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Scientific and social challenges for the management of fire-prone wildland–urban interfaces

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Abstract
At their worst, fires at the rural–urban or wildland–urban interface cause tragic loss of human lives and homes, but mitigating these fire effects through management elicits many social and scientific challenges. This paper addresses four interconnected management challenges posed by socially disastrous landscape fires. The issues concern various assets (particularly houses, human life and biodiversity), fuel treatments, and fire and human behaviours. The topics considered are: 'asset protection zones'; 'defensible space' and urban fire spread in relation to house ignition and loss; 'stay-or-go' policy and the prediction of time available for safe egress and the possible conflict between the creation of defensible space and wildland management objectives. The first scientific challenge is to model the effective width of an asset protection zone of an urban area. The second is to consider the effect of vegetation around a house, potentially defensible space, on fire arrival at the structure. The third scientific challenge is to present stakeholders with accurate information on rates of spread, and where the fire front is located, so as to allow them to plan safe egress or preparation time in their particular circumstances. The fourth scientific challenge is to be able to predict the effects of fires on wildland species composition. Associated with each scientific challenge is a social challenge: for the first two scientific challenges the social challenge is to co-ordinate fuel management within and between the urban and rural or wildland sides of the interface. For the third scientific challenge, the social challenge is to be aware of, and appropriately use, fire danger information so that the potential for safe egress from a home can be estimated most accurately. Finally, the fourth social challenge is to for local residents of wildland–urban interfaces with an interest in biodiversity conservation to understand the effects of fire regimes on biodiversity, thereby assisting hard-pressed wildland managers to make informed choices.

Keywords: fire behaviour, urban–wildland interface, social disasters, 'stay-or-go', defensible space

1. Introduction

Destruction of houses and loss of human lives at the interfaces between urban and wildland (WUI) or rural lands generally (RUI) create headlines around the world. Particularly prone interfaces are those in California in the United States (US) (e.g. Cohen 2008) and those in south-eastern Australia (Victoria, New South Wales, South Australia, Tasmania and the Australian Capital Territory). In 2003, both of these regions had memorable fire episodes (Blackwell and Tuttle 2003, Esplin *et al* 2003, McCaffery and Rhodes 2009; figure 1) adding to previous fires, often recalled by date, or by an informally assigned name such as 'Black Friday'. The most recent tragedy has arisen from the February 2009 fires in

Figure 1. A house burning as a result of a landscape fire spreading from the rural side of the interface into the urban side, Canberra, ACT, January 2003 (Image: A M Gill).

Victoria in which 173 people died (see http://en.wikipedia.org/wiki/2009_Victorian_bushfires) and near 2000 houses were burnt. Such fires sear the memory.

Socially disastrous fires such as those mentioned above create passionate public debate. They pose a particular problem for authorities because they are rare in any one jurisdiction and demand resources far beyond those immediately available for suppression and social services. Such tragic fires at the RUI fit the 'megafire' category of fire situations 'where operational limitations, public anxieties, media scrutiny and political pressures collide' (Williams 2005; see also Stephens and Ruth 2005). Carroll *et al* (2007) refer to the fire problem as being the result of a 'complex mix of physical, ecological, economic and social developments' while Gill (2005) saw the problem as a 'multi-stakeholder, multi-scale, multi-variable' problem. In short, the problem is complex and without a simple solution (Coleman 1995). It is a classic 'wicked' problem (Carroll *et al* 2007, Australian Public Service Commission 2007, pp 3–5) to which there may be no clear solution (Australian Public Service Commission 2007, p 4).

RUIs, in the broad sense, are created when structures are built next to relatively unmodified forests, shrublands or grasslands (wildland/bush) or next to rural properties where vegetation is largely modified. The RUI poses a series of challenges to both rural and urban communities due to ecosystem fragmentation and increased exposure to invasive species, pollution, and unplanned fire (Alvalaparti *et al* 2005, Theobald and Romme 2007). These circumstances are being magnified as land-use changes rapidly in both the US and Australia (Mendham and Curtis 2009). Addressing fire and other matters in the complex and changing landscapes at the RUI requires effective and targeted management.

