The worldwide “wildfire” problem

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Abstract. The worldwide “wildfire” problem is headlined by the loss of human lives and homes, but it applies generally to any adverse effects of unplanned fires, as events or regimes, on a wide range of environmental, social, and economic assets. The problem is complex and contingent, requiring continual attention to the changing circumstances of stakeholders, landscapes, and ecosystems; it occurs at a variety of temporal and spatial scales. Minimizing adverse outcomes involves controlling fires and fire regimes, increasing the resistance of assets to fires, locating or relocating assets away from the path of fires, and, as a probability of adverse impacts often remains, assisting recovery in the short term while promoting the adaptation of societies in the long term. There are short- and long-term aspects to each aspect of minimization. Controlling fires and fire regimes may involve fire suppression and fuel treatments such as prescribed burning or non-fire treatments but also addresses issues associated with unwanted fire starts like arson. Increasing the resistance of assets can mean addressing the design and construction materials of a house or the use of personal protective equipment. Locating or relocating assets can mean leaving an area about to be impacted by fire or choosing a suitable place to live; it can also mean the planning of land use. Assisting recovery and promoting adaptation can involve insuring assets and sharing responsibility for preparedness for an event. There is no single, simple, solution. Perverse outcomes can occur. The number of minimizing techniques used, and the breadth and depth of their application, depends on the geographic mix of asset types. Premises for policy consideration are presented.

Key words: *adaptation; asset; biodiversity; disaster; emissions; fire management; fire regime; human fatality; policy; prescribed fire; smoke; wildland–urban interface.*

INTRODUCTION

Wildfires, also known as forest fires, bushfires, and unplanned fires, occur in landscapes across the globe (Krawchuk et al. 2009, Bowman et al. 2011). They can negatively or positively affect social, economic, and environmental assets. Few of these fires cause major losses of human lives and homes but when they do they make banner headlines in the world’s media. The worldwide occurrence of such fires is evident in examples from Africa (South Africa in 1998 [de Ronde and Goldammer 2001] and in 2000 [Calvin and Wettlaufer 2000]), Asia (China in 1987 [Lifu and Xiaorui 2002]), Indonesia in 1997–1998 [Cochrane 2009]), Australia (e.g., in 2003 and 2009 [Esplin et al. 2003, Teague et al. 2010a–d]), Europe (Greece in 2007 [Xanthopoulos et al. 2009]), Russia in 2010 [Vasquez 2011]), the Middle East (Israel in 2010 [media reports]), North America (Canada in 2003 [Filmon 2004], United States in 2003 [Blackwell and Tuttle 2003, Mutch 2007], Mexico in 1998 [Mutch et al. 1999]), and South America (Brazil in 1998 [Cochrane 2009]).

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Adverse effects define the worldwide wildfire problem (WWP)

In the emotion-charged aftermath of socioeconomic fire disasters like those cited in the last paragraph, single, apparently simple, solutions to the problem such as “stop fires from starting” or “put them out” often arise. Is the WWP just a technical problem, simply awaiting a solution involving bigger, better, and more pervasive technology for fire detection and suppression? This cannot be so, as this “solution” has been found wanting in areas of the United States at least (e.g., Stephens and Ruth 2005). Perhaps it’s just a matter of fuel reduction? Or is it an institutional problem requiring more effective leadership, coordination, and administration of government agencies? Could it be just a matter of determining a suitable land use like irrigated agriculture? Is it simply a scientific problem awaiting better understanding of critical fire probabilities, threshold fire behaviors, the fire ecology of ecosystems, and the fire resistance of buildings? Or is it a social problem requiring everyone to be aware of landscape fire and to take suitable actions on “bad” fire days? Could it be simply a matter of relocating assets? Whatever it is, actions arising from official reports of ever-increasing length (Fig. 1) have not yet solved the problem.

Having a conceptual basis for the understanding of the WWP is a strategic need. Increasing human populations and changing fuels, weather, technology, scientific knowledge, and social expectations are leading to a continually changing fire world. The “incidence of extreme wildfire events is . . . increasing . . . with adverse impacts on economies, livelihoods, and human health and safety” (ISDR WGWF 2005). Our contention is that the problem is complex locally, and on a worldwide basis, because of the multiplicity of assets and parties involved; the variety of socioeconomic, political, and geographic contexts; the complexity of the science (e.g., predicting effects of fires on assets, such as millions of indigenous species across the globe, at the temporal and spatial scales involved); the costs of mitigation efforts, especially in extreme fire circumstances; the multiple pathways for minimizing it on the ground; and the probability of repeated events (residual risk). As a result, the problem can, at best, be minimized rather than solved in most areas of the world.

The scientific literature concerning the extremes of the WWP is most abundant in the United States and Australia, thereby drawing attention to these areas, while the pertinent gray literature can be voluminous, of variable quality, and not readily available worldwide. By focusing on a particular region, the depth of the problem can be addressed and, by referring to worldwide examples, the scope of the problem can be highlighted. Thus, we have chosen our geographical focus for some topics to be southeastern Australia, especially the state of Victoria, a region that is arguably the worst in the world for socially disastrous fires (Gill and Cary 2012), and one known to us. More generally, our examples focus on fires in industrialized countries like the United States and Australia, which cover the range of issues everywhere although the significance of issues varies from country to country and place to place.

Our aim in this paper is to first provide a framework for understanding the WWP highlighted by socially disastrous landscape fires and, second, consider the means to minimize the effects of the problem. In the first main section, some concepts and definitions are given as background; in two subsequent sections, the effects of fires on certain environmental and socioeconomic assets are described; and, in the final sections, ways of minimizing the effects of the WWP are separately outlined.

