

Research priorities arising from the 2002–2003 bushfire season in south-eastern Australia

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Summary

A range of research priorities arising from the 2002–2003 bushfire season in south-eastern Australia are presented. Research imperatives relate to questions about the ignition of fires, the spread of fires in landscapes, the impact on ecosystems, and about managing bushfire risk in a changing world. Research leading to improved understanding of spatial patterns of lightning-fire ignitions will lead to increased efficiency and effectiveness of prescribed burning programs. Similarly, analysis of initial fire-attack success under severe drought conditions may result in improved management of fire ignitions. Models of fire spread that are effective in the domain of severe fire weather are lacking and research into improving fire models is suggested. There is also a need for analysis and simulation of the effectiveness of programs of prescribed burning in reducing bushfire risk at the landscape scale. Related to this is the need for resolving long-lasting and contentious debates about the nature of fire regimes in south-eastern Australia prior to modification by Europeans. Given their geographical extent, the 2002–2003 fires provide a rare opportunity for well-replicated and rigorous evaluation of fire ecology theory developed over the last 25 y. Research on the impact on water supplies is also a priority. The world is also changing. The recent fires have enhanced speculation about the possible impacts of climate change, one aspect of global change, on fire regimes. The ultimate aim of applied fire research must be toward an optimal solution to the sustainable management of bushfire risk.

Keywords: research; project identification; ignition; fuel; environmental management; fire ecology; fire behaviour; fire control; Australia

Introduction

Fire fighters, land managers, members of the community and scientists who observed events during the 2002–2003 bushfire season in south-eastern Australia generated a plethora of research questions about what unfolded before them. The nature of those questions would vary depending on the interests and discipline of the observer, and the location and particular nature of the events they witnessed. Questions also arose from the numerous inquiries held into the conflagrations of that summer.

The topics explored in this contribution range from questions about the effectiveness of prescribed burning and initial fire-attack

success, to those related to the ecological impacts of the recent fires and past fire management (including during the pre-European era), and to questions about the role of climate change and the management of bushfire risk in a changing world. A broader list of research questions is presented in Cary *et al.* (2003) (the proceedings of a national bushfire forum held coincidentally less than a month after the peak of the major fires in 2003), and in Bradstock *et al.* (2002), a collection of papers on fire regimes and biodiversity of Australia.

Some of the research proposed here is already being undertaken within the Bushfire Cooperative Research Centre, some by scientists not involved with the CRC, and some is not being addressed at all. It is not the intention of this paper to review research recommendations from the numerous inquiries into the 2002–2003 fires, especially given that several inquiries are not complete, or have not released findings, at the time of writing. Rather, the aim is to promote discussion about bushfire research relevant to the readership of this journal and encourage scientists and students to engage with these issues in a rigorous and objective manner.

Questions about fire ignitions

Spatial pattern of lightning ignition

Most fires ignited around 8 January 2003 in south-eastern Australia resulted from dry-lightning storms. Land managers wishing to optimise programs of prescribed burning to assist fire suppression are interested in knowing where lightning ignitions are more likely to occur. Effective and efficient programs of prescribed burning can be guided by knowledge of areas with the highest likelihood of lightning ignition.

McRae (1992) has presented a model of areas prone to lightning ignition. The model invokes de-trending techniques to remove large-scale trends in elevation (known as the macro-scale elevation) to produce a meso-scale elevation residual (MSER) surface. This surface is defined as the actual elevation of a point minus its macro-scale elevation so that terrain features such as hills and ridges that rise above the surrounding landscape, at a particular scale, have a positive value of MSER and features such as valleys that are below the surrounding landscape have negative values. McRae (1992) found that lightning ignitions between 1971 and 1989 in the Australian Capital Territory (ACT) (Fig. 1) were



Figure 1. Location of ignition records that were reliably identified as lightning-caused, ACT, 1971–1989 (reproduced from McRae 1992)

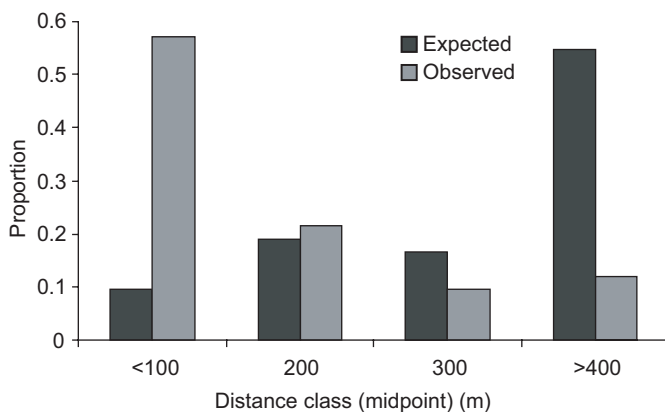


Figure 2. Proportion of expected and observed lightning ignited fires in 100 m distance classes from the zero meso-scale elevation residual contour, ACT, 1971–1989 (data from McRae 1992)