The number of properties on the urban side of the interface, or UI, has been estimated from a fire perspective. Using a generous definition of UI ('within 2.4 km of an area that is heavily vegetated'), it has been estimated that over 1/3 of homes in the US are part of the UI including 5.1 million homes in California (Radeloff *et al* 2005). In Australia, Chen and McAneney (2005) found that 20.3% of near 8.2 million addresses were within 700 m, and 4.1% within 50 m, of 'bushland' in 'all major capital cities and surrounding areas'.

Socially disastrous fires continue to occur despite advances in knowledge and technology. Programmes have been initiated throughout Australia and the US to address such problems. These include zoning, growth boundaries, land acquisition, education and outreach, community assistance programmes, and provision of conservation easements. Additionally, there has been growth in US referenda and ballot measures where citizens have placed restrictions on future development in the UI (Bengston *et al* 2005). Collectively these measures do not appear to have reduced losses of life and property, particularly in California (Stephens *et al* 2009a). In Australia many official enquiries have resulted over the past 70 years yet the problem has not been solved. Why is this so?

The issues surrounding the RUI for private and public land managers and for emergency services are numerous. In this paper our aim is to highlight and review just four of the many scientific challenges involving land management at the RUI. These challenges emerge from a general discussion of wider issues and highlight associated social issues and the challenges that arise from them.

Human life and urban houses are taken as the foci of attention. To help prevent losses, public authorities in south-eastern Australia may create 'asset protection zones' on the wildland side of an urban interface in order to help stop the fire before it penetrates the urban area. However, fires do penetrate urban areas for various reasons so the question then becomes one of where the fire will eventually burn. Because residents can make their houses as 'firesafe' as possible, and fleeing from the fire can be fatal (see Handmer and Tibbets 2005), the issue as to whether they should stay with their prepared house during a fire or be evacuated, or choose to evacuate themselves safely, becomes particularly relevant. With the treatment of public wildland for the protection of urban residents and their homes, community concern may be raised about the loss of public assets such as amenity value and biodiversity. From this brief outline, the four areas of interest identified for scrutiny here are:

(i) asset protection zones;
(ii) urban fire spread and house loss in relation to 'defensible space';
(iii) stay-or-go policy and the time available for safe egress and
(iv) biodiversity conservation in asset protection zones.

Our aim is to identify the most significant scientific challenge in each of these areas and its most significant social challenge.

2. Asset protection zones

In mainland south-eastern Australia, there is an emphasis on 'asset protection zones' (APZs) just beyond the edge of suburbs or towns for the protection of life and property (New South Wales (NSW) Rural Fire Service 2003; Australian Capital Territory (ACT) 2005; Victorian Department of Sustainability and Environment (DSE) 2006; South Australian

Department of Environment and Heritage 2009). For example: 'the Asset Protection Zone (APZ) will provide the highest level of strategic protection to human life, property and highly valued assets vulnerable to damage by wildfire through radiant heat and ember attack' (DSE 2006, p 14). In the APZ, the DSE notes, fuel management will be intensive, may have a significant impact on environmental and economic values but take place on only a small proportion of *public* land (our emphasis). Such 'fuel management' is designed to take place as part of the Fire Protection Strategy (p 16) which aims to provide 'sufficient works for the prevention and suppression of wildfire on public land . . . at a regional level'. (DSE 2006, p 52).

In California and the US generally, the concept of 'defensible space' is used: 'a defensible space perimeter around buildings and structures provide fire fighters a working environment that allows them to protect buildings and structures from encroaching wildfires as well as minimizing the chance that a structure fire will escape to the surrounding wildland' (State Board of Forestry and Fire Protection, California Department of Forestry and Fire Protection 2006). Thus, this idea seems to be focused on the individual home, or other individual structure where there is considerable opportunity for open space. Coleman (1995) views defensible space as an area where there is the use of 'fuel and vegetative management to reduce fire exposure to a vulnerable structure'. We use this latter concept, with its emphasis on fuel management, as the most suitable for discussion (in section 3) in relation to houses within an urban area near the interface. This does not negate the utility of the former view, with its emphasis on agency fire fighters, to more isolated buildings such as farm houses on the rural side of the UI or to low density housing developments.

