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A framework for assessing acute impacts of fire in jarrah forests for ecological studies

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ABSTRACT

Bushfires are commonly described in terms such as rate of spread, flame dimensions or Byram's intensity, which reflect suppression difficulty or general damage potential. Meaningful descriptors of the fire environment for interpreting ecological effects are those which reflect the amount and rate of heat energy released and its distribution. These factors determine the immediate physical or acute impacts of fire which give rise to ecological effects.

The acute impacts of fire in jarrah forests can be studied and predictive models developed by:

(i) stratifying the area within and around the flames (impact zones);
(ii) identifying the physical impacts within these zones;
(iii) identifying readily measurable descriptors of the amount and rate of heat energy release;
(iv) identifying factors affecting the transfer of heat to plant tissue and the soil;
(v) experimenting to develop functional relationships between physical impacts, readily measurable fire descriptors and factors affecting heat transfer.

INTRODUCTION

Forest fires are described according to the level of interest and knowledge of the observer. Fire managers and fire behaviour scientists commonly describe fire in terms that convey information about the difficulty of suppression or the damage potential of the fire, such as linear and area rates of spread, flame dimensions, flame residence time and intensities, and there is ample literature which defines, models, and describes ways of measuring or calculating these variables (e.g., Davis 1959; Luke and McArthur 1978; Gill *et al.* 1981; Chandler *et al.* 1983; Gill and Knight 1988; Johnson 1992).

When studying fire effects on biotic and abiotic ecosystem components, it is important to identify and measure variables which are linked to the immediate impacts of fire. Immediate or acute impacts are defined here as the physical impacts of fire on the ecosystem components imparted during the flaming and smouldering phases of combustion. For jarrah forest fuels, most acute impacts occur over 1-2 minutes during the passage of flames. Friend (1993), in reviewing the effects of fire on small vertebrates, used the definition of acute impact provided by Warren *et al.* (1987), which includes the combustion phase and the time to the commencement of vegetative regeneration, which could be several months after the fire.

Acute impacts give rise to ecological responses, but fire ecologists have generally displayed indifference to how fires actually produce their ecological effects (Johnson 1992). McArthur and Cheney (1966) noted that in a literature review of fire effects by Hare (1961) there was an absence of a precise description of the type of fire causing the effects. Alexander (1982) reported that this trend had continued in spite of advances in the science of fire behaviour.

As well as describing fires for interpreting ecological effects, it is equally important to be able to link fire variables, factors affecting heat transfer and acute impacts so that managed fire can be effectively and reliably applied to achieve a desired ecological outcome. Managing fire in jarrah (*Eucalyptus marginata*) forests of south-west Western Australia includes prescribing fires to reduce fuel levels without damaging the boles and crowns of trees, and prescribing fires to regenerate or control specific plant species.

An understanding of fire-induced ecological responses cannot be gained by simply measuring common fire behaviour descriptors and it is unlikely that the acute impacts of fire will be modelled from first principles in the foreseeable future for several reasons. Firstly, combustion and heat transfer are separate processes, both of which are complex and poorly understood. Secondly, there is limited information linking fire behaviour variables with acute impacts, one exception being the linkage between fire intensity, flame dimensions and scorch height (Van Wagner 1973; Luke and McArthur 1978; Cheney *et al.* 1992). Thirdly, ecosystem responses will depend on numerous other interrelating factors including climate, landform and soils, the fire regime (Gill 1977, 1981), fire size, patchiness, the ecological and biological characteristics of the ecosystem (e.g., life cycles, regeneration and re-colonization strategies, adaptive traits expressed by organisms), and precedent and antecedent weather.

Therefore, in the absence of universal physical models, empirical or semi-empirical models which predict acute impacts from readily measured fire behaviour variables and heat transfer factors will continue to be developed, or existing ones validated for each vegetation type or fuel complex. This paper presents a framework for assessing the acute impacts of forest fires which give rise to ecological responses and to commercial losses.

ACUTE IMPACTS OF FIRE

The precise nature and severity of acute impact varies considerably from one fire circumstance to another, but generally acute impacts can be characterized as:

(i) reduction or removal of live and dead vegetation resulting in changes in cover, structure and habitat to varying degrees;
(ii) some plant and animal death and injury; and
(iii) soil heating and subsequent effects on soil chemistry, structure and various soil borne organisms.

Acute impacts on the vegetation equates to an almost instantaneous change in habitat (food, shelter and breeding sites), particularly if the fire is intense. Thus, the impact on fauna will depend on habitat requirements, the extent to which these have been affected by the fire, and on the biology of various taxa (Friend 1993). Therefore, measuring the impact of fire on vegetation is the key to interpreting impact on fauna.