CONCEPTS AND DEFINITIONS

Assets

An asset is considered to be something we value. Fire-prone assets can be classified as social assets, especially in the form of human lives and homes (they create headlines when adversely affected, but pets, memorabilia, documents, scenery, and features of spiritual value are also assets); economic assets, such as buildings (houses, barns, businesses, and schools), farms (crops, fencing, livestock, fodder, and farm equipment), and

FIG. 1. Lengths of reports into Victorian fires from Royal Commissions, Parliamentary Inquiries, and other independent inquiries. Note the logarithmic scale on the y-axis. Colonial inquests are not included. The reports cited are Tucker et al. (1900), Stretton (1939, 1944), Barber (1977), Miller et al. (1984), Cameron (2003), Esplin et al. (2003), Pandazopoulos et al. (2008), and Teague et al. (2009, 2010a–d).

public infrastructure; and environmental assets, such as biodiversity, iconic fauna and flora, carbon stocks, clean water, and clean air, for example.

In eight “mega-fires,” often large fires with “deep, long-lasting social, economic and environmental consequences,” the adversely affected assets mentioned by Williams et al. (2011) included human life and/or houses (Australia, Greece, Israel, Russia, United States), people’s health via smoke (Brazil in 1998, Russia in 2010), air quality through emission of greenhouse gases (Australia in 2009, Indonesia in 1997–1998), grazing land (Botswana in 2008), farm animals (Greece in 2007), wildlife-reserve vegetation cover (Botswana), forest cover (Israel in 2010; see also Brun [1974]), and economic outcomes (Australia, Botswana, Greece, Indonesia, United States). In the Indonesian fires, human fatalities caused by smoke were estimated to have been in the thousands (see Cochrane 2009) while adverse smoke effects in Europe, Canada, and globally have been noted by Goldammer et al. (2009).

Biodiversity

“Biodiversity” in its simplest form refers to the variety of plants and animals indigenous to a locality. Appreciation of the importance of the biodiversity asset to regions and nations can be seen, for example, in the increase in the area of national parks in Victoria (Gill 1981b) and in Australia generally (Cresswell and Thomas 1997). It is also reflected in Australian legislation such as the Victorian Flora and Fauna Guarantee Act, the national Environment Protection and Biodiversity Conservation Act, and in international agreements such as Ramsar (Parks Victoria 2004: Appendices 1 and 2).

Succession and vegetation or habitat dynamics

Succession, in its simplest form, is the change in vegetation type or biodiversity with time since vegeta-

tion colonization of an area (primary succession) or time since disturbance (secondary succession), the classical approach of Clements (1916). This concept can be extended to encompass the habitat of animals. Vegetation and habitat dynamics implies multiple pathways, multiple changes that can take place over time. Cattellino et al. (1979) outlined a general scheme for multiple pathways of succession in fire prone vegetation based on species attributes and life-history markers, anticipating Noble and Slatyer (1980). We can extend these concepts to include gardens and rural properties where changes in biodiversity and habitats are more directly influenced by people.

Fuels and fires

While “fuel” may be defined as something that actually burns in a fire event, the difficulty in definition is that what actually burns during a fire may be only a portion of that which is possible and depends on the fire properties at the time, which are affected by time since ignition, weather, slope, and spread direction (forward, backward, or sideways in relation to slope or wind). Under mild weather conditions on flat ground, fires in forests will be of low intensity (defined as heat output of the fire edge by Byram [1959]). On a day of high winds, high temperature, and low humidity, flames may reach into the tree canopies such that the whole forest is alight. Even the soil may burn if it is highly organic. Fuel can be biodiversity, pastures, commercial crop, buildings, gardens, suburban parks, and cars.

Fires occur as events lasting for minutes, hours, or months. They are “events” in that they have a definite beginning and a definite end.

The fire properties of particular relevance in the present context are the following:

- 1) Rate of spread. This affects the ability to suppress a fire and ability to move away from a fire safely.
- 2) Intensity (rate of spread of the fire edge multiplied by the amount of fuel consumed by flaming combustion and the heat yield of the fuel; Byram 1959). This can be related to thresholds for fire control (see McCarthy and Tolhurst 1998; see also Fernandez and Botelho 2003) and to flame dimensions (Burrows 1994:180, in southwestern Australian forests).
- 3) Flame length and angle. These affect the ability of a fire to cross barriers and so spread in discontinuous fuels (Finney et al. 2010), reach into tree canopies (Van Wagner 1977), and affect radiation load on buildings (Cohen 2000).
- 4) Firebrand production (burning brands, embers). This can be a potent source of ignition of buildings (e.g., Ramsay et al. 1996, Cohen 2000) and means of carriage of fires across gaps up to tens of kilometers in width (Luke and McArthur 1978:102, Gill and Stephens 2009).
- 5) Smoke from all fires, but perhaps from smoldering peat fires especially (e.g., Goldammer et al. 2009), as

many effects arise therefrom (see also the next subsection).

Fire, smoke, and severity regimes

A fire event may help set the initial conditions of the system for the effects of the next fire event, so sequences of fires, called the fire regime, through its component variables, fire intensity, season of fire, interval between fires, and type of fire (above- or belowground) (Gill 1975, 1981a) can have significant effects. Consideration of the ex situ (as far as the sites of combustion are concerned) effects of smoke invokes the need for consideration of a “smoke regime,” with type (composition), intensity, interval, and season as in the fire regime; for example, see Kennison et al. (2009) for the effects of the timing and repetition of smoke exposure on the quality of wine grapes. For some purposes, identification of a “severity regime” can be helpful; severity, here, is defined simply in terms of the leaf-char zone (black), leaf-scorch zone (brown), and unaffected-leaf zone (green). The severity regime is dependent on the interaction between the fire regime and structural dynamics of the vegetation.

Framing the WWP: Fuel as a basic consideration

In the conceptual depiction of the fire problem, beginning with Fig. 2, we chart the changes in fuel states that occur with time after fire while emphasizing the states present immediately before and immediately after a fire event. This is done to highlight the rapidity and extent of change in fuels and assets that can occur in a very short time period at a geographic point during a fire event and the more gradual changes, though sometimes profound, that occur in the inter-fire period of from one year to hundreds of years; one rotation through the sequence shown in Fig. 2 equals one fire interval. Fuel is emphasized because this is often the variable that receives most attention in seeking solutions to the WWP and is a major contributor to fire behavior. Weather and terrain, as other major contributors to fire properties, are also shown in the diagram but not repeated in subsequent diagrams.