Whether the emphasis is on public or private land, the APZ is designed to create an area in which fire fighters can operate safely and effectively: 'effective fire fighting' in this context is putting the fire out but there are limits to this. For example, in south-eastern Australia, the intensity limit for forest fire control has been put at between 2000 and 6000 kW m^{-1} (McCarthy and Tolhurst 1998), i.e. a midrange value of 4000 kW m^{-1} (Luke and McArthur 1978, p 28; similar suppression thresholds are used in the US), just a small part of the potential range, the upper end of which seems to be of the order of 100 000 kW m^{-1} (Gill and Moore 1990). In the Australian forest fire danger rating system, under a fire danger index of 100—the 'worst possible' value in the original system (McArthur 1967)—the maximum litter-fuel load on level ground that would enable control at 4000 kW m^{-1} is 7.8 t ha^{-1} (see Gill *et al* 1987). However, a recent record peak in the forest fire danger index (FFDI) was 162 on 7th February 2009 in Melbourne, Victoria, and over 120 for some hours (Williams 2009). If these figures become accepted as the new benchmarks for 'worst possible', and fire control was to be effective on every occasion, the calculated fuel load for effective suppression would be considerably less than 7.8 t ha^{-1} in forests: in such an argument, the assumption is that the rate of fire spread with the wind remains proportional to FFDI and the intensity for effective fire suppression remains the same—at 4000 kW m^{-1}, say. The validity of these suppositions is unknown.

The reason for an intensity limit to fire control may be that the fire is burning in tree crowns and generally out of reach of fire fighters and/or producing firebrands (glowing embers and burning brands) that are blowing across fuel breaks and buffer strips and thereby igniting fuels downwind ('spotting'). Radiation from flames is another source of potential ignition; if radiation levels are too high for fire fighters to operate (e.g. using Butler and Cohen's 1998 rule-of-thumb that a safety zone radius for the fire fighter must be 'equal to or greater than four times the maximum flame height') or are adequate for ignition of fuels in the APZ, then the zone is not wide enough.

What then is an appropriate width for an APZ? Even if the APZ was bare, what width would be required under worst possible weather conditions to stop a fire, assuming that fire fighters are fully engaged elsewhere? Potentially, fire could cross the break by flames of sufficient length, by radiation of sufficient intensity, or, by firebrands with sufficient travel. These mechanisms are considered in turn below:

(i) Wilson (1988) found that the published relationship between flame length and fire line intensity (Nelson 1980) neatly separated grassland fires that breached the fuel breaks of different width that he established with those that did not when they were plotted against experimental fire line intensities reaching up to 17 000 kW m^{-1}. In fires having trees within 20 m, fires crossed breaks 10 m wider cf fires in plots without trees, presumably due to spotting;

(ii) model radiation from flames suggest that ignitions are 'unlikely to occur' if greater than 40 m from a structure (Cohen and Butler 1998);

(iii) spot fires provide evidence for the distance of spread due to fire brands. Luke and McArthur (1978, p 102) report a maximum distance of 30 km ('long distance spotting'), presumably from a forest fire. While this and similar distances must be considered rare, it does not mean that fires at such distances can be completely discounted. More common is 'short distance spotting'. Patterns of burnt holes in plastic sheeting downwind of experimental forest fires suggest a negative exponential distribution of fire brands up to about 300 m from the fire front (Gould *et al* 2007, p 128). Wang's (2006) model for ember spread from a *Pinus radiata* plantation in Canberra, ACT, in 2003, suggested that 'the area to receive the most effective ember attack would be between 50 and 400 m downwind of the fire source'. Luke and McArthur (1978, p 107) noted that in grasslands 'spot fires are fairly common up to 100 m or so ahead of the flame front'.

The main scientific challenge arising from this section, then, is to predict the probability of fire crossing breaks of various widths by the various means outlined above. Independent variables should include the height and nature of the fuel array (e.g. Gould *et al* 2007, chapter 3; Sandberg *et al* 2001), wind speed and direction, fuel moisture in significant components of the fuel array and topography. With the exception of long distance spotting, distances less than 400 m may be said to represent current observation, modelling and measurement, as the maximum width needed for an effective fuel break; this is sure to be increased in the light of further experience.

A fuel-free or minimal-fuel APZ 400 m wide (forests), or even 100 m wide (grasslands), could substantially affect the operation and viability of small holdings and public reserves often found at the UI. There, 'wildland', hobby farms, 'bush blocks', grazing or cropping lands, horse agistment areas, tree plantations, vineyards, golf courses and recreation and conservation reserves may be found. This being so, implementation of fuel minimization by all parties on either side of the interface is unlikely to be welcomed. The social challenge then is to plan an APZ that ascribes responsibility to all land holders for fuel minimization and maintenance while not threatening their legally sanctioned land uses bestowed through planning permissions.

