggested that the upper limit for prescribed fire (for the purpose of fuel reduction) is 4000 kW m^{-1}. However both Cheney (1981) and Christensen et al. (1981) suggest that it would be extremely optimistic to expect a result at this intensity with little or no damage.

The economic damage of fire to timber from either native forests or plantations is related to the amount of physical damage that the forests or plantations sustain and/or the effect fire has on growth rates. Abbott and Christensen (1994) noted that growth rates of jarrah (*Eucalyptus marginata*) on long-unburnt and burnt sites did not differ significantly; Kellas (1992) found similar results in messmate (*E. obliqua*). If the boles of the trees are significantly damaged, fire scarring may result and/or epicormic shoots may erupt. Trees may also be killed outright. Visual and structural degrade of wood following fire have been closely associated with drying, splitting, gum veining, insect attack and fungal decay in some eucalypt species (Chesterfield 1984; Smith & Woodgate 1985). The consequent reduction in timber quality will decrease the economic value of that timber and may necessitate salvage logging. Alexander (1991) noted that unpruned pine plantations were more prone to crowning wildfires than similar areas that had been pruned, and that the sizes of individual areas burned are at least four times larger.

Current methods of collecting fire data

A number of methodologies (Bradshaw 1971; Myers 1978; Smith & Woodgate 1985; Lutze & Terrell 1998) have been used to map fire intensity or fire severity. All noted that mapping of a fire should be carried out as soon as possible after the fire—prior to leaf fall and crown recovery (Lutze & Terrell 1998)—so as to obtain an accurate picture of the damage, but not so soon as to miss consequential damage such as subsequent crown death (Smith & Woodgate 1985). Maps of the intensity/severity and extent of a fire can be used for a number of purposes, including for the scheduling of timber salvage, investigating regeneration, planning of rehabilitation programs and as a basis for studying fire behaviour (Smith & Woodgate 1985). A limitation to all methods is that the effects of the fire are often obscured by mapped information about forest structure and type, and vice versa (Lutze & Terrell 1998), and that all remote sensing methodologies require some level of ground-truthing.

The Department's current situation

The Department of Sustainability and Environment's current fire reporting system places no requirement on the recording of such fire data as forward rate of spread, flame height, fire intensity, proportion of area burned within the fire perimeter and proportion of scorch. Any such data that is collected at wildfires is collected in an ad-hoc fashion and is not necessarily included in the final fire report. The fire reporting system does, however, require such data to be recorded for prescribed fires. An estimation of monetary loss caused by a wildfire is recorded; this is only an economic value, however. Ecological and other non-monetary values that are damaged or lost are not recorded.

Timeliness in obtaining the data—whether by aerial photography, satellite imagery or on-ground—is essential. It is also important that the mapping methodologies are evaluated in view of the potential of having to map numerous fires at the same time. (Victoria frequently experiences a number of serious wildfires at the one time.)

Scale

Scale is important, not only because of the level of detail produced, but also the influence that it has on the basic cost of obtaining the imagery. The more extensive the scale, the more data/photos are required, and thus the greater the cost.

Smith and Woodgate (1985) commented that both the choice of suitable film (i.e. methodology) and scale combinations were important. However, as yet, no one scale has been recommended over another. Myers (1978) trialled aerial photography at two scales—1:2500 and 1:15 000. The accuracy of sample points increased by 10% when details captured at a scale of 1:2500 were extrapolated onto 1:15 000 maps, compared to using only the scale of 1:15 000. Using the 1:2500 scale alone yielded only an additional 4% in accuracy compared to the combination of scales. Myers (1978) also found that the 1:15 000 scale did not often allow the identification of bare rock, low intensity fire and/or litter-free soil, whereas the 1:2500 scale did allow such a detailed examination. Myers (1978) commented that the scales of 1:32 000 and 1:16 000 that were used to map prescribed burns in Victoria were not accurate enough for low-intensity surface fires. In trialling aerial photography at scales of 1:30 000 and 1:18 000, Bradshaw (1971) found that the larger-scale photos (1:18 000) enabled no better interpretation than the 1:30 000 scale maps and considered the additional cost of the larger-scale photos was not justifiable. To compare their results from satellite imagery to those from aerial photography, Stigloher and Coppa (1999) used a scale of 1:25 000 for interpretation. They made no analysis or comments regarding the suitability of this scale, as the study focussed on the comparative accuracy of interpretation from the two sources of images.

