Flammability of Australian forests

A. Malcolm Gill[1,2,3,5] and Phil Zylstra[4,5,6]

[1]CSIRO Plant Industry, GPO Box 1600, Canberra, ACT 2601, Australia
[2]School of Resources, Environment and Society, The Australian National University, Acton, ACT 0200, Australia
[3]Email: malcolm.gill@csiro.au
[4]Department of Mathematics and Statistics, University College, University of NSW, Campbell, ACT 2602, Australia
[5]Bushfire Cooperative Research Centre, Australia
[6]Snowy Mountains Region Fire Unit, National Parks and Wildlife Service, Jindabyne, NSW 2627, Australia

Revised manuscript received 24 March 2005

Summary

'Flammability' means different things to different people. Scientifically, it can be defined through three component variables that describe how well the fuel ignites (ignitibility), how well it burns (combustibility) and how long it burns (sustainability). The 'fuel' may be a plant organ, a whole plant or a plant community. While the terms ignitibility, combustibility and sustainability have been developed for laboratory studies, there are conceptual equivalents suited to the field; these are rate of spread, intensity and residence times. Another variable is added for field circumstances — probability of burning at a point. Eucalypt forests can be highly 'flammable' even considering all criteria and scales, while Australian forests in general show the whole range of variation from low ('closed forests' or 'rainforests') to high (e.g. relatively short stringy-barked open forests of *Eucalyptus* with abundant wiregrass). The expression of flammability depends on the local circumstances. In the field this can be summarised in terms of weather, terrain and ignition. Predicting how much potential forest fuel, and the attributes of that fuel, will be involved at any particular time, and under extreme weather conditions, remains a challenge. How social, climatic and fuel-species' changes will affect flammability, directly and indirectly, in the next 50–100 y is uncertain but potentially very significant.

Keywords: forests; combustion; fire behaviour; fuel appraisals; fuel consumption; models; Australia

Introduction

> Its climate, the nature of its forests, the fierce northerly gales that sometimes accompany days of searing heat, make it peculiarly susceptible to outbreaks of fire that can mount in fury within a few hours to uncontrollable proportions (Noble 1977).

There is no doubt that Australia's eucalypt forests can burn well; they are highly flammable. In this general sense, 'flammability' means 'ability to burn' but this ability is manifest only under particular weather and fuel conditions and only when an ignition source is present. Flammability is affected by the plant species exposed to fire, whether these be eucalypts or rainforest species:

> Australian mixed eucalyptus [sic] forest of many species is perhaps the most fire prone and most fire resistant forest anywhere in the world (Komarek 1984).

Rainforest and eucalypt forest communities have different intrinsic flammabilities, but these can change with new understorey species, as is highlighted by the increased flammability accompanying the invasion of Queensland rainforest by the exotic *Lantana* (Fensham *et al*. 1994) or that of eucalypt communities in the Northern Territory invaded by gamba grass (*Andropogon gayanus*) (Rossiter *et al*. 2003). At a finer scale, the elemental units of the community, including leaves, bark and twigs, have flammabilities that contribute to the total flammability of the community.

While flammability is a useful general term, it needs to be defined more closely for scientific purposes. Methods and measures of flammability appropriate to the single leaf or similar sized material are those appropriate to the laboratory (e.g. Gill and Moore 1996), but the methods and measures appropriate to the field for individual plants (e.g. Bradstock and Gill 1993) or plant communities (e.g. Cheney *et al*. 1992) are often different.

Common questions relating to flammability are: 'what can I, as a householder, grow in my garden to keep fires at bay?' and 'how can I, as a manager, reduce forest flammability so as to more successfully put out fires and thereby reduce the risk to economic assets, homes and human lives?'. Scientists may also want to investigate questions like: 'can intrinsic flammability of one species favour it over another in a fire-prone environment?' (e.g. Bond and Midgley 1995; Tran *et al*. 2001); 'what is the flammability of potential firebrands carrying fire downwind?' or, 'what is the capacity of firebrands to ignite fuels once they land' (Bunting and Wright 1974); 'how will the vegetation flammability affect seed in the soil?'; 'what plant attributes do I need to model fires and therefore their effects on the environment?'; and, 'what really makes bushland flammable?'.

This paper seeks to define flammability across a range of scales (e.g. leaf, plant, community) and to briefly consider the challenge of predicting and managing flammability now and in the future. How concepts of flammability can be applied across scales from the laboratory to the field is considered below. The geographic setting is the non-conifer forests of southern Australia.

What is flammability?