There is a feedback mechanism between fuels and fire properties (dotted arrow in Fig. 2) because under some circumstances, such as stratified forests (Gould et al. 2007:18) there can be interactions between the fire and potential fuel. Thresholds for fire access to tree canopies can be crossed contingent upon circumstance (Van Wagner 1977, Cruz et al. 2002). Spatial thresholds for horizontal fire spread are unnecessary in most grassland fuels but do exist in discontinuous grassland, shrubland, and some forest fuels (Bradstock and Gill 1993, Collins et al. 2009). Production of firebrands may be contingent upon fuel types and fire intensities.

When large quantities of fuel are burning across the entire fire perimeter at any one time under conditions of extreme fire weather and atmospheric instability, large

FIG. 3. The effects of fires on terrestrial ecosystems and a subset, fuel. The contingent effects (dotted arrow) are due to the possible effects of erosion soon after fire, or smoke, on necessarily ex situ riverine, and even marine, ecosystems.

places (D. Jamieson, *personal communication*): the parent population was killed just four years previously while the subsequent saplings, arising from seed shed by the parents, had insufficient stature to avoid death from the later fire and insufficient time to develop seed.

The effects of fire regimes on animal species are more difficult to predict and even detect. Fire events can affect the survival of populations but predation immediately after fire can be significant also. The simplest case of fire-event effects, perhaps, is that of the arboreal koala (*Phascolarctos cinereus*) of eastern Australia, which has a mortality in fires and reestablishment after them similar to that of Australian mistletoes (Gill and Bradstock 1995). The effects of fires on the composition of a local faunal community, as habitat, may be *indirect*, via effects on habitat structure, species' composition, and regional predators.

Aquatic habitats, not just terrestrial ones, may be affected by fires. A variety of *indirect* effects of fires on streams can occur due to changes in water flow, increased water temperature, increases in pH, changes in chemistry, and changes in bottom sediments (Lyon and O'Connor 2008). These changes do not occur in all fire circumstances but do so under *some* circumstances (hence dotted arrow in Fig. 3; Dwire and Kauffman [2003] in the United States). If intense storms occur in the year or two after fire then widespread runoff and erosion may occur due to low impedance of regenerating vegetation and the exposure of bare soil (e.g., Shakesby et al. [2007] for southeastern Australia; Brun [1974] for the Mediterranean region). A sediment slug may move downstream through and away from the fire area affecting riverine biodiversity as it goes (Lyon and O'Connor 2008), perhaps entering the sea and affecting biodiversity there. In Indonesia, death of coral reefs was apparently caused by fallout of iron from the smoke of extensive fires there in 1997, an extremely rare occurrence (Abram 2004). These contingent

effects are illustrated in Fig. 3; note that these are ex situ effects.

EFFECTS OF FIRES ON SOCIAL AND ECONOMIC ASSETS

The socioeconomic effects of fire disasters are difficult to measure comprehensively for all stakeholders, all costs, and all benefits. Individuals, small businesses, corporations, and governments are all involved. The unit of currency may well be different according to different assets: dollars, human lives, and air quality are three examples. Certain operations may be targeted for evaluation within governments (suppression, prescribed burning) but externalities (e.g., environmental costs), opportunity costs (e.g., staff at "normal" jobs rather than being diverted to fight fires), infrastructure, and salaries may not be considered, especially if higher levels of government make emergency funds available. The 2009 Victorian fires were estimated to cost A\$4 billion (Teague et al. 2010a:1); in Indonesia, the asymmetric distribution of costs and economic benefits were noted (Williams et al. 2011); and, in recent decades in tropical countries, there have been large economic losses, while in the United States, the escalating costs of suppression have been documented (Cochrane 2009).

In the subsections that follow, the focus is on *selected* assets. First is a consideration of economic assets in broad terms. Southeastern Australian examples are emphasized because detail is available and instructive.

Economic assets

A common economic indicator presented after fires is the estimated cost of firefighting (suppression) to the community, or the cost of insurance payouts or claims; the latter was put at \$A1.2 billion after the tragic 2009 Victorian fires (Teague et al. 2010b:345). Yet, there is no evidence of insurance companies failing as a result of socially disastrous fires. Insured householders receive payouts and governments may assist with the clearance of properties and removal of health risks. Many millions

of dollars may be donated by the public to assist survivors ("victims"), some of whom may be in a position to build bigger and better homes after the event. Subdivision of blocks may also have enabled some residents to increase their wealth as a result of a fire. Other residents may be poorer because of inadequate insurance, or none, and, possibly, because of unsuccessful court cases. Some communities in developing countries do not have an insurance option. Building costs may be higher as the result of new regulations for more fire-resistant buildings or, possibly, the need for approved fire refuges to be built. Community facilities may be improved. Some stakeholders profit, some lose while government decisions, insurance and public donations moderate extremes. In different socioeconomic settings in different countries, and regions, the socioeconomic impact of fires would be expected to be very different.

Fire area can be a useful basis for assessing economic losses (see Bradstock 2010) in some circumstances. For example, losses of livestock, fodder (bales of hay), fences (length), and houses (number) in a rural fire episode in Victoria in 1977 were all correlated with the areas of the individual fires concerned (data of McArthur et al. 1982: Table 7) but such correlations cannot be considered predictive of all cases.

Social assets

People are the main social asset and this section considers the tragic loss of human life that can occur in some unplanned fires. Human fatalities reached 173 in the 2009 Black Saturday Bushfires in Victoria, Australia (Teague et al. 2009:6; see Plate 1), while in China in 1987, 213 persons were killed by landscape fires (Lifu and Xiaorui 2002). Thousands of people can be directly affected economically and emotionally. In the Victorian Black Saturday fires in 2009, thousands of fire fighters were involved, thousands of other emergency-service personnel were called into action, 2029 homes and 57 businesses were lost, 7000 people were made homeless, and 20 000 people registered at relief centers (Parents and Friends Committee of Glenvale School 2009). Many other people were involved in support and recovery roles, servicing numerous fire-fighting vehicles, providing thousands of meals during and after the event, and providing donations (see Gill and Cary 2012).