Past methodologies have been developed throughout Australia for assessing areas burned by fire, and have ranged from numerous burn classes (Bradshaw 1971) to the simple two-class classification of Myers (1978) of burnt and non-burnt. However, due to the high costs, most have only been partially successful. Therefore, the choice of scale will also depend on the number of burn classes chosen.

Aerial photography

Aerial photography has been a popular method for mapping fire intensity and has generally involved only a few damage classes. Dexter et al. (1977) devised a methodology using only three damage classes—lightly burnt, moderately burnt and severely burnt—based on the amount of damage the dominant vegetation sustained after fire. Dexter et al. (1977) and Myers (1978) noted that it was difficult to distinguish between unburnt areas, areas only lightly burned (i.e. burnt surface fuel only), bare rock and litter-free soil, although Myers (1978) did find that by enlarging the scale, such details could be examined. However, aerial photography is very time consuming in both the collection of the photography and in the analysis of the photos, and even more so for large tracts of land (Smith & Woodgate 1985). Smith and Woodgate (1985) and Allen (1984) suggest that aerial photography be used to supplement the interpretation of multi-spectral data. Smith and Woodgate (1985) based their seven damage classes on visible crown scorch supplemented by ground observations of fire intensity. The damage classes ranged from 100% crown burnt to 100% unburnt. They found that for the four classes that included unburnt to less than 75% crown scorch, green leaves remaining on the trees obscured the forest floor and extensive ground truthing was required to verify boundaries. This resulted in less accuracy for these four damage classes. Smith and Woodgate (1985) also noted that intensive field checking had to be carried out in young mountain ash (*E. regnans*) stands to determine whether additional seeding or planting was required. Myers (1978) used only the classifications of *burnt* and *unburnt*, which assumes that all burnt areas were burned at exactly the same fire intensity. This general assumption is acceptable only if the aim is to determine which areas were or were not burned.

Allen (1984) took a series of aerial photographs during a number of fires to map fire behaviour of individual fires. This is both time-consuming and very expensive.

Meyer (1978) noted that the success of interpretation of aerial photography depends on the timing of the photography (i.e. season, time of day, etc.). Myers (1978) considered that it was essential to have stereoscopic coverage at the scale of 1:2500; this would further add to the costs.

Thermal infrared scanning and photography

Thermal infrared scanning is currently used throughout Australia to acquire real-time fire information to assist in fire suppression operations. Because thermal sensing is not restricted by the limitations of visible wavelengths, this methodology can be used day or night and through dense smoke (Warren & Wilson 1981; Lacey & Friedrich 1984). The technology is based on sensing the differences between the radiation sources of the terrain background and the thermal emissions from a fire. Lacey and Friedrich (1984) trialled thermal mapping with the objectives of establishing the extent of active fires, determining the rate of spread of the front and where there were unburnt islands and identifying spot fires that had ignited ahead of the main fire front. A drawback with this technology is that the more oblique the scanning angle and the greater the foliage cover and interception by the canopy, the greater the reduction in the thermal signal from the fire. Thermal sensing relies of good background knowledge of the terrain (Lacey & Friedrich 1984). This same equipment and technology could be used to map fire severity after a fire event.

Bradshaw (1971) recommended that small-scale aerial photography be used where possible to decrease costs and that colour infrared film, exposed through a yellow filter, be used (this enabled the imagery to penetrate haze, which can be a problem during the autumn and spring prescribed burning seasons). Bradshaw (1971) used colour infrared aerial photographs to map burnt areas into four categories—not burnt, shrub layer burnt, tree crowns scorched and trees defoliated—in the jarrah (*E. marginata*) and karri (*E. diversicolor*) forests of Western Australia. He found that interpretation was more accurate in the karri forests than in the jarrah forests because of the greater contrast in the denser vegetation of the karri forests and if the photos were taken within ten weeks of burning.