In laboratory research, flammability has been defined in terms of three components — ignitibility, sustainability and combustibility (Anderson 1970). Ignitibility in this context is the time from the application of an ignition source to flames appearing, or 'ignition delay time', t_i (Gill and Moore 1996). Sustainability can be measured in terms of how long something burns with a flame, t_r, or burns with a flame and by smouldering, t_b. Combustibility describes how well a material burns, a rate, and can be measured as W_r/t_r, where W_r is the amount of weight lost during flaming combustion, or as W/t_b where W is the total weight of material burnt. Combustibility can also be measured using a flame dimension (Gill *et al.* 1978). Sustainability and combustibility can be seen as a way of simplifying the time course of fuel weight loss (Gill *et al*. 1978). A variety of measures of flammability have been used in the laboratory (see Gill and Moore 1996) but some are more readily translated into the field than others.

Plucinski (2001) determined ignitibility in the laboratory by applying a standard ignition source to a tray of litter and measuring the success of that ignition by the spread of the fire to the edge of the tray. He found wide differences in the ignitibility of litter beds made of different species, the extremes being *Banksia ericifolia* — which failed to ignite even at low moisture content — and *B. serrata* — which ignited at relatively high moisture content. Fuel bed characteristics as well as particle characteristics were important in these results.

Fires are usually measured in the field according to rate of spread, *ROS*, and intensity, *I*, with units m sec^{-1} and kW m^{-1} respectively. *H* is the heat yield of the fuel in kJ kg^{-1} and is usually regarded as a constant:

$$I = H W_r ROS \quad \text{(Byram 1959a).}$$

Flame dimensions are important to some phenomena, such as the propensity for the forest canopy at various heights above ground to catch alight: flame depth, *d*, is the distance from the leading to the trailing edge of the flame at ground level, while flame height above ground and flame length are self explanatory. The time for the fuel bed to burn by flame at any point is called the 'residence time' in field studies, and is equivalent to 'sustainability'. Residence time, t_r, is equal to flame depth divided by fire rate of spread and, because these two variables are linearly correlated with a zero intercept, t_r remains constant when fuel loads are constant (McArthur 1967), but is proportional to litter fuel load (Cheney 1981). Similarly a burnout time, t_b, can be seen as equivalent to the laboratory concept. These measures are classic fire behaviour measures (see Cheney 1981). Combustibility can be considered as W_r/t_r as in the laboratory, but needs a spatial variable as well (weight per unit area) in the field; adding heat yield, *H*, makes the measure more general (Cheney 1981). 'Intensity' is a suitable field measure of 'how well the vegetation burns'. Intensities up to 100 000 kW m^{-1} — an enormous rate of heat release — may be possible in some south-eastern eucalypt forests (Gill and Moore 1990).

The variable 'ignition delay time' is difficult to apply in the field in the same way as in the laboratory but the concept of ignitibility is manifest in fire *ROS*: the more ignitable the material, the faster the *ROS*. Ignitibility will be affected by environmental factors as well as vegetation variables, just as it is in the laboratory. Thus, ignition delay time in the laboratory is shortest for dry, thin leaves exposed to a strong ignition source (Gill and Moore 1996). In the forest, a simple examination of fuels, live and dead, large and small, does not adequately describe forest flammability because variables such as terrain and weather can have a major effect also.

A novel way of describing ignitibility in the field would be to consider it to be the 'delay' in the ignition of any point on the forest floor — from one fire to the next. This is not the delay between the time of applying an ignition source to the point and measuring the seconds it may take to catch alight as in the laboratory: rather it is the time between fires at that point; it introduces the chance of an ignition source being present, rather than given, and is usually a fire arriving at that point rather than being the point of origin of the fire. This concept represents a change in time scale for 'ignitibility' and can be called 'probability of burning at a point'. The probability of burning at a point is mathematically related to the statistical distribution of between-fire intervals and times-since-fire (McCarthy *et al*. 2001). Average intervals between fires in Australian forests before white settlement have been estimated to vary from about 3 y in jarrah (*Eucalyptus marginata*) to 300 y in southern rainforests (Gill and Catling 2002).

Table 1 provides a summary of variables appropriate to flammability.

Predicting flammability

The Australian tradition for the study of fire behaviour has been to informally divide plant communities into types, such as 'grassland', 'forest' and 'shrubland', rather than to explicitly use plant and community attributes affecting flammability (like those in Table 2) to form the basis of a classification. As demand increases for greater accuracy for a wider variety of forests, further attention to understorey species and their effects is likely. For example, the presence of succulent shrubs such as the introduced boneseed (*Chrysanthemoides monolithera*) at high density will reduce the flammability of the community and call for an adaptation of current models. Alternatively, in eastern Victoria, a native species, a scrambling, climbing, native grass called wiregrass (*Tetrarrhena juncea*), significantly raises the flammability of that forest, considered one of the most flammable in Australia (Buckley 1990; Fogarty 1993). By observation, one would expect that the flammability among eucalypt forests would vary significantly between tall open forests with a rainforest understorey and the relatively short forests of stringybarks with wiregrass and sclerophyll shrubs, for example. Furthermore, the east coast forests with a tussock-grass understorey would be expected to differ substantially from similar forests with a litter-only understorey.