3. Urban fire spread and house loss

In this section, the aim is to examine the processes that culminate in the presence of an ignition source on, in or immediately adjacent to, a house, and the width and nature of 'defensible space' (*sensu* Coleman 1995, noted above; see also Nelson *et al* 2004) in relation to the scientific challenges which face us. The ignitibility of the house itself is not considered here. The 'space', a garden, is considered to be vegetated by a variety of plants of potentially different architecture, density and flammability—serving a range of purposes such as aesthetics, recreation, entertainment area and source of vegetables and fruit.

The house (and other built structures) can be a fuel 'element' in itself as can the various parts of the garden apart from the plants—including organic mulch, stored wood or other fuel, piped natural gas to external meters, children's play structures, and fences of various flammability. When the house and garden are considered as units making up just a part of an urban zone, the fuel–fire situation becomes even more complex because of the presence of a network of suburban roads and road verges, parks and playgrounds, vacant blocks (lots) with an overlay of various degrees of house, garden and public-area maintenance. Further complexity occurs because wind can be channelled along roads and around and between houses of different shapes and sizes; buildings and gardens can also reduce wind speed at ground level.

Because a house may be burned down yet have a garden around it that was non-ignitable at the time (Cohen 2008) and because fire may spread despite discontinuities in the urban 'fuel' (e.g. across roads, driveways, recently watered gardens etc) firebrands are considered to be a major ignition source both in Australia (Leonard and Blanchi 2005) and the US (Stephens *et al* 2009a). Firebrands may be generated outside the urban area or within it from burning houses (Leonard and Blanchi 2005), individual burning plants or flaming vegetation generally. The extent of production of firebrands by individual species of plants varies (e.g. McArthur 1967). Firebrands may set a garden alight which then carry the fire to the structure or they may lodge in the structure itself and set it alight. Flame radiation across breaks cannot be discounted but in the presence of an APZ on the rural side of the RUI is likely to be less important than firebrand fire transmission.

While the study of fire behaviour in homogeneous landscape fuels has occurred over a period of 90 years (from Show 1919), and produced many models of fire spread, the study of fire spreading into urban communities has begun only recently (Rehm *et al* 2002, Evans *et al* 2004). Models are difficult to construct in the urban environment for many reasons:

(i) events are relatively rare in any one area;
(ii) gaining access to the affected area during an emergency is difficult even if the observer is nearby;
(iii) observing fuels, weather and fire behaviour when in an urban fire (as was the senior author in ACT in 2003, see Gill 2005) is difficult because of the need to help (yourself and others) and the lack of visibility;
(iv) the inappropriateness of 'field' experiments in urban areas;
(v) reconstruction of the pre-fire state of the system from the remains is difficult and
(vi) the number of variables involved for building design, siting and construction, gardens and outdoor 'furniture', suppression alternatives and fences, let alone the fires external to the site, is large.

Four approaches to modelling fire relevant to the loss of houses in urban areas as the result of landscape fires have been proposed or developed:

(i) risk models (Martin 1991, Fried *et al* 1999, Bradstock and Gill 2001, Tolhurst *et al* 2008);
(ii) empirical, retrospective, models of house loss versus distance from the urban edge (Ahern and Chladil 1999, Tolhurst and Howlett 2003, Chen and McAneney 2004);
(iii) a fluid-mechanics-based or other physics-based model to portray fire spread in some way, namely predict rate of spread, pattern of spread or final perimeter, but such models (Linn *et al* 2002, Rehm *et al* 2002, Evans *et al* 2004) are likely to be the most complicated yet potentially the most predictive and
(iv) linking of house loss with fire intensity estimated *post hoc* (Wilson and Ferguson 1986).

Risk models vary from: the conceptual chain of fire events leading to house destruction (Bradstock and Gill 2001) to the chance of a fire destroying a house once near the structure (Fried *et al* 1999) and from the use of biophysical variables only (Bradstock and Gill 2001) to the inclusion of structural and human-behaviour variables also (Martin 1991).