Multi-spectral satellite imagery

There are many remote sensing satellites available for mapping fire severity. They vary widely in the frequency of availability, their level of resolution, the spectral bands detected, their reliability and the cost of the data. Data collected by satellites are in a digital format and therefore lend themselves to computer analysis compared to aerial photographs that require human interpretation; unless they are scanned and converted to digital data. However, in spite of being in a digital format, there are significant variations in the sensing conditions, such as the atmospheric composition, temperature, sensor calibration and seasonal effects on the vegetation and soils. These variations mean that it is not possible to produce a fully automated image analysis process. The main advantage of satellite images over aerial photographs is that they cover large areas in a short period of time and large areas can be classified in a systematic way, even if the level of accuracy may only be 50 to 70%. The consistency of interpretation and the relatively low cost of satellite imagery has been a major attraction of the technology.

Some existing satellite imaging systems and their characteristics are listed in the Appendix. The Landsat series has been one of the most widely used satellites for land management.

Landsat TM

Landsat TM (thematic mapper) are satellites with multispectral sensors. Landsat TM records in seven spectral bands where each band covers a limited segment of the electromagnetic spectrum, including the non-visible wavelengths (Appendix). The data can be processed by computer or reconstituted into photograph-like products comprising either single-band images or multi-band false-colour composite images.

Landsat4-TM and Landsat5-TM are two satellites that orbit the earth at an altitude of 705 km (Lillesand & Kiefer 1987), a frequency of 16 days and provide digital images at a spatial resolution of 30 m per pixel (Lacey & Friedrich 1984; Lillesand & Kiefer 1987; Stigloher 1998). Landsat imagery is only two-dimensional spatially (Lillesand & Kiefer 1987) but is multi-dimensional both temporally and spectrally.

Pereira and Setzer (1993) quote numerous studies that have been carried out around the world using Landsat4 and –5 data to study and locate fires in vegetation. Lillesand and Kiefer (1987), however, refer to the use of satellite imagery for the observation of forest fires as a 'hit-or-miss proposition' although the area burned by fire will often leave a dark image tone after the event.

It is most important that the spectral band or combination of bands used is appropriate to the type of interpretive use to which the technology is to be put (Lillesand & Kiefer 1987). The limitations of this method are that it relies on Landsat imagery being available on time, smoke and/or cloud cover cause interference (Pereira & Setzer 1993; Stigloher 1998) and the broad spatial resolution—a Landsat *scene* covers approximately 34 000 km^2 (a *scene* being an arbitrary unit of imagery which is usually about as long as it is wide where the width of the scene is the swathe width of the scanning device).

Classification of fire severity and production of a plot of the spatial pattern of a burn can be achieved by using before- and after-fire-event images or by combining two Landsat images and then applying standard classification methodologies. Combining two Landsat images and enhancing the changes through various transformations of data from each of the spectral band data—such as relative scaling of different spectral band data or various combinations of bands can also achieve them. For example, dividing the value of one band by the value of another to produce a third spectral attribute, using some combination of bands to produce a new attribute, and so on (Richards & Milne 1984; Ribed & Lopez 1995). Ribed and Lopez (1995) used a statistical analysis technique to derive the 'principal components' of the multi-variate (multi-band) data to explore vegetative changes over time (i.e. areas burnt, unburnt, etc.). However, they looked at changes over years; this methodology may therefore not be useful for immediate results.

Stigloher and Coppa (1999) used Landsat TM data to map six damage classes for an area of approximately 34 000 ha in eastern Victoria based on the survival and regenerative ability of mountain ash (*E. regnans*) and alpine ash (*E. delegatensis*). The damage classes were based on specific percentages of the area of burnt, scorched and unburnt crowns. Spectral bands 3, 4, 5 and 7 were used as they are considered to have the 'highest potential' (Stigloher & Coppa 1999) for mapping changes in vegetation. Despite the number of different classification methods used by Stigloher and Coppa (1999), accuracy above 63% was never achieved without removing some of the vegetation types, which increased the accuracy of one methodology to 72%.