In the United States, a more general approach to predicting flammability has been used, based on a set of plant organ and vegetation attributes together with a general fire model (Rothermel

Table 1. Measures of 'flammability' appropriate to scale

Scale	Measures of:			
	Ignitibility	Combustibility	Sustainability	Probability of burning at a point
Leaf and whole plant	Ignition delay time	Weight loss rate; flame length or flame volume	Duration of flaming or of total weight loss	n.a.
Vegetation community	Rate of spread	Intensity; flame length or volume; combustion depth (peat)	Flame residence time or burnout time	Between-fire interval

Table 2. Plant factors affecting flammability at different plant scales (see also Tran *et al*. 2001 for an overlapping list)

Organ attributes (leaves, twigs, stems)	Whole-plant attributes (in addition to all organ attributes)	Community attributes (in addition to all whole-plant attributes)
Chemical composition[1,2] (lignin, water, minerals, volatiles)	Plant architecture (packing)	Fuel-species composition including native and exotic species
Surface area : volume ratio[2,3]	Amounts of dead and live material in canopies	Structural array of fuel species
Particle density[2,3]	Amount and compaction of dead plant material[3] on ground	

[1]Owens *et al*. (1998); [2]Dimitrakopoulos (2001); [3]Catchpole *et al*. (1998)

1972). This was adopted for predicting fire spread — though a set of 13 standard models (Albini 1976) was found to be of practical convenience. Recently, however, Sandberg *et al*. (2001) have proposed a new, wider, system of fuel description because 'The existing fuel models do not accurately characterize the actual fuel character and variability found in nature'. Their system involves six 'fuelbed strata' (e.g. 'canopy' and 'ground fuel'), 'fuelbed categories' (e.g. 'shrub' and 'needle drape'), 'physiognomic variables' (e.g. 'litter type' and 'litter arrangement') and 'gradient variables' (e.g. 'height', 'width', and 'length'). The authors' aim was to 'create a system that may eventually have international applicability'. Such systems make the organic elements of flammability explicit.

A step in the same direction has been made for Australian forest fuels with the evolution of a guide to forest fuel arrays (McCarthy *et al*. 1999). The guide considers the influences of litter on the forest floor, bark in situ, 'near-surface fuels' of 'grass tussocks, dead bracken, low shrubs or low wiregrass up to 0.5 m high', and 'elevated fuels' consisting of shrubs and suspended material. The crowns of the trees are not considered.

The flammability of Australian forests shows extreme variation in time and space. Maximum flammability is that found when a forest with dry litter, thick loose bark (stringybark) and abundant fine understorey fuels is exposed to extreme fire weather over a wide area in rugged terrain. Minimum flammability occurs when everything is wet. Despite the apparent ease of predicting the extreme conditions, predicting flammability in general is not simple.

Predicting rate of spread in Australia

Current Australian fire behaviour models use various inputs to predict *ROS* of fires burning with the wind. Using *ROS* together with the amount of fuel burnt, an intensity value can then be calculated. The models provide an example of the effects of weather and slope on flammability. The equations of Noble *et al*. (1980) express the quantitative relationships between fire weather and *ROS* of the McArthur forest fire model (McArthur 1967). The variables used for predicting forest fires are air temperature, relative humidity, drought index (an index of soil moisture), daily rainfall, numbers of days since the last rainfall and wind speed in the open at a height of 10 m. Drought index has no direct relationship with fire-behaviour outputs but may relate to live-fuel moisture, the successive involvement in the fire of litter, shrubs and bark, large-dead fuels and tree canopies, and to landscape continuity of fuels. These variables are not explicit in Australian fire behaviour guides and predicting the importance of these is a challenge. 'Slope' is the only terrain variable used. In the McArthur model (Noble *et al.* 1980), fire rate of forward spread doubles for each 10° of slope and each 30 km h^{-1} addition of wind speed.

The inputs to the fire behaviour models are those from weather stations (in practice) and contour maps or those measured on-the-spot (in research), and a consideration of these gives some idea of limitations to prediction. For example, Takken and Croke (2004) estimated slopes from a 20-m resolution Digital Elevation Model (DEM); then compared them with field measurements. They found that slope calculated from the DEM generally underestimated it, an effect that was most obvious above about 10° among the very wide scattering of data points. An example for wind speed is that from the major weather station at Sydney airport. There, developments around the airport decreased the wind speed by an estimated 15% while instrument problems caused an underestimate of wind speed of about 2.6 m sec^{-1} (9.4 km h^{-1}) (Potts *et al*. 1997).