Deaths from landscape fires in Australia between 1900 and 2008, numbering 552, occurred largely as the result of flames and heat (77%) but also smoke inhalation, vehicle crashes, flying and falling debris (including falling trees), and heart attack (Haynes et al. 2010). In the latter period of their study, 1955–2008, Haynes et al. (2010) found that, of the 260 people involved, 26% died in the process of late evacuation, 25% died while defending property, 14% died "inside defendable property," and 11% died while traveling through the area.

The 173 deaths in the 2009 Victorian fires add significantly to the total fatalities since 1900. Of the

173 recent deaths one was a fire fighter; of the other 172, about one-quarter had prefire "chronic clinical health conditions" that may have an age component; 69% of the people who died were sheltering in a building, about one-third of these in a bathroom; males were more frequently represented than in the general population; and older people (>70 years old) were more likely to die and children less so (Handmer et al. 2010).

Socioeconomic assets

In this section, the loss of houses is the focal point but a link to human fatalities and policy is also made.

Of the houses burned in landscape fires in Australia, about two-thirds were lost when the maximum Forest Fire Danger Index (FFDI) on the day was over 100 (Blanchi et al. 2010), once considered the "worst possible" level (McArthur 1967). These are national data, so they do not take into account the frequency of days per year on which these FFDI values occurred. However, the frequency of days on which values of FFDI occurred has been taken into account by Bradstock and Gill (2001): for the Sydney region between 1955 and 1995, they found that the percentage of days on which destructive fires occurred rose from zero at an FFDI of about 15 to 40–50% when FFDI reached 70, the maximum value in their analysis. When the chance of a fire occurring on a day with a particular FFDI was considered as well, the chance of house loss given a fire rose from about 9%, when the FFDI was between 10 and 20, to 100% when FFDI was greater than 30.

It can be reasonably expected that loss and damage will be related to fire intensity, intensity being dependent on fire rate of spread and fuel amount and condition that, in turn, will be related to flame radiation, firebrand density (including embers), and flame contact, all potential sources of house ignition (Ramsay et al. 1996, Blanchi and Leonard 2008). In the 1983 fire at Mt. Macedon in Victoria, Wilson and Ferguson (1986) showed a rise in percentage house loss as intensity increased, with losses of about 11% occurring even at the relatively low intensity of less than 500 kW/m and reaching 86% in the class 10 000 to 60 000 kW/m.

Loss of houses is more common than death of people, yet can be related, so using house loss as a guide to this prime social effect of fires has value in indicating a near miss to human death (house loss without human fatality) or as a correlate. Fig. 4 shows a relationship between the loss of houses and deaths of people in fire episodes in California in 2003 and in Victoria in 2009. The correlation between losses of houses and deaths does not necessarily represent an unqualified cause and effect, however, because circumstances vary so widely around the globe.

After fatalities and housing losses, there may be intense media interest and various official and unofficial investigations within organizations. Governments may adopt recommendations arising therefrom or ignore them. Policy through regulation or legislation may or

FIG. 4. Number of human fatalities as a function of the number of houses burned in separate fires in California in 2003 (Blackwell and Tuttle 2003) and in major Victorian fires in 2009 (Teague et al. 2009). The differences in the curves need to be interpreted with caution.

may not take place (see Boin et al. [2009] in the general disaster context). New policies can affect the initial conditions for the next fire event that, in turn, can affect the outcomes of that fire event (Fig. 5). Each official procedure can have an impact on individuals and communities through their emotional states, careers and economic status in some cases. “The human toll on those involved can be immense” (Dunlop 2004).

RESPONDING TO THE WWP: GENERAL

Three general responses to the WWP are to solve it, live with it, or minimize its effects. In many areas, history has shown that solving it is not yet possible. “Living with it” may mean different things to different people but may be seen to have a fatalistic element. “Minimizing its effects” suggests doing everything possible to achieve the best possible outcome.

In minimizing the effects of the WWP, there are four main strategies:

- 1) Control fuels and fire regimes (reducing the number of unwanted fire starts, fuel modification [especially through the use of prescribed-fire regimes] and, fire suppression). Ex situ, keep fires away from individual fire-sensitive assets (e.g. houses, people); smoke may be managed to avoid smoke-sensitive assets (people, agricultural products etc.). In situ, optimize fire regimes for naturally fire-prone assets (e.g. biodiversity, timber from resistant trees, catchments for drinking water, rangeland renovation).
- 2) Increase the resistance of assets, such as houses, to damage or protection of people exposed to fire in prepared houses or special shelters.
- 3) Move assets from the path of a fire, especially vulnerable people, or avoid locating assets such as houses in potentially damaging situations.
- 4) Enhance recovery from disasters and promote adaptation, e.g., by continually improving preparedness and responses to social disasters, and by having insurance.

The control of fire regimes might be attempted through fuel management (Fig. 6) using grazing regimes or slashing for grassy vegetation or mechanical treatments in forests (Agee and Skinner 2005, Stephens et al. 2009b), but the interactions between prescribed fire regimes and unplanned fires are a focal point here largely because of the long-standing debate over the use of prescribed fire. For example, prescribed burning is excluded by law in Greece (Williams et al. 2011) and Namibia (Goldammer et al. 2002) while choosing the most suitable burning regime in dealing with “the fire problem in tropical savannas” was emphasized by Gillon (1983). Control of fire regimes may also be through fire suppression or controlling unwanted fire starts; these topics are considered in the following section along with prescribed burning. Asset-based solutions are considered subsequently.

REDUCING THE NUMBER OF UNWANTED FIRE STARTS

Prescribed-fire starts, as a legal land-management option, need to be distinguished from unplanned, unwanted, fire starts. Of the latter, there are a relatively few natural sources: lightning mostly, but also, even if very rarely, spontaneous ignition, rock falls, and volcanoes. In contrast, there are numerous sources of human-caused ignitions that are unwanted by land managers, especially, or by society in general, e.g., clashing power lines, accidental escapes from campfires or prescribed burning, inappropriate cigarette disposal, sparks from welding and machinery, and arson.