Smith and Woodgate (1985) used Landsat imagery to determine accurate boundaries of damage classes. The imagery available at the time used 80 m square pixels. They established spectral signatures for each damage class at known points on the ground (i.e. ground-truthing), and then used various computer-processing techniques to identify every other pixel. A benefit of using multi-spectral satellite data and computer processing is that it is relatively quick in producing a final product. An obvious limitation with this data, however, is the resolution. Further, multi-spectral data, the computer processing facilities and expertise may not always be readily available post-fire.

NOAA-AVHRR

NOAA (National Oceanographic and Atmospheric Administration) is a United States agency involved in collecting meteorological and oceanographic information from across the globe twice daily. NOAA currently has three operational AVHRR (Advanced Very High Resolution Radiometer) satellites, NOAA-14, NOAA-15 and NOAA-16. These satellites are polar-orbiting. That is, they circumnavigate the earth from north to south passing across the poles and progressively advancing around the earth at the same rate as the earth rotates so that each satellite passes the same point on the earth at the same time each day. These satellites are useful for mapping fires and fire scars at a coarse resolution (1.1 km) every morning and every afternoon. The Department of Land Information (DLI, previously DOLA – Dept. of Land Administration) in Western Australia routine provides this information for northern Australia. NOAA-14 and -15 collect spectral data in five bands and NOAA-16 collects six bands.

Spectral data from NOAA-AVHRR satellites can be used in several ways to map fires and firescars. One method that has proven successful with multi-spectral scanners, including AVHRR, is the calculation of the Normalised Difference Vegetation Index (NDVI), which is determined by finding the ratio of the Near-Infrared signal minus the Red signal to the Near-Infrared signal plus the Red signal. The NDVI is often referred to as the 'greenness' index and has been found to be very useful in assessing vegetation condition, including the degree of grass curing as well as the degree of foliage scorch resulting from fires.

NDVI data have been used successfully in Alaska (Kasischke & French 1995) to determine the area and location of fire scars. However, the methodology must be completed immediately after a fire, before the forests 'green up' (Kasischke & French 1995; Barbosa et al. 1998, Stigloher & Coppa 1999) and thus increase the NDVI. This is considered vitally important in tropical areas where 'greening up' occurs relatively quickly after fire. Barbosa et al. (1998) recommended that composites be collected within one week, and definitely within 16 days, of a fire. Barbosa et al. (1998) found that the use of a composite data set reduced the problems of cloud cover and atmospheric effects on individual images. The technique also differentiated between burnt and unburnt areas. However, the category 'burnt' was only given to pixels displaying a burnt area greater than 20%.

Stigloher and Coppa (1999) also found that the cost of NDVI interpretation using the higher resolution Landsat-TM imagery was one-sixth of the cost of aerial photo interpretation, based on the same area and the same classifications. However, aerial photo interpretation achieved an accuracy of 90%, whereas that of Landsat-TM NDVI interpretation was only 59% (when all areas were interpreted) or 72% (when vegetation type data from a GIS database was used in conjunction with the satellite imagery).

Satellite radar imagery

Satellite-based radar has been used in the past to assist in the differentiation of burnt vegetation. Radar operates in the microwave region of the electromagnetic spectrum, thus allowing it to be used during the night or at low sun angles. It is also able to penetrate both smoke and cloud. Only two operational radar satellites currently offer commercially available data within Australia. Data from both must be specifically requested so that the sensors are turned on and the data collected.