House loss versus distance models have been produced in two Australian studies. Chen and McAneney (2004) analysed data for the Canberra, ACT, 2003, fire and reconfigured data of Ahern and Chladil (1999) for the Sydney, NSW, 1994 fires, to show in both cases that proportional house loss was a negative linear function of the distance from the urban–rural interface. However, Tolhurst and Howlett (2003) produced a negative exponential relationship for house loss in the same fire as that studied by Ahern and Chladil (1999). These purely descriptive models can be more functional in two ways, albeit speculative at this stage. In the first of these, Tolhurst and Howlett (2003) pointed out that the shape of their 'house loss with distance' relationship is similar to that of the density of spot fires with distance from a fire edge, a correlation if not a causality. The second is based on a sketch map of burnt areas drawn for part of the 2003 Canberra fire (Gill 2003) which indicated that while house loss varies linearly with distance from the UI, proportional house loss *per unit area burnt* dropped only slightly with distance from the interface. If this is so, then the presence of fire in any one event at any one location with distance from the edge becomes more important than change in fire characteristics, or other variables, with distance. Predicting what the proportion of houses lost per unit burned area would be under particular conditions would still remain a problem—the intercept on the distance–loss graph.

While housing loss may decline with distance from an urban edge up to hundreds of metres in some cases, fires can spread through whole neighbourhoods and burn every house (Gordon 2000); a two-parameter equation of house loss with distance can describe it. The parameters of the equations may be expected to vary according to the properties of houses, gardens, road verges etc, together with variables affecting fire behaviour and suppression.

Current regression models give no indication in themselves of practical steps for urban residents to take in reducing fire risk. They provide a description of how far a fire with certain attributes has spread into an urban area but not how far it may do so in another event. The physics-based model described by Rehm *et al* (2002) and Evans *et al* (2004) has the potential to describe how far a fire will penetrate urban areas but the model apparently does not do this yet.

Wilson and Ferguson (1986) estimated the fire intensity that occurred 'at each house' in their study of an Ash Wednesday fire in Victoria in 1983 from a relationship between tree-scorch-height and fire intensity or from an estimation of the intensity necessary to completely consume tree crowns. They then calculated the percentages of house losses in four fire intensity classes up to an upper limit of 60 000 kW m^{-1}. Using the midpoint of their intensity classes, there was a semi-logarithmic relationship between percentage house loss and estimated intensity. For their logit model, the authors included not only a series of intensity classes and building materials but also whether or not someone was in attendance and whether or not the 'outer-zone garden vegetation' was greater than 5 m tall. They concluded that fuel reduction was a major priority for house protection. Similar results were observed from the 1990 Paint Fire in southern California (Foote 1994).

The extent of fuel reduction or elimination around houses has been expressed in terms of the width of 'defensible space'. The required minimum 'separation between structures and vegetation' in many regulations of the USA is 9 m (Gettle and Rice 2002) while 'many' suggest a defensible space 9 m wide around the house and a 'reduction of vegetation up to and beyond 30 m' (US Forest Service 2001), quoted by Nelson *et al* (2004). The effective width of the defensible zone would be expected to vary with topography and fuel (see Nelson *et al* 2004), weather conditions, wind direction and local suppression capacity.

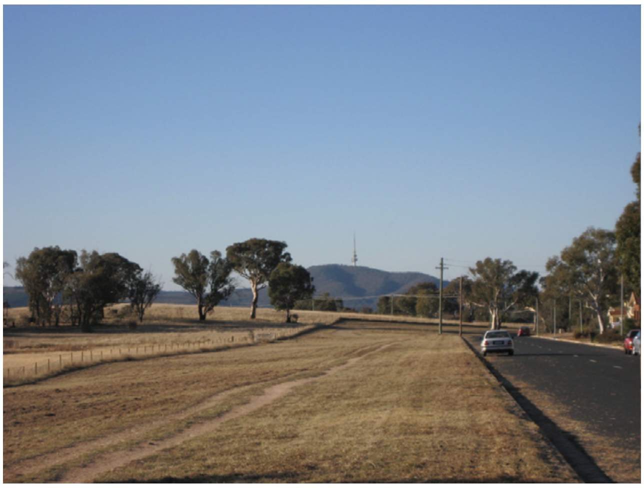

Figure 2. A rural–urban interface in Canberra, Australian Capital Territory. House loss occurred in the urban area on the right-hand side of the road during the 2003 fires. The rural area is evident in the wide, mown, road verge (public land) and a rural property on the left-hand side of the road. The trees are native *Eucalyptus* spp (Image: A M Gill).