Uncertainties in inputs can lead to serious errors. Trevitt (1991) looked at the sensitivity of fire *ROS* models in Australian forests to wind and moisture content. He found an extreme sensitivity to moisture content when moisture contents were low, and a lesser but significant sensitivity to wind inputs. The seriousness of these problems depends on the application but, for prediction of fire rates of spread, such errors are highly significant under the most severe conditions. Because of problems of input errors, intrinsic variation and the assumptions made in models, a probabilistic approach to fire prediction (Burrows 1994 p.239) seems worth pursuing (Fujioka 2001; Gill 2001). Rather than predicting a fixed single value for *ROS*, values within certain limits would be forecast.

The numbers of variables used in any model is deliberately kept to a minimum. The aim is to achieve the maximum output for the minimum input. This leads to some practical and conceptual difficulties. Five examples follow.

The first example is the discovery that the width of the head-fire, a variable not included in current models, affects fire *ROS* (Cheney *et al*. 1993; Cheney and Gould 1997). This means that the *ROS* cannot be considered in isolation from the fire's history. The assumption in current models is that rates of spread have reached quasi-equilibrium levels.

It is well known that atmospheric conditions affect fire behaviour (McArthur 1967), especially under extreme conditions (Byram 1959b), but these do not appear in Australian models, a second example. Their inclusion is not a simple matter. Modelling the fire–atmosphere interaction is complex, computer demanding and very sensitive to the quality of data inputs (Jenkins *et al.* 2001). Data suitable for this are available at few weather stations in Australia.

Thirdly, forest structure is not yet linked into fire behaviour models, although increases in *ROS* can be 'dramatic' as successively taller strata are engaged (Cheney and Gould 1997).

The fourth example is the exclusion of the effects of spot fires on fire *ROS*. Cheney and Bary (1969) noted that 'concentrated short distance spotting can … increase the rate of spread by a factor of 3 to 5 times that which would occur without spotting'. This 'spotting' is caused by burning brands of bark and other material which vary widely in their occurrence. Spotting potential of eucalypt bark varies from 'very low' for ironbarks like *E. sideroxylon*, to 'very high' for stringy-barked species like jarrah, *E. marginata* (Cheney and Bary 1969). The rates of spread measured by Gould *et al*. (2001) in jarrah forest tended to be faster than those predicted by Western Australia Tables or McArthur's model, but this could have been due to the algorithms of the model rather than spotting behaviour.

The final example of difficulties in predicting the rate of even forward fire spread — the most intensively studied variable — is in relation to the slope × wind interaction. The difficulty is that wind may vary significantly as a function of the position on a slope and the nature of the vegetation (Cheney *et al*. 1992). However, these cannot readily appear in a fire behaviour guide although it is theoretically possible to include them in geographic information systems. This example shows the variation in the wind reduction from that in the open and implicit in the model. Forest height and the variety in heights and densities of shrubs across forest types will affect this factor.

Fire rates of spread combine with fuel loadings to estimate fire intensity. Rates of spread with the wind have been considered above; attention now focuses briefly on fuel.

Fuel

Forest fuels of various types usually increase to a quasi-equilibrium loading as a function of 'time since fire' (Raison *et al*. 1983). However, one fuel component, shrubs, may increase, reach the end of their life span, collapse (McCaw 1986), then gradually disappear from the fuel array. Changes in succession or understorey dynamics may introduce species of different flammability.

In litter accumulation models, yearly accessions and decomposition rates are considered to be constants. This is a useful way of averaging variations in decomposition rates and the yearly accessions of materials with different flammabilities (such as bark, leaves and twigs), but seasonal and between-year variation may also be important in affecting fuel loads and its fire consequences (Mercer *et al*. 1995). The composition of the litter may change with time (Simmons and Adams 1986).

The importance of fire climate

Fire behaviour guides provide some insight into the flammability of forests according to various weather variables but they do not provide the weather context. To do this, the Forest Fire Danger Index (FFDI) of McArthur (1967), expressed as equations (Noble *et al*. 1980), can be applied to the weather record. The input variables have been noted above. To illustrate the fire climate, the weather record of Canberra in the Australian Capital Territory (ACT) is used as an example (Lindesay *et al*. 2004). About 50 y of daily 3 pm data are available.

The logarithm of the frequency of days with FFDI in 10-unit classes was almost linear across the whole range from zero to 100, but there was a small lift in frequencies at the start and end of the sequence. On average about two days per year were in the 'extreme' range. Most 'extreme' days were in January, the time of the extensive and severe 2003 fires near Canberra.

Modifying forest flammability by management practice

Because the intensities of fires, along with their spot-fire potential, can exceed the limits of fire control, modifying the flammability of forests becomes an important issue. In Australian forests this is usually done by prescribed burning, but grazing is used at times where the grass component is significant. Mechanical intervention is sometimes used.