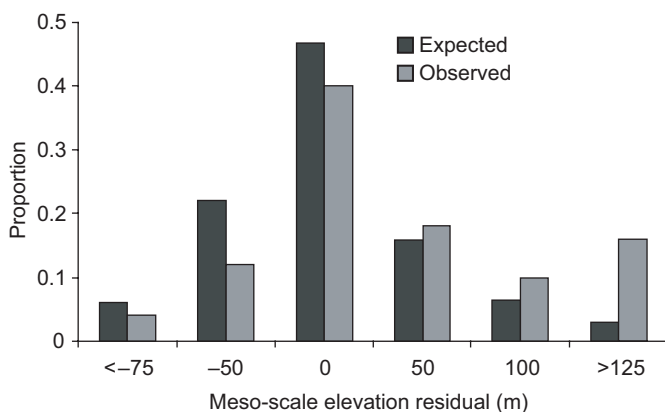


Figure 3. Proportion of expected and observed lightning ignited fires in 50 m classes of meso-scale elevation residual, ACT, 1971–1989 (data from Cary 1998)

more likely to occur nearer to the zero MSER contour, defined as the line joining points in the landscape that had zero MSER, than would be expected by chance (Fig. 2). Using the same data set, Cary (1998) presented an alternative interpretation, that is lightning-ignition location was unrelated to distance from the zero MSER contour but better explained by the MSER of a site itself (Fig. 3).

The large number of lightning-ignited fires during the 2002–2003 season provides an opportunity to further investigate spatial patterns of lightning fires at the commencement of a major fire event. Further, technology not available to McRae (1992), and capable of locating cloud-to-ground lightning strike location, irrespective of whether it results in ignition, now exists. Models of spatial patterns of lightning strike or fire occurrence can be developed using either data source by invoking the methods described by McRae (1992) and Cary (1998). Information on parts of the landscape with a high propensity for lightning ignition may assist managers in determining the optimal patterns of prescribed burning for the maximum reduction of bushfire risk, given that the overall fuel array is important for managing fire ignitions.

Initial fire-attack success

Successful initial fire-attack prevents a fire ignition from developing into a larger fire requiring a different approach to suppression, and therefore is discussed in this section on questions about fire ignition. The likelihood of successful initial attack on a fire is a probabilistic variable even though the actual outcome of initial fire-attack is binary (success or failure). Given a particular set of fuel, weather and terrain circumstances, some fires will be successfully suppressed in the initial phase while others will grow beyond the initial-attack size: hence the probabilistic nature of the process. In a major advancement in our understanding of initial fire-attack success, McCarthy and Tolhurst (1998) studied factors contributing to initial-attack success for 2038 fires that occurred in fire protected areas in Victoria from the 1991–1992 to the 1994–1995 seasons. The 2002–2003 season presents an opportunity to ask how the probability of initial attack success is affected by severe drought, a situation outside the domain of the existing model.

McCarthy and Tolhurst (1998) found that the two variables with greatest explanatory power with respect to initial-attack outcome were the Fire Danger Index (McArthur 1973) and Overall Fuel Hazard, an index describing the levels of surface fine fuel, near-surface fine fuel, elevated fuel and bark fuel (McCarthy *et al.* 1998) (Fig. 4). It is likely that the curves representing the probability of initial-attack success would shift to the left given severe drought conditions because of the almost complete availability of fuel, the propensity for sustained glowing combustion, and a greater likelihood of failure of control lines.

The 2002–2003 fire season may provide an invaluable opportunity to refit McCarthy and Tolhurst’s (1998) model for severe drought conditions. The extent that this can be achieved will depend on constraints on data availability, particularly for fuel data. However, the overriding importance of initial fire-attack success in determining overall bushfire risk warrants further research.

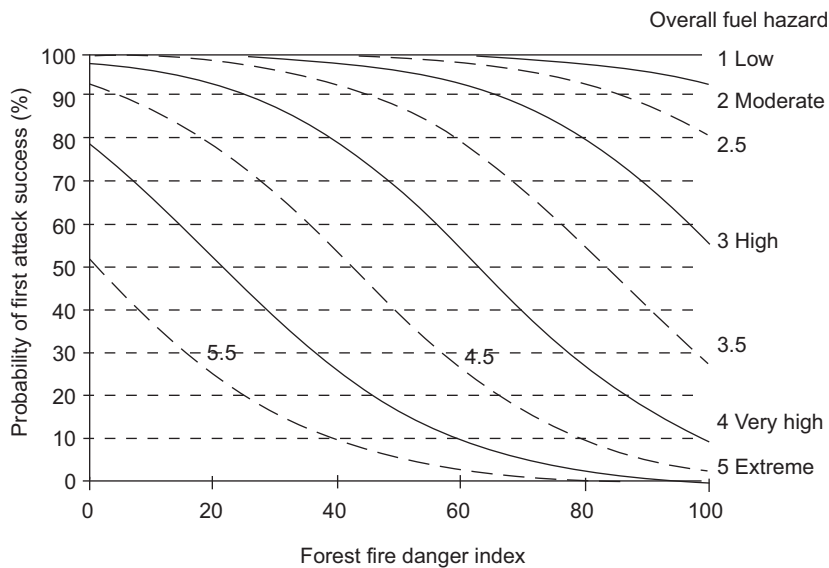


Figure 4. Probability of initial-attack success for Victorian forests according to the Forest Fire Danger Index and Overall Fuel Hazard (Source: McCarthy and Tolhurst 1998, reproduced with permission of the authors)

Questions about spread of fire in landscapes

Rate of fire spread

As with any series of major fire events, questions about the adequacy of models of fire spread were raised during and after the 2002–2003 fire season. It is generally accepted that the fire behaviour table on the reverse of the Forest Fire Danger Index (McArthur 1973) under-estimates rates of spread at high wind speed. This has been confirmed by research on the behaviour and spread of high-intensity bushfires in dry eucalypt forests (i.e. Project Vesta, *pers. comm.* Jim Gould, CSIRO 2004).