The extent or severity of acute impact on an ecosystem will depend on the amount and rate of heat energy released and on the amount and rate of heat transfer to plants and the soil. Flames are the essence of a bushfire. Flame temperature *per se* does not necessarily relate to the amount of heat given off as temperature is a measure of the degree of hotness while heat is the quantification of the work transferred from a warm body to a cool body. However, the temperature history experienced by plant tissues does relate to thermal death time (Wright 1970; Engle *et al.* 1989) so intuitively relates to the threat posed by fire to plant tissue. For example, Ryan (1982) found that Douglas Fir (*Pseudotsuga menziesii*) seedlings can tolerate a temperature of 50°C for 1 hour, 60°C for 1 minute and 70°C for 1 second.

It is therefore important to measure and describe the fire and factors affecting heat transfer in terms that best reflect or characterize the temperature histories experienced by plant tissue and the soil at critical locations. Measuring the temperature histories of bushfires to characterize fire intensity has met with mixed success, mainly because of the high degree of temporal and spatial variation in temperature (e.g., see Hobbs and Atkins 1988; Cheney *et al.* 1992; Moore and Gill, this conference). There are also practical difficulties with using this technique beyond small, intensively monitored experimental fires. However, thermocouple temperature histories can be a useful means of correlating temperature histories with meaningful and more easily measurable fire descriptors such as flame dimensions and measures of fire intensity (see Moore, Gill and Tolhurst, this conference). Examples of thermocouple temperature histories recorded during an experimental jarrah forest fire are shown in Figure 1. These are typical of temperature histories reported by many workers for other fuel types (e.g., Pompe and Vines 1966; Rothermel 1972).

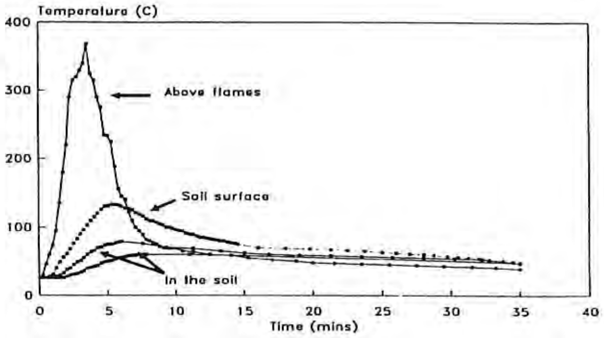

Figure 1. An example of thermocouple temperature histories at various locales during a jarrah forest fire.

ACUTE IMPACT ZONES

I present a framework which I have found useful for describing the acute impacts of fire which give rise to ecological responses in the jarrah forest. This framework, shown in a broader context in Figure 2, is comprised of four elements:

(i) Biophysical, biological and ecological information;
(ii) Fire regime information;
(iv) Factors affecting combustion and heat transfer;
(v) Physical, acute impacts of fire on the biota.

No attempt is made to predict temperature histories at a particular locale. The notion is that temperature history, therefore the acute impacts of fire, are related to fire behaviour variables which reflect heat output, and factors affecting heat transfer; variables which are more readily measurable in the field than temperature histories.

The approach I have taken for jarrah forest fires is to:

(i) stratify the area within and around the combustion zone;
(ii) identify important physical impacts within these strata;