Management burning in jarrah fuels was seen to be needed before critical levels of 'flash' fuel loads were attained (Underwood and Christensen 1981). The suggested critical fuel load is 8 t ha^{-1}, the level at which fires burning under the 'worst' weather conditions but on level ground may be expected to be controlled (see Gill *et al*. 1987). A target of around 70% areal coverage by prescribed burning has been suggested as an effective level to limit the spread of unplanned fire (see Gill and Moore 1997).

In a review of fuel data, Walker (1981) quoted the levels of litter accumulation in Australian forests at quasi-equilibrium to be up to 40 t ha^{-1}; about half this value might be considered more common but this is well above 8 t ha^{-1}. Bark on trees may also be a significant contributor to fuel load. Peet and McCormick (1965) estimated that nearly 10 t ha^{-1} of the bark on jarrah may be consumed in an intense fire. Buckley (1990), in Victoria, considered that 'the modification of the shrub layer and the bark on the stringybark trees, as well as the reduction of litter fuels' was an important part of prescribed burning. Buckley (1990) found that the dry weight of twigs and leaves <6 mm diameter forming shrub crowns in a East Gippsland forest was around 5 t ha^{-1}.

Prescribed burning will be practised most where the quantity of fuel at quasi-equilibrium levels is too great to permit effective suppression under extreme weather conditions. Fires are ignited under mild weather conditions to burn litter under the forest canopy, ideally without crown scorch. The history of prescribed burning varies with forest jurisdictions, the Western Australian case perhaps being the best documented (see Gill and Moore 1997). The changing extents of prescribed burning (e.g. Gill and Moore 1997) automatically change the fire regime there.

Trees and their understoreys may be expected to interact such that loss of tree canopy would allow greater growth of the understorey. Opening up of canopies by logging and thinning, or through the death of trees caused by feral pig activity or insects and disease, may allow species like the exotic shrub *Lantana* spp. to invade. In a rainforest example, *Lantana* proliferated in the more open conditions and supported intense fires which reduced the tree canopy until *Lantana* completely dominated the site (Fensham *et al*. 1994).

Forest flammability can also be modified by changing the pattern of ignition or by effective suppression of fires. Most fires are small but a few large fires will have a disproportionate effect on fire interval. The Victorian 'Fire Ecology Working Group' (2002) analysed the data available concerning the current between-fire interval for Victoria's plant communities and decided that fire intervals across the landscape were generally too long to sustain most of them. This exemplifies the idea that fire suppression may be so successful that fire intervals increase, fuels build up and fires that escape suppression efforts attain much higher intensities than would have occurred otherwise.

Johnson *et al*. (2001) argued that effective suppression may have changed the fire situation in North American forests where understoreys had been kept short by frequent fires but, when fire intervals later increased, grew to establish continuity of fuels from ground to crown. However, this was not the case, they argued, for boreal forest and other closed canopy communities in North America with 'crown-fire regimes'. In Australian eucalypt forests fine litter fuels build up until a quasi-equilibrium amount is reached; bark and shrubs may do the same but perhaps at different rates. Thus, if fires have already occurred at intervals greater than the time to reach quasi equilibrium for fuels, then extending that interval may have little effect on fire size if fuel is the controlling variable. The critical question is at what interval fires have occurred throughout the history of human occupation of the country, let alone the changes that have taken place in the last 200 y. The limited historical data available were reviewed by Gill and Catling (2002).

Future changes in flammability

Climate change is usual, but the current changes in climate and earth systems are unprecedented, rapid, and human induced (Laurance 2001). Beer and Williams (1995) have used two models of the projected changes in the annual sum of FFDI (ΣFFDI) across Australia: both models show an increase in ΣFFDI for most of the country but there are differences between the projections. In south-eastern and south-western Australia, an increase in ΣFFDI is common to both models.

Cary (2002) has estimated what the potential effects on fires would be of climate projected for the year 2070. He used a process-based model of fire occurrence that accounts for lightning ignitions, terrain, weather, and fire spread and extinguishment, for the forests of the Brindabella Ranges in the ACT. The model was run repeatedly to give an indication of the fire intervals to be expected in the landscape. Fuels in the model are assumed not to change in type. The model projects that intervals between fires will shorten under the 2070 weather scenario.

Other changes are likely to impinge on the between-fire interval distributions in forests. With increasing human populations there is likely to be a greater frequency of ignitions. With climate change and changed fire regimes (*sensu* Gill 1975) there are likely to be changes to fuels in ways that are presently unknown.

Discussion and conclusion

The flammability of Australia's forests is significant at various scales. From a structural point of view the scale varies among single elements from strips of bark — significant for the behaviour of burning brands — to that of hollow trees where ember production and habitat are important matters. Also, scale varies amongst aggregates of elements: from litter beds — significant in low-intensity fires — to the whole forest structure where fire suppression and plant-population responses are important. Flammability is significant also from the scale of plants of a single species — for evolutionary considerations — to that of the complete assemblage of plant species forming the forest community, where ecological effects are of importance.