The uncertainty surrounding predictions from models of fire spread is a major constraint to effective planning during fire events, general fire management, and simulation modelling of fire events and regimes. The performance of existing models of fire spread (e.g. McArthur 1973; Cheney *et al.* 1998) and others yet to be published (e.g. CSIRO Project Vesta) must be continually subject to rigorous evaluation against records of observed fire behaviour to determine what level of error may be expected in predicted spread rates, especially under extreme conditions.

The behaviour of the 2002–2003 fire events, particularly those that occurred in the ACT region, have been the subject of unprecedented investigation, largely in response to the numerous inquiries resulting from them. These inquiries provide a valuable opportunity to compare observed and predicted rates of fire spread across a range of meteorological and topographic conditions. It will be argued by some that it is impossible to determine fuel, meteorological and slope inputs with sufficient accuracy for a fair model test. Nevertheless, slope estimates are available from high-resolution digital elevation models. Some information on meteorological conditions is available from on-ground measurements, measurements at fire towers and from automatic

and standard weather stations. Fuel loads can be estimated from fuel accumulation curves (Walker 1981; Raison *et al.* 1983; Hutson and Veitch 1985; Raison *et al.* 1986) and time since the previous fire. Estimates of other fuel array characteristics required by newer models may be difficult to obtain, but might be reasonably estimated by practitioners with sufficient knowledge of particular localities.

Testing of fire spread models should be represented in the form of a graph of predicted rate of spread (vertical axis) versus observed rate of spread (horizontal axis) so that the extent of margins of error in predicted rates of spread are apparent. Gill (2001) and Wasson (2003) argue that predictions of spread should be presented in the form of probabilities of different spread rates, although none of the models currently used in Australia produce this. The analysis should not be limited to observations from the 2002–2003 fires but should include observations from a wide

range of fire events, particularly those characterised by rates of spread beyond contemplation for experimental research. In the absence of the research outlined here, confidence in predictions of fire spread under very high and extreme fire danger conditions will remain low, and this will significantly limit the usefulness of the models for the purposes outlined above.

There should be no *a priori* expectation that empirical models developed for relatively benign weather conditions will perform successfully under conditions of very high or extreme fire danger. A new empirical model, designed specifically for these conditions, may outperform existing models irrespective of poor estimates of independent variables (terrain, fuel, meteorological conditions). The 2002–2003 fire season provides an opportunity to address this.

Effectiveness of prescribed burning

Questions about the effectiveness of prescribed burning (as a bushfire risk reduction strategy) are inevitable after major fire events and the inquiries resulting from them (e.g. Esplin *et al.* 2003a). Some individuals and groups advocate significant increases in burning programs while others argue that fuel reduction has little or no impact on the extent of conflagration-scale fires.

Reducing the fuel load at a point will generally result in reduced rate of spread (McArthur 1967) and intensity (Byram 1959) of a fire at that point, all other factors being equal. This may facilitate enhanced suppression effectiveness at that point in the event of direct fire attack, and near that point in the event of indirect attack. Nevertheless, managers are generally, but not solely, concerned about ecosystem and built assets elsewhere in the landscape (e.g. houses at and near the rural/urban interface, plantations, populations of threatened flora and fauna, etc.). Therefore, a relevant question is what effect fuel reduction by prescribed burning at one point in the landscape has on the likelihood of unplanned fire at other critical locations.

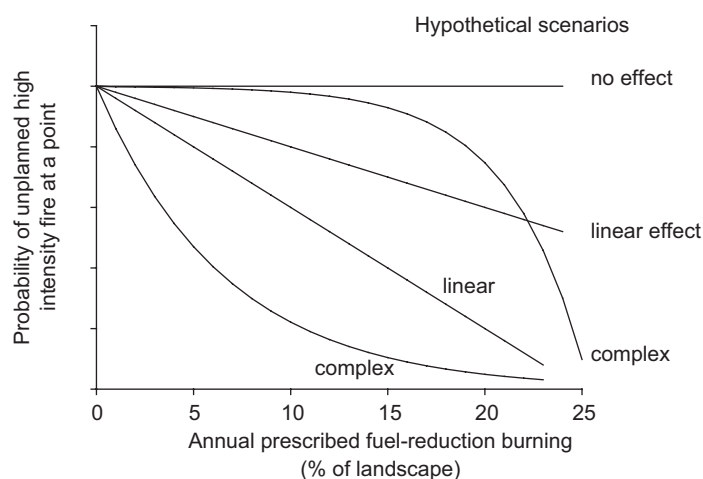


Figure 5. Hypothetical relationships between annual amount of prescribed fuel-reduction burning in a landscape and the probability of unplanned fire (at a point) of sufficient intensity to threaten residential structures at an urban interface of the landscape. Note that these relationships are hypothetical and do not represent results from real landscapes. (Source: Cary and Bradstock 2003).

Cary and Bradstock (2003) defined the problem as a set of two axes, the horizontal axis defining the extent of prescribed burning in a landscape and the vertical axis defining the probability of unplanned fire of sufficient intensity to threaten assets within or adjacent to the landscape (Fig. 5). The extent of prescribed burning in a landscape is a simplistic measure of this management activity and more complex measures that include particular strategies and patterns can be derived. Nevertheless, they argue that:

to have an effective debate about the importance of prescribed burning on the probability of unplanned high intensity fire, the actual relationship between the two axes ... must be rigorously determined. In the absence of this fundamental information, managers and experts can only speculate on critical levels of fuel-reduction burning required to meet particular management objectives. Research to address this problem, determine the general nature of this relationship and test its relevance in real landscapes is required.