The numbers of fires starting on a particular day in a particular region vary from zero to many depending on the weather, fuels, season, and causes. Fires can be so numerous on a day that fire-fighting authorities have to choose between them in allocating scarce suppression resources (Gill 2008:9). On Black Saturday in Victoria in 2009, there were 316 fires “attended or patrolled,” five of which caused human fatalities (Teague et al. 2010a:1, 4).

While lightning cannot be prevented, it is possible that the number of fires originating in this way can be reduced by fuel treatment. If there is no fuel, there can be no fire. If time-since-fire is short, then fuel is most likely to be discontinuous and fires less likely to spread in them (Stephens et al. 2008, Collins et al. 2009), especially under moderate fire-weather conditions. There are few data but, for part of Western Australia in 1961, McArthur (1965) reported that 60% of lightning fires occurred in fuels unburned for 20 years or more, 30% were in fuels 10–20 years old, and only 10% were in lighter fuels. While these figures are indicative, the areas covered by fuels of these ages and the number fires involved were unstated. Perhaps, planning for strategic fuel reduction (Finney 2007) could consider the most likely places for lightning ignitions as depicted in models of McRae (1992) and Cary (2005) in southeastern Australia and Latham and Williams (2001) in North America.

Major fires in Victoria sparked by the electricity grid occurred in 1969 and 1977 (Barber 1977:132) and 2009 (Teague et al. 2010c:148). There are a number of ways that

FIG. 5. The effects of socially disastrous fires on aspects of the social system. Note that the postfire social asset state (e.g., social disaster) is contingent on the fire circumstances and is, in part, *ex situ*. The indirect effects of policy and other aspects on fuel states are not shown.

fires may be started by the electricity grid including the clashing of conductors or trees contacting them (Teague et al. 2010c: chapter 4). Conductors can be fitted with spacers to hold them apart, insulated, and bundled or placed underground, increasing costs (Teague et al. 2010c:154). Fuel beneath overhead conductors can be removed or reduced.

Often, even usually, unwanted fires are caused by people, in southern Africa (Hoffmann et al. 2009), the Philippines (Goldammer et al. 2002), southeastern Australia, and the United States (Willis 2005), but not all are deliberately lit. Muller and Bryant (2008) found

that “up to 60% ... may be deliberately lit”; perhaps as many as 60–75% of these were started by children (U.S. statistics from Dittmar [1991], as cited in Stanley [2002]). Arson is a commonly ascribed cause of fire but accurately ascribing the cause of a fire to a motive such as arson, rather than a mechanism (e.g., molten welding metal), is difficult. A variety of interventions are needed to minimize unwanted fire starts.

Most states of Australia have fire agencies that conduct “juvenile arson intervention programs” (Muller and Bryant 2008) while other methods of “preventing”

FIG. 6. A simplified schematic showing responses to the unplanned fire (wildfire) problem in relation to an asset cycle and a fuel cycle moderated by altered in situ fire regimes (especially by prescribed fires). Dotted arrows represent contingencies.

FIG. 7. A hypothetical illustration of the effects of increasing the extent of prescribed fire on the standardized proportion of landscape burned by unplanned fires per year (upper solid curve) and the effect of fire suppression added (lower dashed curve). The standardized proportion of landscape burned at $x = 0$ is the proportion of landscape burned by unplanned fire divided by the proportion burned in the absence of prescribed burning, i.e., 1. The upper curve is based on Boer et al. (2009).

fire-setting include surveillance, closing public lands on days of substantial fire danger and making it a criminal offence to start a fire (Teague et al. 2010c:192).

PRESCRIBING FIRE

Prescribed fire, here, is the “deliberate and safe use of fire to achieve an explicit outcome under specified conditions of fuel, weather, and ignition in a designated area” (see Gill 2008:43). A prescribed fire may, under some circumstances, become an unplanned fire (dotted arrows from “alter in situ fire regimes” in Fig. 6). Prescribed fires are part of a program of burning and are therefore a component of a fire regime. The timing of prescribed fires may be seasonally different to those of unplanned fires and often of a much lower intensity. If the change to more frequent fire, perhaps in a different season and with a different average intensity, transcends the safe fire-regime domain of some native plant species (e.g., see Whelan et al. 2009), then local extinction logically follows.

Adverse effects on economic assets (e.g., farms and some plantations [Gill 2005]) and unsuitable climates limit the area for prescribed burning (in southeastern Australia [Gellie 2003], in the United States [Williams et al. 2011], and more generally [Fernandez and Botelho 2003]), but prescribed burning can be used to enhance an in situ (e.g., biodiversity, mature timber) asset (Stephens et al. 2012), as part of a suitable fire regime, or to help suppress a fire before it reaches an ex situ asset (such as an urban interface).

In prescribed burning programs in Australian eucalypt forests, one aim is to maintain the potential litter-fuel load to less than 8 Mg/ha, the amount at which fire control may be considered to be just possible when the weather is extreme, the ground is level, and the threshold for losing control is set at a fire intensity of 4000 kW/m (Gill et al. 1987; see also Fernandez and Botelho 2003

more generally). While this may be seen as a convenient target for assisting suppression, it does not preclude unplanned fire occurrence because the minimum amount of forest litter for fire spread can be as low as 4 Mg/ha (Gould et al. 2007:78).

The area over which prescribed burning is instituted to reduce the area of unplanned fires is important in terms of its outcomes on assets. The relative proportion of landscape burned by prescribed fires in relation to the area burned by wildfire has been depicted for southwestern Australian vegetation, especially eucalypt forests (Boer et al. 2009). For present purposes, the shape of Boer et al.’s graph is used but extended to the y-axis and standardized to unity (Fig. 7). The average area of unplanned fire reduced by a unit area of prescribed fire (each 0.01 fractional increase), or leverage (Loehle 2004), is near one initially in our model but becomes very much less (reaching near 1/7) as the area of prescribed burning increases. However, because not all of the area, nor litter in the fuel profile, necessarily burns during prescribed fires, southern Australian fuel managers aim for 50–60% of surface-fuel to be reduced in large area fuel-reduction programs (Underwood et al. [1985] in southwestern Australia; Victorian Department of Sustainability and Environment [2003] in Victoria); a nominal hectare of unplanned fire in fuel-reduction terms is greater than a nominal hectare of prescribed fire in this case. This is magnified when the extreme conditions under which unplanned fires sometimes burn are considered.