The European owned ERS (Earth Resources Satellite) has a central incidence angle of 23° (Bourgeau-Chavez et al. 1997), making it well suited for measurements over quite steep topography. Bourgeau-Chavez et al. (1997) found that ERS could detect fire scars as old as 13 years in the Alaskan tundra, but was more accurate and consistent for fire scars up to five to seven years old. Seasonality played a major role in the ability to discern a fire scar using ERS, with late spring and early autumn proving to be the best times for their detection (ibid.). Visibility of fire scars was also influenced by topography, although not to the same extent as other forms of remote sensing. Another disadvantage of this methodology is that wetlands appeared in the images as bright as fire scars. In most situations, this would not be a problem, as wetlands will not usually burn. However, during the infrequent times when wetlands have dried out sufficiently to burn, differentiating between burnt vegetation and burnt wetland areas will be difficult (Bourgeau-Chavez et al. 1997). When Bourgeau-Chavez et al. (1997) compared the radar imagery results to those of AVHRR, they found that AVHRR was 16% more accurate than ERS-1 in detecting the number of fire scars and 21% more accurate in determining the total area burned. By using the two methods concurrently, however, they found 81% of the number of fires and determined 91% of the total area burned. This combined method enables some fires that were too small to be seen by the 1.1 km resolution of the AVHRR sensor to be picked up by the ERS-1.

Evaluation of economic loss

The Forests Commission (Victoria) in 1976 developed a model—intended for use during and after a fire incident—that was to be trialled to evaluate the direct damage caused by wildfires (Anon 1976). The model was designed to give ‘a reasonable estimate of fire damage using estimated field data on area, yield and in some cases degree of scorch’ (ibid.). However, this methodology relied on putting a monetary value on all areas of damage, including log and pulp products, minor forest products (such as eucalyptus oil or honey), departmental products, property and structures, grazing, water, recreation, wildlife, air quality and aesthetics. Unfortunately, there was no further documentation regarding this methodology, and the processes for evaluating the monetary value of loss in water, recreation, wildlife, air quality and aesthetic values were never developed.

A Canadian system for classifying fire intensity has been developed alongside their Fire Weather Index, incorporating both the Initial Spread Index (ISI) and the Buildup Index (BUI). It used five classes based on fireline intensity, flame height and the Fire Weather Index (FWI). This methodology was developed only for stands of softwoods, however, and would therefore need some adjustment to the descriptions of type of fire and fire suppression difficulty if it were to be used with any accuracy in native eucalypt forests.

Proposed method of assessing fire severity

Manual mapping

It is proposed here that a methodology for assessing fire severity be developed for use on the ground. That is, to be used when aerial photography and/or satellite imagery are not available or when more detailed mapping is required, such as for the mapping of an individual species. This methodology could also be used to ground-truth the other methodologies. The methodology is to be based on observations from the ground that are easy to examine, not open to excessive subjectivity and do not rely on knowing actual fire behaviour at the time.

The proposed manual method for assessing fire severity is described in Table 2 and is based on findings from McCarthy and Tolhurst (1998). Estimated flame height (i.e. height of charring), the type of fuel consumed by the fire (i.e. surface fine fuel only or a combination of surface fine fuel, elevated fuel and bark fuel) and the amount of crown scorch are used as parameters to estimate the fire severity class, and thus fire intensity.

Table 2 Fire Severity Classes and their associated seasonal dryness (KBDI1), flame height and fuel consumption in forests

Fire Severity Class	Estimated fire intensity (kW/m)	Typical KBDI[1]	Expected fire behaviour and fuel consumption
0	0		Unburnt
1	< 500	< 75	Maximum flame height of 1.5 m. Surface fuels only are consumed unless bark or elevated hazard greater than High. No crown scorch.
2	500 – 3000	75 – 100	Maximum flame height about 6 m, dependent on presence and height of bark and elevated fuels. Most surface fuel consumed, and significant bark and elevated fuel burnt if hazard level greater than High. Moderate to severe canopy scorch.
3	3000 – 7000	100 – 120	Maximum flame height about 15 m, dependent on presence and height of bark and elevated fuels. Complete consumption of surface fuel, with exposure of mineral soil in some places, and virtually all bark and elevated fuels consumed. Complete crown scorch.
4	7000 +	120 +	Crown fire. All fuels including crowns are consumed.