This research can be addressed by experimentation, scientific surveys of fire regimes in managed systems, and/or simulation. Experiments are likely to be of limited usefulness in this case because the minimum design would most likely be intractable from financial, temporal and operational perspectives, and would yield insight only into effects of prescribed fire in one landscape type (e.g. with a particular topographic complexity). On the other hand, a combination of surveys of managed systems and simulation models of fire regimes in landscapes (Gardner *et al.* 1996; Li 2000; Keane *et al.* 2002; McCarthy and Cary 2002), provided they are rigorously validated, provides the most promise in addressing this fundamental research question.

Prescribed burning remains the most contentious aspect of fire management, both domestically and internationally (Keeley and Fotheringham 2001; Minnich 2001; Fernandes and Botelho 2003). It will remain so until evidence in the form of the analysis outlined above is collected and validated by a range of researchers and managers. The 2002–2003 bushfire season, and the debate surrounding it, has reinforced this conclusion with great effect.

Nature of Aboriginal fire regimes

Questions about the nature of pre-European fire regimes are inevitably raised in association with major fire events. These are of historical interest, and are related to — and can be as contentious as — debates over prescribed burning for fuel reduction. A range of commentators have argued that adopting a regime of frequent, low-intensity fire, which apparently mimics that resulting from Aboriginal practices in pre-European, south-eastern Australia, would limit the extent of high-intensity bushfires, although others argue that any attempt to introduce aboriginal burning regimes in south-eastern Australia would be an experiment in land management (Esplin *et al.* 2003b).

The fundamental research question — what were the fire regimes of the past? — with respect to the nature of pre-European fire regimes remains unanswered. Banks (1989), in discussing a history of forest fires in the Australian Alps, stated that

it is possible to recognise three inter-connected and overlapping, but separate phases based on sources of information. They are a folklore phase which accumulates oral accounts of important fires, fire frequencies and fire use; a historical phase which is the repository of the written record of actual fire events and a dendrochronological phase which provides detailed records of fires in forest stands drawn from tree fire scars and related sources.

Banks' (1982, 1989) dendrochronological study provides data on the frequency of scarring in the snow gum forests of the Brindabella Range, ACT, between 1746 and 1975. His data indicate a low frequency of fire-scarring prior to European contact compared with a relatively higher incidence after the mid-1840s (Fig. 6). A simple explanation for the pattern is that European-style land management resulted in a large increase in the frequency of fire. However, Bowman (1998) raised an alternative interpretation that suggested the increase in the number of fire scars in Banks' fire history reflected a shift from frequent, low-intensity fires to frequent, high-intensity fires. In extending the thesis of Burrows *et al.* (1995), Bowman (1998) argues that:

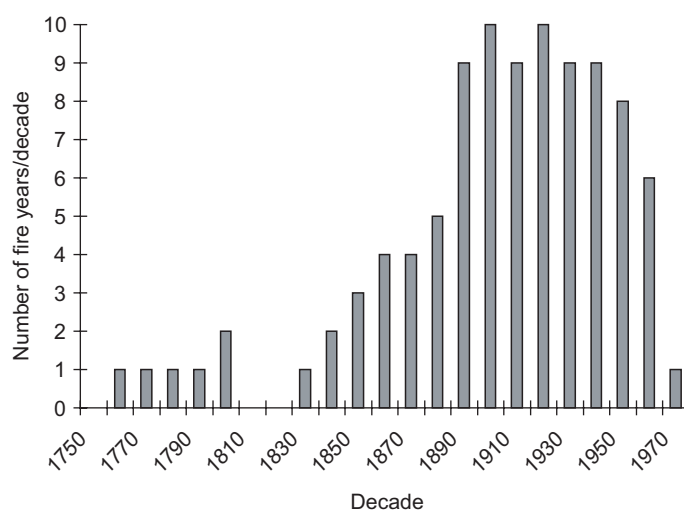


Figure 6. Temporal trends in the total number of fire years recorded per decade across all stands in a dendrochronological study of fire frequency in snow gum on the Brindabella Range (adapted from Banks 1982)

given the fire prone environments in which *Callitris glaucophylla*, *Eucalyptus marginata* and *Eucalyptus pauciflora* occur, the absence of fire scars cannot reasonably be interpreted as an absence of fires.

Richards *et al.* (2001) conducted a comprehensive survey of fire damage to snow gum (*Eucalyptus pauciflora*) in the Piccadilly Circus Fire Ecology Plots, a (then) 25-y-old, manipulative fire-regime experiment on the Brindabella Range, ACT. The field survey demonstrated that around six out of every ten fires resulted in damage consistent with scarring in snow gum, even for the lowest-intensity fires in the most frequently burnt plots (burnt every 2–4 y). The number approaches eight scars out of ten fires if the more frequently scarred trees (upper 50th percentile of trees with respect to maximum number of segments of the dry face) are analysed in an attempt to more closely mimic Banks' method of selecting trees for his study. These results suggest that Banks' fire history may not support the hypothesis of frequent Aboriginal burning of snow gum forest in the Brindabella Range as suggested by some authors.

Researchers should continue to study the nature of pre-European fire regimes, using a range of independent methods, because they will continue to form the basis of arguments about historical fire regimes and their relevance to contemporary fire management.