If houses in urban areas are close together then the options for fuel management within the householder's authority are reduced. The householder cannot have an intensively fuel managed zone of 30 m wide, say, if the house lot itself is 30 m wide (see also Cova 2005). If forest in the wildland abuts a house owner's block and crown fire and extensive ember production is possible, the owner's efforts in fuel management may be inadequate to prevent ignition of the house during a fire. Thus, a co-ordinated neighbourhood fuel management system on both sides of the interface would be more effective in asset protection (Stephens and Ruth 2005). The main social challenge here, as above, may be to convince whole neighbourhoods to prepare for a fire event that may be quite rare, then act as a cohesive unit in managing their fuels, and perhaps suppression, despite having divergent values and contrasting levels of fire awareness (Gill 2009).

Social equity issues may be involved when urban people with relatively small blocks expect rural neighbours with relatively large blocks to modify fuels over large areas even if such actions affect the viability of the rural enterprise. For example, expectations that a farmer will keep fuels to minimal levels when 'fuel' is fodder for livestock may be unrealistic (figure 2). Either certain land uses have to be banned locally or compromises accepted.

A key scientific challenge is to be able to predict the presence of an ignition source at, in, or on, a house: this will of necessity be expressed as a probability because of the intrinsic variation in weather variables, fire-path contingencies, presence of suppression options, and the need to restrict the number of variables in a practical model. Furthermore, the vegetation itself may act as a modifier of wind and a trap for firebrands. How accurately can this probability be calculated? Note that this challenge is expressed not in terms of houses being burned but in terms of an ignition source reaching a potentially vulnerable asset. Many more variables are involved when the loss of structures is examined in a way that will allow improvements to the survivorship of the structure (Kearns *et al* 2007).

4. Stay-or-go? The time available for egress

Two basic options are available to people when a fire approaches; they can either stay where they are or leave the area. In south-eastern Australia, the policy of the Australasian Fire Authorities Council has been to recommend people to 'either prepare, stay and defend their properties, or leave the area well before the fire front arrives' (see Handmer and Tibbets 2005). This policy has not always been followed because police in some jurisdictions have had powers of mandatory evacuation (Handmer and Tibbets 2005). In California, mandatory evacuation has been considered to be the norm (Stephens *et al* 2009a) but 'fire safe designs (have allowed) residents to shelter in place' (Blackwell and Tuttle 2003, p 6).

If you are going to leave then 'leave early' is reasonable but how early is 'early'? Here we consider the minimum time available for safe evacuation of premises given that a fire has started. Because stakeholders are numerous, and their situations diverse, consideration of a single 'rule' can seem unwieldy, in terms of both policy and practice. Evacuating a nursing home or kindergarten is quite different than evacuating a group of robust young men in a rental house. Leaving an area in mountainous terrain with narrow roads (Cova 2005) is different than leaving the edge of a city for a nearby, safe, internal destination.

The problem of 'what is early?' can be seen in the light of current types of warnings. In Australia, fire danger warnings based on forecast weather and antecedent drought are given routinely in many jurisdictions: these warnings take the form of a fire danger rating, one of five classes of fire danger index (FDI). Similar systems exist in North America and Europe (Fujioka *et al* 2009). The FDI in Australia is based on the expected rate of spread of the fire burning with the wind on level ground. The public seems generally unaware of the basis of the danger rating and its implications (Dawson 1991, Gill 2008). However, if the actual range in the expected rate of spread of a fire were given, rather than the index, then:

(i) the public, not just agencies, would be empowered;
(ii) people could calculate the expected time of arrival of a fire at their location, given its present location, and act accordingly and
(iii) gain an understanding of fire behaviour especially if other messages about fire behaviour were routinely given—such as 'rate of spread doubles for each ten degrees of slope', 'firebrands travel faster than fire fronts' and 'fires may spread in severely grazed grasslands at half the normal rate' (Cheney and Sullivan 1997); or, have access to maps plotting contours of expected times of arrival.