Note 1: KBDI = Keetch-Byram Drought Index

Conclusions

It is operationally difficult to accurately measure fire intensity itself, but fire *severity* (a function of fire intensity, residence time and soil and plant dryness) seems to be the most appropriate measurable indicator of fire intensity. Fire severity can thus be used as *a measure* of the degree of impact a fire has on the environment.

The direct negative relationship between fire intensity and economic damage is clear. The more intense the fire, the more likely an economic effect will result. The relationship between fire intensity and the ecological effect is less clear. In some cases, fire is required for regeneration purposes and therefore has a positive effect. In other cases, however, fire can cause significant structural and compositional changes to an ecosystem and therefore has a negative effect. In the case of ecological damage, it is important to consider vegetation type, the scale of the mapping and the overall fire regime.

Numerous methods for the collection of fire data have been used in the past, including aerial photography, satellite imagery and on-ground methods, none of which have convincingly proved efficient and accurate. High-resolution remotely-sensed imagery does not greatly increase the level of accuracy of interpretation, so imagery collected at a resolution of 10 to 50 m is probably a good compromise between accuracy and operational costs. Aerial photography taken at a scale of between 1:15 000 and 1:25 000 provides the majority of the fire intensity detail. However, unburnt areas will be the more difficult to identify on smaller scale photographs.

Based on work carried out by McCarthy and Tolhurst (1998), a five-class classification system has been proposed for use in the field and for ground-truthing any other method that may be trialled. Five classes of fire severity (Table 2) would appear to be adequate for a wide range of fire management purposes.

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Appendix Some commonly used satellites and their characteristics

Satellite	Country	Bands	Frequency / path	Resolution
NOAA 15 & 16 - AVHRR	USA	Bands 2, 3, 4 (5 / 6 bands)	Twice daily, morning and afternoon	1.1 km
Landsat 4 & 5 – TM	USA	Band 1 (0.45-0.52 μm, blue) Band 2 (0.52-0.6 μm, green) Band 3 (0.63-0.69 μm, red) Band 4 (0.76-0.9 μm, near-IR) Band 5 (1.55-1.75 μm, mid-IR) Band 6 (10.4-12.5 μm, thermal-IR) Band 7 (2.08-2.35 μm, mid-IR)	16 days, sun-synchronous, near-polar orbit	30 m
Landsat 7 – ETM+	USA	Bands 1 to 7	16 days, sun-synchronous, near-polar orbit	15 m panchromatic 30 m multispectral
MODIS (Terra & Aqua)	USA	36 spectral bands (0.405–14.385 μm)	Twice daily, morning and afternoon	250, 500, 1000 m
SPOT	France	Visible (0.51–0.73 μm)	Daily	10 m panchromatic 20 m multispectral
IKONOS		Red, blue, green, near-infrared	Daily, about 10.30am.	1 m panchromatic 4 m multispectral
EO-1	Japan	Hyperion: 220 spectral bands (0.4 to 2.5 μm) ALI: 10 spectral bands	16 days (one minute behind Landsat 7)	10 m panchromatic 30 m multispectral
ERS-2	European Space Agency (ESA)	C Band, 5.7 cm, 5.3 GHz VV polarization (Synthetic Aperture Radar)		
JERS-1	Japan	(Synthetic Aperture Radar)		
RADARSAT	Canada	C Band, 5.7 cm, 5.3 GHz HH polarization	Upon request	10 to 100 m
Aerial photographs	Any	Visible, IR	Project based	20 m for 1:20,000

Key to acronyms in Appendix

ALI Advanced Land Imager
EO Earth Observation
ERS Earth Resources Satellite
ETM+ Enhanced Thematic Mapper Plus
IKONOS Greek for '*image*'
IR Infrared
JERS Japanese Earth Resources Satellite
MODIS Moderate Resolution Imaging Spectroradiometer
RADARSAT Radar Satellite
SPOT Systéme Pour l'Observation de la Terre
TM Thematic Mapper
VV polarization Vertical polarization
HH polarization Horizontal polarization