Questions about ecosystem impacts

There is insufficient evidence to support or to reject the proposition that the major fires of the 2002–2003 fire season were unprecedented in their extent, intensity and effects. Charcoal records in sediments demonstrate that south-eastern Australia has been characterised by relatively constant fire activity over the Holocene period (i.e. the last 10 000 y) (Kershaw *et al.* 2002). If fires of the nature witnessed during the 2002–2003 season re-occurred at a point in the landscape every hundred or so years, then similar events may have occurred at that point in the order of one hundred times since the beginning of the Holocene. If the frequency of severe fire events is greater, then the number increases and *vice versa*. Therefore, it would seem unlikely that the extent, intensity and effects of the 2002–2003 fires were unprecedented.

Nevertheless, history will record that the area burned, and the area burned by high-intensity fires, in south-eastern Australia during the 2002–2003 season was among the greatest recorded for any season since European arrival (around 200 y ago). Therefore, the events provide an unprecedented opportunity to evaluate theories about fire ecology and fire effects developed over the last 25 y.

Ecological impacts

Animal and plant species are adapted to fire regimes characteristically comprised of fire intensity, season, inter-fire interval and type — not to individual fire events (Gill 1975; Gill and Bradstock 2003). That is, the effect of a fire event on a population of a particular species depends not only on the nature of the most recent event, but also on the nature and timing of previous fires that will have influenced the number, maturity and physiological status of individuals (and propagules) in the population. Populations of predators and competitors of the species of interest will also be influenced by past fires.

Some models of the dynamics of species subject to recurrent fire are based on a sound understanding of underlying mechanisms. For example, Noble and Slatyer (1980, 1981) developed a qualitative model of fire succession based on the 'vital attributes' of species (similar to the adaptive traits of Gill 1975), and which facilitates the development sequences of species dynamics through time.

The extent of the 2002–2003 fires, and the spatial variation in their intensity, provide a rare opportunity for rigorous validation of models of fire ecology across a broad range of ecosystems. They provide an opportunity to address questions like: Are the responses of individuals, population and communities of plants and animals to the 2002–2003 fires consistent with the theory of ecological models *and* the characteristics of recent fires *and* the fire history at individual sites?

For example, alpine ash (*E. delegatensis*) is a widely recognised forest tree existing on sheltered aspects of montane landscapes in south-eastern Australia. There is considerable knowledge about the important attributes of *E. delegatensis* that affect likelihood of survival under particular fire regimes, including: (i) a relatively thin bark which, after scorching, does not produce a new periderm quickly (Jacobs 1955); (ii) the absence of a well-formed lignotuber, particularly on high quality forest sites (Gill 1975; Ashton 1981); (iii) poor epicormic sprouting after fire (Jacobs 1955); and (iv) a long period between germination and onset of seed production (after reproductive maturity), and the lack of a dormant seed bank that can survive any period of time (Shugart and Noble 1981). With knowledge of the fire history of any particular *E. delegatensis* stand burnt in the 2002–2003 fires, and the severity with which it was burnt, a prediction about the impact of the most recent fire can be made and subsequently tested. Furthermore, predictions about the dynamics of stands of *E. delegatensis* with time since fire can be tested by implementing long-term monitoring.

The decades following the 2002–2003 fires will provide a valuable research opportunity to test and refine models of the dynamics of species subject to recurrent fire. The extensive nature of the fires of that season provide a rare opportunity to develop properly replicated surveys of plant and animal populations designed to evaluate the robustness of ecological theory developed to date. It may be some considerable time before the opportunity for such broad-scale validation of theory arises again.

Water quality and yield

Given the geographical extent of the 2002–2003 fires, it was inevitable that many water supply catchments, some of them supplying significant urban centres, would be impacted. An important question arising in all water catchments is: What are the future trends in water yield that will result from the ecological impacts of the 2002–2003 fires?

Considerable research on the impact of fires on catchments exists. Kuczera (1985) (in Vertessy *et al.* 2001) developed an idealised curve for the relationship between water yield and stand age for mountain ash (*E. regnans*) forest, based on the hydrologic response of eight catchments to the 1939 bushfires in Victoria. Assuming long-unburnt mountain ash forest before a fire, followed by a rapidly developing regrowth, water yield decreases to about half