Flammability is a function of the environment. Achieving an adequate understanding of the environment of significance, from the forest floor up through the forest, through the boundary layer and up into the atmosphere for kilometres is a formidable task.

The development of a system comprehensive and versatile enough to serve a wide variety of flammability-related purposes, even for fuel elements (Sandberg *et al*. 2001), is elusive. Part of the difficulty in achieving this is that as the scale changes from litter-fuel bed to whole forest (for example), the number of variables multiplies and the complexity of interactions increases. Some categorisation within a general system seems inevitable for convenience, at least.

The above discussion presupposes that there is an agreed definition of flammability. In this paper, the terms of Anderson (1970) have been used — ignitibility, combustibility and sustainability — or ease of ignition, rate of combustion and length of burning period, but there is a wide variety of laboratory methods (see Gill and Moore 1996). Anderson's terms allow an extension of the concepts from laboratory to field. There they are seen to be manifest as fire *ROS*, intensity and residence times (both flaming and smouldering) respectively. An extension to 'ignitibility' was suggested here — the 'probability of burning taking place at a point' from year to year.

The definitions used have little meaning if values are correlated. While there is some overlap, there are areas of independence. Fire *ROS* in the same fuel type of the same age varies with the weather. Fire *ROS* is a component of 'fire intensity' which has an explicit fuel-load term. Fuel load is also considered to be a variable affecting *ROS* (McArthur 1967), but this conclusion is being reviewed in Project Vesta (CSIRO Forestry and Forest Products and WA Department of Conservation and Land Management). The residence time of the fire is a function of fuel load (Cheney 1981), but independent of fire *ROS* within a constant fuel bed (McArthur 1967). The probability of burning at a point is most likely a function of the chance of occurrence of large fires in a natural system (Strauss *et al*. 1989); this probability is related to a combination of weather, terrain and fuel factors as well as the chances of ignition and effective suppression.

Flammability is manipulated directly and indirectly in Australian forests. Suppression measures have the potential to lengthen the intervals between fires, while prescribed burning may tend to decrease the interval. Prescribed burning takes place at low rates of spread and intensities, while unplanned fires can be of low or extremely high intensity.

Shifts in flammability occurring now — due to changing fuel types, ignition rates and climate — are likely to continue for decades, if not centuries. The attainment of a set of robust validated models of flammability able to cope with such changes is a worthwhile goal.

Acknowledgements

We thank Drs Geoff Cary and Ross Florence for commenting helpfully on the draft manuscript.

References

Albini, F.A. (1976) *Estimating Wildfire Behavior and Effects*. USDA Forest Service General Technical Report INT-30.

Anderson, H.E. (1970) Forest fuel ignitibility. *Fire Technology* **6,** 312–319, 322.

Beer, T. and Williams, A. (1995) Estimating Australian forest fire danger under conditions of doubled carbon dioxide concentrations. *Climatic Change* **29,** 169–188.

Bond, W.J. and Midgley, J.J. (1995) Kill thy neighbour: an individualistic argument for the evolution of flammability. *Oikos* **73,** 79–85.

Bradstock, R.A. and Gill, A.M. (1993) Fire in semi-arid mallee shrublands: size of flames from discrete fuel arrays and their role in the spread of fire. *International Journal of Wildland Fire* **3,** 3–12.

Buckley, A. (1990) *Fire Behaviour and Fuel Reduction Burning*. Victorian Department of Conservation and Environment, Research Report 28.

Bunting, S.C. and Wright, H.A. (1974) Ignition capabilities of non-flaming firebrands. *Journal of Forestry* **72,** 646–649.

Burrows, N.D. (1994) Experimental development of a fire management model for jarrah (*Eucalyptus marginata* Don ex Sm.) forest. PhD thesis, Australian National University, Canberra.

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

Byram, G.M. (1959b) Forest fire behavior. In: Davis, K.P. (ed.) *Forest Fires: Control and Use*. McGraw Hill, New York, pp. 90–123.

Cary, G.C. (2002) Importance of a changing climate for fire regimes in Australia. In: Bradstock, R.A., Williams, J.E. and Gill, A.M. (eds) *Flammable Australia: The Fire Regimes and Biodiversity of a Continent*. Cambridge University Press, Cambridge, UK, pp. 26–46.

Catchpole, W.R., Catchpole, E.A., Butler, B.W., Rothermel, R.C., Morris, G.A. and Latham, D.J. (1998) Rates of spread of free-burning fires in woody fuels in a wind tunnel. *Combustion Science and Technology* **131,** 1–37.

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

Cheney, N.P. and Bary, G.A.V. (1969) The propagation of mass conflagrations in a standing eucalypt forest by the spotting process. *Collected Papers, Mass Fire Symposium,* Canberra, 10–12 February 1969, Paper A6.

Cheney, N.P. and Gould, J.S. (1997) Fire growth and acceleration. *International Journal of Wildland Fire* **7,** 1–5.