The main technical difficulties associated with the use of a rate-of-spread as a fire danger index are:

(i) Rate of spread models generally may be more explanatory than predictive. Fujioka (2001) notes that the major fire models used in US, Canada and Australia 'can err significantly in predicting the spread rate of fire'. Rothermel's (1972) model gave values that may be expected to fall within a factor of 2 of the real value (Gelobter *et al* 1998). In the most recent and comprehensive Australian experimental study of forest fires, fuel and wind variables (i.e. without moisture involved as a variable) accounted for 69% of the variance (Gould *et al* 2007, p 91)—a satisfactory outcome for explanatory purposes—whereas, arguably perhaps, having more than 80% variance explained might be considered to provide satisfactory predictions.
(ii) Empirical rate of spread models are derived under safe experimental conditions which do not cover the range of experience. In the Gould *et al* (2007) study referred to above, the rates of spread in their major experimental programme covered about 11% of the range of estimated rates of spread in unplanned fires (pp 64–65 and p 100).
(iii) Rate of spread models do not usually consider spot fires. McArthur (1967) noted that spot fires increased the rate of spread three times in one example; his tables were not appropriate when crown fires were expected and, we may assume, spotting became more prominent.
(iv) Rate of spread models are currently deterministic rather than probabilistic. Expression of a range of likely rates, or locations at particular times, may be better (e.g. Burrows 1994, p 239; Fujioka 2001).
(v) Input sensitivity of models may be substantial (Trevitt 1991) and input levels across the region of concern, especially for wind, uncertain.
(vi) Significant variables may be poorly studied or omitted for various reasons. For example, the influence of slope in the McArthur (1967) model is for slopes up to only 20° and field experimental results of slope effects are lacking. Atmospheric instability was recognized as being important by McArthur (1967) but is absent from his model.

A consequence of publicly broadcasting the expected rates of spread of a fire would be the revelation that such predictions are not necessarily particularly accurate (a wide span of values might be given). This does not mean they are useless as they still could inform residents of potential fire conditions. In the future, expected rates of spread or predicted fire boundaries at certain times might be transmitted on mobile phones (cell phones) or via the internet for local areas. In the event of a fire, residents could determine for themselves how much time they had to prepare and leave in safety, given that the whereabouts of an approaching fire was known. Knowing more about fire behaviour, and the limits of the science, they might leave before any fire had started, based on a forecast of fire danger.

The scientific challenge is to accurately forecast the effects of various fuel arrays on firebrand travel and its effect on the spread of the fire front. While scientists have been trying to predict rate of fire spread for decades, letting the public know what the state of prediction is at any one time creates awareness of the general challenge and allows an appreciation of the difficulty of prediction. Having fire rate of spread information available to the public creates the social challenge—that of its use and interpretation for local conditions, followed by making the appropriate choice of leaving under safe conditions or staying with the home. The time of arrival of the fire is only one of a number of considerations affecting decision as to whether to 'stay-or-leave'. However, all homeowners should prepare their homes and gardens to resist spot-fire ignitions whether or not they intend to stay with their property (Stephens *et al* 2009a).

5. Biodiversity in asset protection zones

People may move to the urban edge in order to enjoy wildland scenery or biodiversity. With the introduction of fuel management programmes such as prescribed burning and mechanical treatments in the wildland adjacent to the urban area (Agee *et al* 2000, Stephens *et al* 2009b), as in an APZ, the problem has been seen to come down to a choice between houses or biodiversity in some regions. 'In many urban areas, the objective of property protection by fuel reduction conflicts with biodiversity values' (Whelan *et al* 2006). Interestingly, property protection is usually considered only in terms of one fire event, perhaps because house loss at any one location is rare.

While a homeowner is naturally concerned about house loss at a specific location, loss of houses is considered by agencies every year at a coarser geographic level. Agencies necessarily view the problem across their jurisdiction rather than on an individual house level. For example, for the large area of Sydney, NSW, the probability of house loss is a function of forest fire danger index (Bradstock and Gill 2001) and, while this is also true of individual houses, the probability level then is much lower.

In contrast to houses, conservation of biodiversity on the wildland side of the interface is governed by the effects of multiple fires (including fires prescribed for fuel modification), the fire regime (Gill 1975, 2008), and mechanical fuel treatments (Potts and Stephens 2009, Schwilk *et al* 2009). The intensity of the fire, the type of fire (peat or above ground), interval and even the season of the year can be important (Gill 1975, 1981). The same is likely for non-fire fuel treatments as well (Potts and Stephens 2009) but our focus here is on fire.