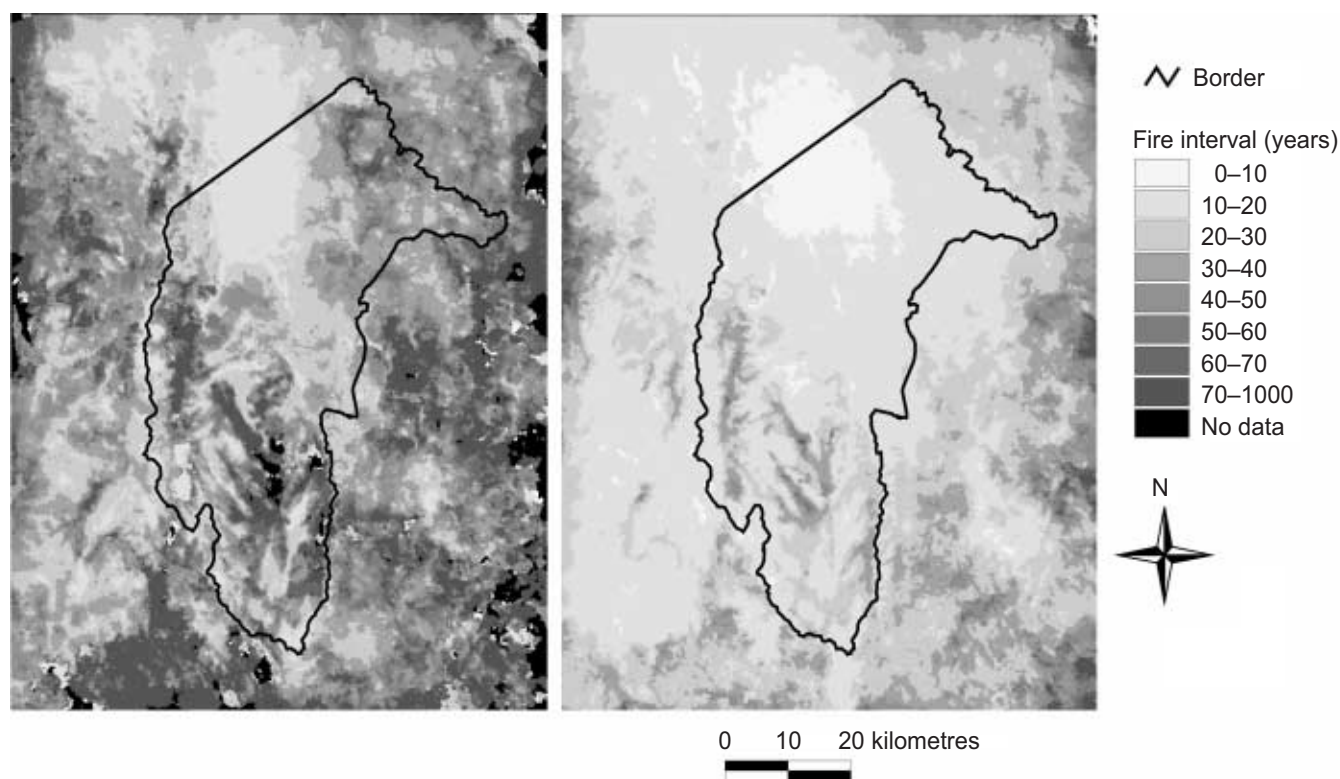


Figure 7. Spatial patterns of average inter-fire interval (IFI) (y) predicted for the ACT region for a) present climate and b) a moderate change in climate (modified from Cary 2002)

of the pre-fire level by around 30 y after fire. Water yield gradually increases, taking up to 150 y to reach pre-fire levels as the regrowth reaches an advanced stage. The general shape of the relationship has been confirmed by models of long-term yield trends (Kuczera 1987), and water balance measurements (Vertessy *et al.* 2001).

Eucalyptus regnans has a suite of adaptive traits similar to those of *E. delegatensis* and responds similarly to fires of comparable severity (Gill 1975). The dynamics of water yield for catchments characterised by species with adaptive traits different to *E. regnans* can depart significantly from the idealised curve presented for *E. regnans*. A study of stream flow in Licking Hole creek, situated in the upper Cotter River Catchment in the ACT, found that after an initial increase, stream flow returned to pre-fire levels within 3 y (Kuczera 1998), presumably because of a greater proportion of resprouting eucalypt species found in that catchment.

The opportunities to examine the impacts of fire on water yield arising from the 2002–2003 fires in south-eastern Australia are arguably unprecedented. They provide a valuable opportunity to extend the research on these topics into a new set of catchments where records of water yield have been compiled over many decades. Associated questions on the impact on water quality are also being addressed.

Managing bushfire risk in a changing world

Climate change

There has been speculation over whether the events of the 2002–2003 bushfire season might become more frequent as a result of a

changing climate. Williams *et al.* (2001) compared the frequency of different fire danger rating (FDR) (Low, Moderate, High, Very high and Extreme) days that would occur during a fire season, for simulated $1 \times \text{CO}_2$ and $2 \times \text{CO}_2$ climates for southern and northern Australia, using the CSIRO9 General Circulation Model. In southern Australia, distributions of FDR were significantly different between climates for Sale and marginally so for Mildura, but not for Hobart and Katanning. Nevertheless, the common trend across all sites was for a decrease in the number of low FDR days and a general, but not necessarily consistent, increase in the number of higher FDR (Very High and Extreme) days.

Cary (2002) predicted spatial variation in the fire regime, using a landscape fire model that includes lightning ignition only, for the ACT region, and hypothesised that inter-fire intervals would be half under a $2 \times \text{CO}_2$ climate (Fig. 7). The models addressed the sensitivity of fire regimes to changes in expected weather only, and did not incorporate expected change in biomass productivity, ignition likelihood (Goldammer and Price 1998), nor anthropogenic activities such as fire suppression.

Research to date suggests that fire danger and fire regimes are sensitive to potential changes resulting from climate change. Research into this aspect of bushfire occurrence will need to continually address the possible effects of new climate change scenarios, resulting from updated general circulation models and projections on energy policies and population growth, as they are developed.

Optimal solutions to the management of bushfire risk

The 2002–2003 fires have provided a stark reminder of the complexity of contemporary land management, although there are many similar examples around the world (e.g. Keeley *et al.* 2003). Whereas researchers, policy experts and interest groups often focus on a small number of issues, land managers are responsible, and accountable, for a much broader range of issues including fire mitigation and management, conservation of biological diversity, air quality, water quality and yield, recreation and aesthetic values, agricultural and timber production, and others. Furthermore, land managers are constrained by pressing financial, occupational health and safety, and knowledge limits.