In extreme conditions, unplanned fires burn much more than just litter fuels. The total potential fuel for long-unburned jarrah (*Eucalyptus marginata*) forest of southwestern Australia, including litter, under extreme conditions, is estimated to be of the order of 44 Mg/ha without considering variations due to understory type and the highly variable quantities of logs and branches that are the legacy of logging and previous fires (Burrows 1994:50, 58). There are 18 Mg/ha of non-litter fuel involved in this example without considering coarse woody debris. What is actually burned at any one spot will vary widely due to differences in weather, slope and spread direction. The amount of fuel consumed and the area burned will affect the amount of smoke produced and its attendant adverse effects.

Gaseous or particulate emissions (smoke) from fires, including prescribed fires, are important in two main ways: (1) they affect the composition of the atmosphere, potentially warming it through greenhouse-gas emissions, cooling it through particulates transported into the stratosphere in extreme fire circumstances (Fromm et al. 2006), and affecting fuels (see Williams et al. 2009, Cary et al. 2012); and (2) they can directly affect human enterprises, and human health, which can have a negative effect, through public demand, on the extent of the prescribed-fire program. The amount of smoke produced over sensitive areas can be reduced by reducing the area burned and by using smoke-dispersal

models (Wain et al. 2009), and by choosing days for prescribed burning when wind direction carries smoke away from assets of most concern. In some tropical savannas, at least, prescribed fires have the capacity to reduce total emissions because they burn relatively little fuel and have a direct tradeoff with unplanned fires in terms of area burned (see Williams et al. 2012).

In the final analysis, it is the effects of fire (and smoke) regimes on assets of significance across the landscape that matters, whether or not these regimes are dominated by prescribed or unplanned fires. The effectiveness of prescribed burning in minimizing the WWP is contingent on land use (Gill 2005)—inappropriate in a householder's backyard and in a farmer's improved pastures or crops while useful in some forests for wood products and biodiversity—and impossible to carry out in some environments. Even if the leverage is less than one, a manager may still see the program as being worthwhile because the cost of prescribed burning per hectare may be less than the sum of the costs of suppression of unplanned fires and the potential cost of burned houses and the potential loss of human lives.

FIRE SUPPRESSION: STOP WILDFIRES SPREADING?

Fire suppression, or fire-fighting, can be implemented by an organization or business with formally constituted brigades, or it can be an action of rural landholders or urban-edge householders when fire threatens. Government agencies may be able to call upon the assistance of large numbers of volunteers for seasonal surges in demand or in extreme years. Surges in demand may also be met by crews and equipment from outside the affected area, from other places in the nation and from overseas. Urban and rural brigades can be involved.

Fire suppression systems are becoming more and more sophisticated in terms of their equipment and operations, e.g., fire detection systems (aerial spotting, satellites), communication technology, suppression equipment (fixed and rotary winged aircraft, all-terrain vehicles), interagency agreements, incident management systems, and fuel-break networks. In Victoria, after the infamous 1939 fires, the main government agency involved with fires, the Forests Commission of Victoria, saw that "emphasis [was] placed on greatly improved access, a network of fire lookouts for early detection of smokes and a small but highly trained workforce equipped to combat forest fires" (Dexter 1975). Now, like many other industrial countries, there is access to a fleet of aircraft with a range of capacities (Gill 2008: chapter 2) as well as a large group of trained fire fighters (professional and volunteer). It is a far cry from "the early days [when] fire suppression was usually confined to those fires within a day's ride on horseback" (Dexter 1975). Socioeconomic circumstances vary widely and not all people in all countries have access to sophisticated suppression systems; in the Indonesian fires referred to above there was "little or no suppression" (Williams et al. 2011).

Where fire crews are available, they may arrive at the fire when its head is already too intense, the perimeter too extensive, and its rate of growth too great for immediate containment (Gill 2008: chapter 1). Effort for fire containment may be reduced by the need to protect point assets like houses. Thus, unplanned fires, especially on extreme days, can reach substantial sizes despite sophisticated suppression systems. If fuels have been reduced, the chance of effective suppression is improved (e.g., Moghaddas and Craggs 2007) but weather conditions may have a dominant effect on fire behavior under extreme weather conditions (e.g., Gould et al. 2007:71; Moritz et al. 2010).

The influence of suppression effort on forest area burned by unplanned fire is expected to show a similar negative exponential form to that of prescribed fire. The effect of suppression is to lower the curve (Fig. 7). This is reasonable given that suppression can reduce the extent burned by unplanned fire in an area where prescribed fire or other fuel treatments are not possible. A complication arises when fuel is burned out ahead of a fire because it can potentially increase its extent.

Suppression practices to minimize the WWP may be possible everywhere but their effectiveness is limited. Perversely, successful suppression has been postulated to lead to larger fire outbreaks in Europe (see Moreira et al. 2011) and in the United States (see Keane et al. 2008).

As part of a suppression system, a fuel-break network might be established. A fuel break is the ultimate in local fuel reduction because there is no fuel present there. While such networks are common in many fire-prone countries, in others, like Namibia, they are not economically justified (see Goldammer et al. 2002). Fuel-free breaks can have a role to play but determination of effective width is a serious question given that spot fires from lofted firebrands can be a problem (Gill and Stephens 2009).

MAKE ASSETS MORE RESISTANT?

People can be made more resistant to injury from fire. People defending property can wear clothing, boots, masks, and helmets that enhance resistance, called personal protective equipment (PPE). This might not occur among citizens to the extent that it does for professional fire fighters but, nonetheless, is helpful. Having a full PPE kit does not guarantee survival.