Cheney, N.P., Gould, J.S. and Knight I. (1992) *A Prescribed Burning Guide for Young Regrowth Forests of Silvertop Ash*. NSW Forestry Commission Research Paper 16, 92 pp.

Cheney, N.P., Gould, J.S. and Catchpole, W.R. (1993) The influence of fuel, weather and fire shape variables on fire spread in grasslands. *International Journal of Wildland Fire* **5,** 237–247.

Dimitrakopoulos, A.P. (2001) A statistical classification of Mediterranean species based on their flammability components. *International Journal of Wildland Fire* **10,** 113–118.

Fensham, R.J., Fairfax, R.J. and Cannell, R.J. (1994) The invasion of *Lantana camara* L. in Forty Mile Scrub National Park, north Queensland. *Australian Journal of Ecology* **19,** 297–305.

Fire Ecology Working Group (2002) *Analysis of Disturbance by Fire on Public Land in Victoria*. Victorian Department of Natural Resources and Environment, Melbourne.

Fogarty, L.G. (1993) *The Accumulation and Structural Development of the Wiregrass* (Tetrarrhena juncea) *Fuel Type in East Gippsland*. Victorian Department of Conservation and Natural Resources Research Report 37.

Fujioka, F.M. (2001) A new methodology for the analysis of two-dimensional fire spread simulation. In: Pearce, G. and Lester, L. (eds) *Bushfire 2001. Proceedings of the Australasian Bushfire Conference, Christchurch, New Zealand*. Forest Research Institute, Rotorua, New Zealand, pp. 104–111.

Gill, A.M. (1975) Fire and the Australian flora: a review. *Australian Forestry* **38,** 4–25.

Gill, A.M. (2001) A transdisciplinary view of fire occurrence and behaviour. In: Pearce, G. and Lester, L. (eds) *Bushfire 2001. Proceedings of the Australasian Bushfire Conference, Christchurch, New Zealand.* Forest Research Institute, Rotorua, New Zealand, pp. 1–12.

Gill, A.M. and Catling, P.C. (2002) Fire regimes and biodiversity of forested landscapes of southern Australia. In: Bradstock, R.A., Williams, J.E. and Gill, A.M. (eds) *Flammable Australia: Fire Regimes and Biodiversity of a Continent*. Cambridge University Press, pp. 351–369.

Gill, A.M. and Moore, P.H.R. (1990) Fire intensities in eucalypt forests of south-eastern Australia. *International Conference on Forest Fire Research*, Coimbra, Portugal. Proceedings **B**.24, 1–12.

Gill, A.M. and Moore, P.H.R. (1996) The ignitibility of leaves of fifty Australian species. Report to the Australian Flora Foundation, October 1996.

Gill, A.M. and Moore, P.H.R. (1997) Contemporary fire regimes in the forests of southwestern Australia. Report to *Environment Australia*, Canberra. 115 pp.

Gill, A.M., Trollope, W.S.W. and McArthur, D.A. (1978) Role of moisture in the flammability of natural fuels in the laboratory. *Australian Forest Research* **8,** 199–208.

Gill, A.M., Christian, K.R., Moore, P.H.R. and Forrester, R.I. (1987) Bushfire incidence, fire hazard and fuel reduction burning. *Australian Journal of Ecology* **12,** 299–306.

Gould, J.S., Cheney, N.P. and McCaw, L. (2001) Project Vesta — research into the effects of fuel structure and fuel load on behaviour of moderate to high intensity fires in dry eucalypt forest: progress report. In: Pearce, G. and Lester, L. (eds) *Bushfire 2001. Proceedings of the Australasian Bushfire Conference, Christchurch, New Zealand*. Forest Research Institute, Rotorua, New Zealand, pp. 13–21.

Jenkins, M.A., Clark, T. and Cohen, J. (2001) Coupling atmospheric and fire models. In: Johnson, E.A. and Miyanishi, K. (eds) *Forest Fires. Behavior and Ecological Effects.* Academic Press, San Diego, pp. 257–302.

Johnson, E.A., Miyanishi, K. and Bridge, S.R.J. (2001) Wildfire regime in the boreal forest and the idea of suppression and fuel buildup. *Conservation Biology* **15,** 1554–1557.

Komarek, E.V. (1984) Fire, nature and man. In: Ealey, E.H.M. (ed.) *Fighting Fire with Fire.* Proceedings of the Symposium on Fuel reduction Burning, Monash University, September 17–18, 1983. Graduate School of Environmental Science, Monash University, Melbourne, pp. 6–34.

Laurance, W.F. (2001) Future shock: forecasting a grim fate for the earth. *Trends in Ecology and Evolution* **16,** 531–533.

Lindesay, J., Colls, K., Gill, A.M. and Mason, I. (2004) Historical climate and fire weather in the ACT region: a review. Report to ACT Department of Urban Services.