Thus, there remains a need for the development of optimal mixtures of management options, across a diversity of ecosystems, which address these (often conflicting) constraints (Bradstock and Gill 2001). This will require a range of methodologies, including simulation modelling, insights from landscape fire ecology projects and statistical analysis of fire occurrence. Researchers should be asking questions like: What level of prescribed burning activity will be required under future climates to afford the same level of protection provided by a given level of activity under current climate? What will be the impact of this on air and water quality, and on plant and animal community dynamics? What are the financial implications? Are there alternatives?

These are examples of the fundamentally important questions that have been brought to the front of our minds as a result of the 2002–2003 fire season. It is at times like this, when there is community and government focus on fire research, that advances may occur more rapidly and be communicated more effectively.

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References

- Ashton, D.H. (1981) Fire in tall-open forests. In: Gill, A.M., Groves, R.H. and Noble, I.R. (eds) *Fire and the Australian Biota*. Australian Academy of Science, Canberra, pp. 339–366.
- Banks, J.C.G. (1982) The use of dendrochronology in the interpretation of the dynamics of the snow gum forest. PhD thesis, Department of Forestry, Australian National University.
- Banks, J.C.G. (1989) A history of forest fire in the Australian Alps. In: Good, R. (ed.) *The Scientific Significance of the Australian Alps*. The Proceedings of the First Fenner Conference on the Environment. Canberra, September 1988, pp. 265–280.
- Bowman, D.M.J.S. (1998) Tansley Review No. 101: The impact of Aboriginal landscape burning on the Australian Biota. *New Phytologist* **140**, 385–410.
- Bradstock, R.A. and Gill, A.M. (2001) Living with fire and biodiversity at the urban edge: in search of a sustainable solution to the human protection problem in southern Australia. *Journal of Mediterranean Ecology* **2**, 179–195.
- Bradstock, R.A., Williams, J.E. and Gill, A.M. (eds) (2002) *Flammable Australia: Fire Regimes and Biodiversity of a Continent*. Cambridge University Press, Melbourne.
- Burrows, N.D., Ward, B. and Robinson, A.D. (1995) Jarrah forest fire history from stem analysis and anthropological evidence. *Australian Forestry* **58**, 7–16.
- Byram, G.M. (1959) Combustion of forest fuels. In: Davis, K.P. (ed.) *Forest Fire: Control and Use*. McGraw-Hill, New York.
- Cary, G.J. (1998) Predicting fire regimes and their ecological effects in spatially complex landscapes. PhD thesis, Australian National University.
- Cary, G.J. (2002) Importance of a changing climate for fire regimes in Australia. In: Bradstock, R.A., Gill, A.M. and Williams, J.E. (eds) *Flammable Australia: The Fire Regimes and Biodiversity of a Continent*, Cambridge University Press, pp. 26–46.
- Cary, G. and Bradstock, R. (2003) Sensitivity of fire regimes to management. In: Cary, G., Lindenmayer, D. and Dovers, S. (eds) *Australia Burning: Fire Ecology, Policy and Management Issues*. CSIRO Publishing, Melbourne, pp. 65–81.
- Cary, G., Lindenmayer, D. and Dovers, S. (eds) (2003) *Australia Burning: Fire Ecology, Policy and Management Issues*. CSIRO Publishing, Melbourne, 268 pp.
- Cheney, N.P., Gould, J.S. and Catchpole, W.R. (1998) Prediction of fire spread in grasslands. *International Journal of Wildland Fire* **8**, 1–13.
- Esplin, B., Gill, M. and Enright, N. (2003a) Measuring effectiveness of prescribed burning. In: *Report to the Inquiry into the 2002–2003 Victorian Bushfires*. Department of Premier and Cabinet, Victorian Government. Chapter 11, pp. 108–116.
- Esplin, B., Gill, M. and Enright, N. (2003b) Traditional burning practices of Aboriginal people and the prescribed burning debate in Victoria. In: *Report to the Inquiry into the 2002–2003 Victorian Bushfires*. Department of Premier and Cabinet, Victorian Government. Chapter 12, pp. 115–122.
- Fernandes, P.M. and Botelho, H.S. (2003) A review of prescribed burning effectiveness in fire hazard reduction. *International Journal of Wildland Fire* **12**, 117–128.
- Gardner, R.H., Hargrove, W.W., Turner, G.M. and Romme, W.H. (1996) Climate change, disturbances and landscape dynamics. In: Walker, B. and Steffen, W. (eds) *Global Change and Terrestrial Ecosystems*, Cambridge University Press. Cambridge.
- 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. NZFRI, Rotorua, New Zealand, pp. 1–12.
- Gill, A.M. and Bradstock, R.A. (2003) Fire regimes and biodiversity: a set of postulates. In: Cary, G., Lindenmayer, D. and Dovers, S. (eds) *Australia Burning: Fire Ecology, Policy and Management Issues*. CSIRO Publishing, Melbourne, pp. 15–25.
- Goldammer, J.G. and Price, C. (1998) Potential impacts of climate change on fire regimes in the tropics based on MAGICC and a GISS GCM-derived lightning model. *Climatic Change* **39**, 273–296.
- Hutson, B.R. and Veitch, L.G. (1985) Relationship between litterfall rate, litter mass and decomposition in *Eucalyptus* forests in south-eastern Australia. *Australian Journal of Ecology* **10**, 443–450.
- Jacobs, M.R. (1955) *Growth Habits of the Eucalypts*. Forestry and Timber Bureau, Department of the Interior, Canberra.
- Keane, R.E., Parsons, R. and Hessburg, P. (2002) Estimating historical range and variation of landscape patch dynamics: limitations of the simulation approach. *Ecological Modelling* **151**, 29–49.