The PPE example illustrates the level of detail at which minimizing the WWP may apply. With a structure like a house, fine details such as ensuring that there are a minimum number of weak spots (Gill 2005), such as nooks and crannies where embers can lodge, is important (Blanchi and Leonard 2008). However, there are also larger elements of buildings like windows and cladding that can be made more resistant (Ramsay et al. 1996) along with many building details (Gill 2005). In the USA, the vulnerability of houses with wooden roofs has been highlighted, survivability in one study being 70% if the roof was nonflammable compared with only

PLATE 1. Aftermath of Australia's Black Saturday 2009 bushfires at Saint Fillans in Victoria. The effects of the fire on cars and a house as economic and social assets is apparent. Economic and biodiversity assets are also present in the form of an impacted forest in the background. Photo credit: G. J. Cary.

19% if flammable (see Cohen 2000). Houses can be made relatively more resistant temporarily as well by closing windows to minimize ember entry and wetting down the exterior. The ultimate form of fire protection for people caught in a high-risk circumstances may be in a purpose-built shelter, but there are many questions of design, size, cost, ventilation, and the extent that fires can be seen and monitored, that need to be considered.

What level of fire resistance should be recommended? Brown (2009) and CSIRO (Leonard 2009) considered that the post-2009-fire Australian Standard AS 3959-2009 was inferior to the 1999 version. Orr (2009), in a companion article, was not as critical but conceded that "there are technical issues within the document that require ongoing consideration and review." Leonard (2009: section 8) details these. Having an official standard increases the possibility that people will assume that their preparation is adequate to withstand any fire because they have conformed to it (Orr 2009).

Governments may declare a level of perceived threat posed by fires by creating zones with various fire-threat levels. In Victoria the broad zone of high threat comes under the title of the Wildfire Management Overlay

(WMO) (Hughes and Mercer 2009). In such zones, there may be requirements for a particular building standard, provision of a static water supply, and vegetation management (Hughes and Mercer 2009). Woody fuels near houses increased house loss in the 2009 Victorian fires (Gibbons et al. 2012). In California, Troy (2007) described a state zoning scheme that, for various reasons, could be bypassed by local government, thereby giving people a false sense of security (see below).

RELOCATE ASSETS TO A FIRE-FREE, OR LESS-EXPOSED, PLACE

If the asset can be removed from the path of a fire, and moved safely to another place away from the fire, the asset can be fully safe. Relocation can take place tactically in anticipation of a fire arriving soon or can be a planning strategy.

For people, relocation is the basis of the "leave early" part of the Prepare, Stay and Defend, or Leave Early policy in Australia (see McLeod 2003: Appendix H, Gill 2005, Handmer and Tibbits 2005, Teague et al. 2010c: chapter 1). Relocation may occur early not only on a fire day but also when extreme weather is forecast.

While there are only two options if you are in a fire path, stay or leave, there are many issues affecting the outcome in practice. There is a rapidly growing literature on this (e.g., see McLeod 2003, Gill 2005, Handmer and Tibbits 2005, Gill and Stephens 2009, Whittaker et al. 2009, Handmer et al. 2010, Haynes et al. 2010), which includes debate in the United States in the light of the Australian experience and policy (Stephens et al. 2009a, Mutch et al. 2011). Thus, people faced with the possibility of fire may be unaware of how early “leave early” means, if they do leave, and may not understand what being “well prepared” means if they do decide to stay. People may be caught unaware in a fire path or be overconfident in their capacity to cope with it when it arrives; the unexpected emotional impact of intense fire and noise on inexperienced people may cause them to leave at the worst time: the time of impact. Some people are more vulnerable than others. Furthermore, some places are more likely to be heavily impacted than others because of the nature of the fuels nearby and aspect and position on a slope affecting exposure to the wind and the ferocity of the fire.

Teague et al. (2010a:5) concluded their intensive investigation by declaring that the “central tenets of the stay or go policy remain sound” but that there needed to be “greater emphasis on important qualifications” made. In particular, the policy needs, for example, to “allow for variations in fire severity”: recognize that individuals do not always know what to do and that they expose themselves to danger by waiting to see what happens, recognize the need for alternatives such as evacuation to places of community refuge or bushfire shelter, recognize that defending a house requires “at least two able-bodied, fit, and determined adults who are physically and mentally prepared to work long and hard in arduous and dangerous conditions”, and recognize that not all houses are defensible.

The qualifications raised above concerning the relocation of people who are actually or potentially threatened by fire are one of the reasons for the contingent designation of the relocation solution in Fig. 6; a further reason is that this strategy does not apply to all assets. Predicting and broadcasting the potential rate of fire spread, at least, would allow people to estimate how much time they had before the arrival of a fire front and the time available for safe relocation (Gill and Stephens 2009); the potential rate of fire spread could be given each day of the fire season along with the fire-weather forecast.

ENHANCE RECOVERY AND PROMOTE ADAPTIVE BEHAVIOR?

If all solutions combined fail, or cannot be implemented given the realities of economic cost, human freedoms, and priorities, then governments and responsible citizens will need to be prepared for the occurrence of social disasters. In invoking the need for the

enhancement of recovery and the promotion of adaptive behavior, a new suite of mitigating actions arise. The obvious social objective is to return affected communities to normal but, better still, communities can be helped to adapt to a new improved state rather than re-attain a previous state (Norris et al. 2008). In Fig. 6, this is depicted as contingent because intervention may not occur; recovery, there, is considered in the broadest sense and applies to rehabilitation works, such as replanting, as well as rebuilding of structures and counseling, for example. In this section, we consider insurance as a means of assisting economic recovery and people as a prime asset.

Insurance is a common means used by governments, businesses, and private citizens to minimizing economic loss in adverse circumstances. Insurance claims after the 2009 bushfires in Victoria elicited claims of A\$1.2 billion (Teague et al. 2010b:345). In the Canberra fires of 2003, an estimated A\$350 million was paid out (Henri 2003) but “one in three properties . . . was either under insured or not insured at all” (Tooley 2009).

Understanding why people do, or do not, insure is difficult. The results of the survey of customers of a large Swedish insurance company “strongly support[ed] the notion that [potential] ‘consequences’ dominate [the] evaluation of insurance options,” rather than the likelihood of an event, and that “demand for risk reduction is driven by the severity of consequences, not probability of harm” (Sjoberg 1999). If no chance of an adverse event was visualized, the conclusion would be that there was no chance of an adverse consequence and so no need for insurance.