The effects of a fire regime on plant-species' composition (plant-species' biodiversity) depends to various extents on the functional type and time to maturity and longevity of the individual species (Noble and Slatyer 1980, Gill 1981, Pausas and Bradstock 2007). Animal species may also be categorized into functional groups (e.g. Corbett *et al* 2003, Burrows 2008) but plants only are considered here for illustration.

'Sprouter' species have individuals that resprout after a fire event whereas 'seeder' species have populations that die in a fire event if the intensity of the fire is at least sufficient to kill the plant's canopy (Gill 1981, Keeley 1987). Sprouter populations can decline as the number of successive fires at short intervals grows (Grano 1970) while seeder populations may be eliminated by two fires of the appropriate intensity within the period from germination to maturity if the soil seed bank is absent or exhausted. Thus, with the introduction of a prescribed burning programme that decreases the fire interval, local extinctions are possible: with the encroachment of an urban area into the wildland, fire intervals may decrease due to increased ignitions from people with the same biodiversity result (Keeley 2006). Situations are many and varied however.

Given the above, the challenge becomes one of preserving 'native' species in wildland while carrying out fuel management at the interface. There may be changes due to the management practices that can be discerned in retrospect (such as increases in invasive species; Keeley *et al* 2005) but can they be predicted?

The problem of prediction is that there are many more species of organisms present in an area than just plants; there are animals, invertebrates, cryptogams, fungi and microbes to be found many of which have unknown responses to fire regimes. Experiments are difficult because the range of fire intensities available under safe conditions is small compared with the possible range.

Rather than use fires as agents of fuel management at the interface, managers may choose to use slashers, harvesters, and masticators, grazing by various species of animals, herbicides, and even hand removal (as mentioned above). Use of these techniques increases the level of difficulty of the prediction of effects. Because of the above circumstances, managers may choose to effectively reduce the sizes of reserves of wildland by treating the interface zone as one for economic-asset protection (as above), not for biodiversity at all. This may not appeal to all local residents.

The scientific challenge is to be able to predict the effects of disturbance regimes on biodiversity (native and exotic) in the areas of intensive management adjacent to urban areas. This is a major task. The concepts of fire regime and functional group are scientifically valuable in predicting the effects of fires on plants, particularly (e.g. see Bradstock *et al* 2002) but functional groups have been largely defined with a single fire interval in mind. If functional groups could be defined with all components of fire regimes included (e.g. after Gill 1975), the effects of fires on plants and animals would be better predicted.

Because residents near wildland areas are often passionate about local biodiversity, and because biodiversity is impacted by disturbance regimes designed to protect houses, the social challenge is to transmit the idea that fire regimes or other disturbance regimes, not just one event, change biodiversity outcomes. This may then enable meaningful dialogue about the predictability of management actions at the interface to be made in relation to biodiversity conservation. Knowledgeable residents may also be able to monitor change and thereby provide hard-pressed managers with local information which can assist them to make informed choices about urban-edge management.

6. Conclusion

The 'fire problem' is remarkably complex. Our selection of four scientific and social challenges represents just a subset of the larger problem. Each problem has revealed considerable scientific complexity and issues of neighbourhood co-operation and learning.

Perhaps because of the nature of the problem, much of the literature is qualitative, and semi-technical, published in conference papers, pamphlets and reports and often not readily available. An apparent assumption is that the problem can be readily solved. Perhaps, society would be better informed if the problem was defined in economic terms (Coleman 1995) such as a cost–benefit ratio for ever increasing reductions in apparent risk (Finney 2005). Or, is the problem a classic 'wicked problem' in which stakeholders recognize that there is a problem but some see it in terms of 'too much of the wrong kind of forest management' while others see it as a 'lack of adequate management' (Carroll *et al* 2007).

Solving the problem of socially disastrous fires at the RUI may never be complete because of continual changes in social and biophysical systems associated with population growth, cultural change, fuel and climatic shifts. However, the problem can be addressed incrementally with an aim towards 'long-term system improvements rather than short-term fixes' (Carroll *et al* 2007). The challenges presented here are considered to represent steps in this incremental process.

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