McArthur, A.G. (1967) *Fire Behaviour in Eucalypt Forests*. Commonwealth of Australia Forestry and Timber Bureau Leaflet 107.

McCarthy, G.J., Tolhurst, K.G. and Chatto, K. (1999) *Overall Fuel Hazard Guide*. Victorian Department of Natural Resources and Environment Fire Management Report 47.

McCarthy, M.A., Gill, A.M. and Bradstock, R.A. (2001) Theoretical fire interval distributions. *International Journal of Wildland Fire* **10,** 73–77.

McCaw, L. (1986) *Behaviour and Short-term Effects of Two Fires in Regenerated Karri* (Eucalyptus diversicolor) *Forest*. Western Australia, Department of Conservation and Land Management Technical Report 9.

Mercer, G.N., Gill, A.M. and Weber, R.O. (1995) A flexible, non-deterministic, litter accumulation model. In: *Bushfire '95.* Presented Papers of the Australian Bushfire Conference 27–30 September 1995, Hobart, Tasmania. Forestry Tasmania, Tasmanian Parks and Wildlife Service, Tasmanian Fire Service. 10 pages unnumbered.

Noble, I.R., Bary, G.A.V. and Gill, A.M. (1980) McArthur's fire-danger meters expressed as equations. *Australian Journal of Ecol*ogy **5,** 20l–203.

Noble, W.S. (1977) *Ordeal by Fire. The Week a State Burned Up*. The Hawthorn Press, Melbourne.

Owens, M.K., Lin, C., Taylor, C.A. and Whisenant, S.G. (1998) Seasonal patterns of plant flammability and monoterpenoid content in *Juniperus ashei*. *Journal of Chemical Ecology* **24,** 2115–2129.

Peet, G.B. and McCormick, J. (1965) Bark reduction by intense fires in the jarrah forest. WA Forests Department *Forest Notes* **3**(2)**,** 23–26.

Plucinski, M.P. (2001) Ignition thresholds and fire development in heathlands. In: Pearce, G. and Lester, L. (eds) *Bushfire 2001*. Proceedings of the Australasian Bushfire Conference, Christchurch, New Zealand. Forest Research Institute, Rotorua, New Zealand, pp. 36–42.

Potts, R., Monypenny, P. and Middleton, J. (1997) An analysis of winds at Sydney Kingsford Smith airport. *Australian Meteorological Magazine* **46,** 297–310.

Raison, R.J., Woods, P.V. and Khanna, P.K. (1983) Dynamics of fine fuels in recurrently burnt eucalypt forests. *Australian Forestry* **46,** 294–302.

Rossiter, N.A., Setterfield, S.A., Douglas, M.M. and Hutley, L.B. (2003) Testing the grass-fire cycle: alien grass invasion in the tropical savannas of northern Australia. *Diversity and Distributions* **9,** 169–176.

Rothermel, R.C. (1972) *A Mathematical Model for Predicting Fire Spread in Wildland Fuels*. USDA Forest Service Research Paper INT–115.

Sandberg, D.V., Ottmar, R.D. and Cushon, G.H. (2001) Characterizing fuels in the 21st century. *International Journal of Wildland Fire* **10,** 381–387.

Simmons, D. and Adams, R. (1986) Fuel dynamics in an urban fringe dry sclerophyll forest in Victoria. *Australian Forestry* **49,** 149–154.

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

Takken, I. and Croke, J. (2004) Modelling road to stream connectivity: the development of a cost-effective framework using GIS. In: Croke, J., Mockler, S. and Takken, I. (eds) *Forest Management Workshop Proceedings.* Canberra 23–25 March 2004. CRC for Catchment Hydrology, Canberra. Pages unnumbered.

Tran, C., Wild, C. and Zubrinich, T. (2001) Testing Mutch's hypothesis in southeast Queensland: plant flammability revisited. In: Pearce, G. and Lester, L. (eds) *Bushfire 2001*. Proceedings of the Australasian Bushfire Conference, Christchurch, New Zealand. Forest Research Institute, Rotorua, New Zealand, pp. 43–52.

Trevitt, A.C.F. (1991) Weather parameters and fuel moisture content: standards for fire model inputs. In: Cheney, N.P. and Gill, A.M. (eds) *Conference on Bushfire Modelling and Fire Danger Rating Systems*. Proceedings. Australian Forestry Council, Canberra, pp. 157–166.

Underwood, R.J. and Christensen, P.E.S. (1981) *Forest Fire Management in Western Australia*. Forests Department of Western Australia, Perth. 34 pp.

Walker, J. (1981) Fuel dynamics in Australian vegetation. In: Gill, A.M., Groves, R.H. and Noble, I.R. (eds) *Fire and the Australian Biota*. Australian Academy of Science, Canberra, pp.101–127.