Insurance may be rejected because it may appear to be too expensive, especially when there is a levy for fire services to be paid on top of the premium in some jurisdictions (Tooley 2009); omit covering all the assets at risk, including personal items and pets, air quality, biodiversity, and water quality, or other nonmarket assets (Talberth et al. 2006); and inadvertently create perverse outcomes (Troy 2007).

Troy (2007) outlined the consequences of the state of California’s decision to become “an insurer of last resort”; the well-intentioned insurance scheme that resulted provided a “perverse incentive to developers to build housing in some of the more hazardous and ecologically sensitive lands in the state, furthering the cycle of fire suppression and catastrophic conflagration.”

Insurance may be considered as a stand-alone solution to minimizing the WWP but homeowners surveyed in New Mexico, USA, considered insurance and “averting activities, like fuel management, together thereby implying that there was an optimal mix of actions for minimizing adverse outcomes” (Talberth et al. 2006). Potential losses from fires were seen to include noneconomic assets that were uninsurable. The “enhance recovery, adapt” component of Fig. 6 is shown as a contingency (dotted arrows) because not all assets of

importance to stakeholders are covered by insurance and not all insurable assets are insured by everyone with assets at risk.

“Recovery” is a concept pertinent to an individual event as it implies a return to the status quo, whereas “adaptation” is a concept pertinent to repeated adjustment to multiple fires, a regime concept. Adaptation involves learning from fire experiences (Ellis et al. 2004), whereas recovery is a matter of “getting over” a fire event. The extent and frequency of loss, especially, will likely affect the probability of people adopting adaptive behavior.

Cultural adaptation may be thought of in terms of individuals, communities, and institutions (Taylor 2007). Even individuals who have been through a fire experience may lose the benefits of their newly acquired experience (e.g., in terms of the need for preparedness and knowing what to do when fire threatens) after some years (see Gill 2009), perhaps believing that it won’t happen again in their lifetimes. A counter to this trend is to promote involvement in community groups dealing with fires (e.g., Volunteer Rural Fire Brigades, city-edge Community Fire Units of local urban volunteers [see Gill 2009] or Fire Safe Councils in the United States). For regional governments, fires occur more frequently within their jurisdictions than those of individuals and communities so there is more incentive to adapt and more opportunity for adaptive change to be incorporated into the fabric of the institution.

What the relative responsibility that should be assigned to governments, agencies, communities, and individuals in responding to and preparing for socially disastrous fires should be is a recurring theme. It is being resolved in terms of a shared responsibility between all parties (Ellis et al. 2004:ix). Each of these parties can be affected by extreme events but governments, especially, are subject to official inquiries and court cases that can modify their practices, encouraging them to change and adapt, sometimes through legislation that changes social practice, not just agency practices. Individual citizens are not formally influenced in these ways and many, but by no means all, have been regarded as apathetic (Miller et al. 1984), “unprepared, apathetic, unconcerned, or vague” (see Gill 2009), or as having “a remarkable ability to live in hazardous places with relative equanimity” by denying the likelihood of an event or by discounting its potential impact (Beebe and Omi 1993).

We can benefit by learning from experience, if not by other forms of learning; we need to modify our behavior so that the unfortunate conclusion reached by George Bernard Shaw that “we learn from experience that men never learn anything from experience” becomes a thing of the past (see also Bardsley et al. 1983).

CONCLUSIONS

Landscape fires—bushfires, wildfires, unplanned fires—can be started by humans or natural causes

and spread across “natural” or highly modified rural, even suburban, areas. They have a wide variation in properties. They create a charred fire footprint within which they have effects on environmental, social, and economic assets; they also create smoke that can affect assets outside the charred area as well as within it. They have direct effects and indirect effects. They can be relevant at point scales and global scales, for a short time or for decades or centuries.

While our knowledge of the WWP and how to minimize it is growing, it is limited. Scientifically, prediction of fire properties and their interrelationships is partial; quantifying the probability of asset-negative events and regimes is still very difficult, yet critical; and, assessing the efficacy of minimizing actions is usually relative (e.g., “better”) rather than absolute.

Multiple actions seem most likely to lead to the minimizing of adverse outcomes from landscape fires across all cultures, including those in developing countries (Goldammer et al. 2002). The challenge may be to gain agreement for action among multiple stakeholders holding different values (after Gill and Stephens 2009): a socioeconomic, political-legal, issue.

This paper has by no means explored all the intricacies of the worldwide wildfire problem or all the effects possible on all assets perceived by all stakeholders. It has provided a framework for understanding the problem and a view of the breadth and depth of exploration we need to understand the nature and adequacy of the many partial solutions to the WWP available in different circumstances.

We suggest, here, a number of premises that could be helpful to policy makers dealing with the worldwide wildfire problem.

- 1) The problem is how to manage the adverse effects of landscape fires on assets.
- 2) “Assets” can be public or private and social, environmental, or economic in nature and may change as human societies and their environmental contexts change.
- 3) Different people perceive different things to be assets.
- 4) Responsibility for the cost-effective management of fire-prone assets is to be explicitly shared, not just borne by governments alone.
- 5) Management includes addressing fire-event and fire-regime control (starts, fire suppression, fuel treatments), increasing resistance of assets to damage, relocation to safe sites (or locating assets there), and community recovery and adaptation; there is a short- and a long-term aspect to each of these categories.
- 6) There is a residual probability of a disastrous fire event even after a variety of measures have been introduced to counter it.

- 7) Some strategic knowledge about fires, including escape routes, and personal protection can increase chances of personal survival.
- 8) The occurrence of a socially disastrous fire provides an opportunity for rapid institutional and social adaptation to future events rather than simply providing an imperative to return to an inappropriate norm as soon as possible.
- 9) Facilitating the empowerment of survivors and the functioning of emergent organizations, especially voluntary ones that see specific, local needs, aids in the adaptation of societies to the pre- and postfire situation.
- 10) The scientific knowledge underpinning our understanding is growing but is still limited.

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