- Keeley, J.E. and Fotheringham, C.J. (2001) History and management of crown-fire ecosystems: a summary and response. *Conservation Biology* **15**, 1561–1567.
- Keeley, J.E., Witter, M.S. and Taylor, R.S. (2003) Challenges of managing fires along an urban-wildland interface — lessons from the Santa Monica Mountains, Los Angeles, California. *Proceedings of the 3rd International Wildland Fire Conference*, October, Sydney. US Department of Interior and Bureau of Land Management, Sydney, pp. 1–9.
- Kershaw, A.P., Clark, J., Gill, A.M. and D'Costa, D.M. (2002) A history of fire in Australia. In: Bradstock, R.A., Gill, A.M. and Williams, J. (eds) *Flammable Australia: The Fire Regimes and Biodiversity of a Continent*. Cambridge University Press, pp. 3–25.
- Kuczera, G.A. (1985) *Prediction of Water Yield Reductions Following a Bushfire in Ash — Mixed Species Eucalypt Forest*. Catchment Hydrology Research Report No. MMBW-W-0014. Melbourne and Metropolitan Board of Works, p. 163.
- Kuczera, G. (1987) Predictions of water yield reductions following a bushfire in ash — mixed species eucalypt forest. *Journal of Hydrology* **94**, 215–236.
- Kuczera, G. (1998) *Assessment of Water Yield Trends Following the 1983 Wildfire in Licking Hole Catchment*. Ecwise Environmental Ltd, Canberra.
- Li, C. (2000) Reconstruction of natural fire regimes through ecological modelling. *Ecological Modelling* **134**, 129–144.
- McArthur, A.G. (1967) *Fire Behaviour in Eucalypt Forests*. Leaflet No. 10, Forestry and Timber Bureau, Canberra.
- McArthur, A.G. (1973) *Forest Fire Danger Meter Mark V*. Forest Research Institute, Forestry and Timber Bureau, Canberra.
- McCarthy, G.J. and Tolhurst, K.G. (1998) *Effectiveness of Firefighting First Attack Operations by the Department of Natural Resources and Environment from 1991/92–1994/95*. Fire Research Report 45, Fire Management Branch, Department of Natural Resources and Environment, Victoria.
- McCarthy, M.A. and Cary, G.J. (2002) Fire regimes of landscapes: models and realities. In: Bradstock, R.A., Gill, A.M. and Williams, J.E. (eds) *Flammable Australia: The Fire Regimes and Biodiversity of a Continent*. Cambridge University Press, pp. 76–93.
- McCarthy, G.J., Tolhurst, K.G. and Chatto, K. (1998) *Overall Fuel Hazard Guide*. Fire Research Report 47, Fire Management Branch, Department of Natural Resources and Environment, Victoria.
- McRae, R.H.D. (1992) Prediction of areas prone to lightning ignition. *International Journal of Wildland Fire* **2**, 123–130.
- Minnich, R.A. (2001) An integrated model of two fire regimes. *Conservation Biology* **15**, 1549–1553.
- Noble, I.R. and Slatyer, R.O. (1980) The use of vital attributes to predict successional changes in plant communities subject to recurrent disturbances. *Vegetatio* **43**, 5–21.
- Noble, I.R. and Slatyer, R.O. (1981) Concepts and models of succession in vascular plant communities subject to recurrent fire. In: Gill, A.M., Groves, R.H. and Noble, I.R. (eds) *Fire and the Australian Biota*. Australian Academy of Science, Canberra, pp. 311–335.
- Raison, R.J., Woods, P.V. and Khana, P.K. (1983) Dynamics of fine fuels in recurrently burnt eucalypt forests. *Australian Forestry* **46**, 296–302.
- Raison, R.J., Woods, P.V. and Khana, P.K. (1986) Decomposition and accumulation of litter after fire in sub-alpine eucalypt forests. *Australian Journal of Botany* **11**, 9–19.
- Richards, R.M., Cary, G.J. and Bradstock, R.A. (2001) The sensitivity of snow gum to fire scarring in relation to Aboriginal landscape burning. *Bushfire 2001*. Proceedings, Australasian Bushfire Conference, 3–6 July 2001, Christchurch, New Zealand. NZFRI, Rotorua, New Zealand, pp. 282–292.
- Shugart, H.H. and Noble, I.R. (1981) A computer model of succession and fire response in the high-altitude *Eucalyptus* forest of the Brindabella Range, Australian Capital Territory. *Australian Journal of Ecology* **6**, 149–164.
- Vertessy, R.A., Watson, F.G.R. and O'Sullivan, S.K. (2001) Factors determining relations between stand age and catchment water balance in mountain ash forests. *Forest Ecology and Management* **143**, 13–26.
- 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.
- Wasson, R.J. (2003) Connectivity. In: Cary, G., Lindenmayer, D. and Dovers, S. (eds) *Australia Burning*. CSIRO Publishing, Melbourne, pp. 166–169.
- Williams, A.A.J., Karoly, D.J. and Tapper, N. (2001) The sensitivity of Australian fire danger to climate change. *Climatic Change* **49**, 171–191.