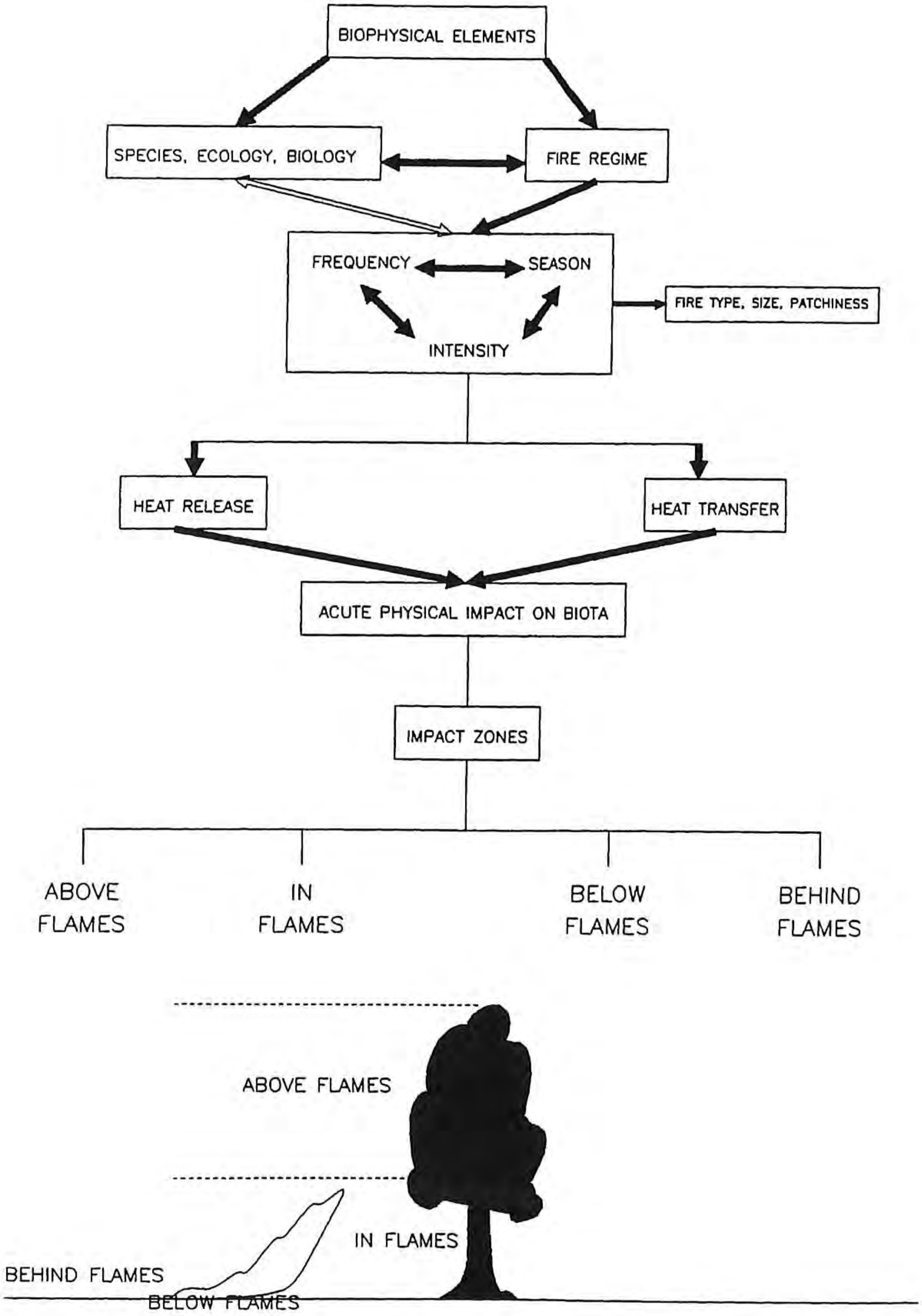

Figure 2. Fire impact linkages

(iii) identify factors that are likely to affect heat transfer to plants and soil; and
(iv) seek correlations between 'easily measured' fire variables, variables which are likely to affect heat transfer, and the impacts.

To study acute impacts of fire, it is convenient to recognize four strata or 'impact zones', as shown in Figure 2 and described in Table 1.

Impact Zone Above the Flames

This zone is affected by hot (but not burning) turbulent gases rising above the flames. The most obvious impact in this zone is crown scorch or leaf browning as leaves, fine twigs and fruits experience a lethal time-temperature regime. For most species in the jarrah forest this leads to crown replacement (Christensen and Kimber 1975; Bell *et al.* 1989) but in other forests (e.g., *Pinus radiata)* plants may be killed outright by full crown scorch. The result is a reduction in cover and density of vegetation and often massive and synchronized seed release.

Flame characteristics, particularly flame height and flame length, are the most meaningful measures for predicting the height at which lethal temperatures (lethal to leaves and fine twigs) occur in this zone because flame size reflects the amount of heat being given off (fire intensity) (Luke and McArthur 1978). An empirically derived relationship between flame height and crown scorch height for jarrah forest fuels is shown in Figure 4 (from Burrows 1994).

The amount of heat transferred to vegetation above the flames is also affected by ambient temperature and wind speed. Semi-empirical models for predicting scorch height (e.g., Van Wagner 1973; Cheney *et al.* 1992; Tolhurst *et al.* 1992) incorporate wind speed and ambient temperature as factors which effect scorch height independent of the effects of these factors on fire behaviour. Van Wagner's (1973) scorch height model is an example of determining an acute impact (scorch height) from a measure of heat energy released (Byram's intensity) and factors affecting heat transfer (ambient temperature and wind speed).

Burrows (1994) found that Byram's fire intensity also relates reasonably well to scorch height experienced in jarrah forests (Fig. 3). Theoretically it should, as it characterizes the total heat output from the flames. Alexander (1982) and Cheney (1990) provide details on how to correctly calculate and interpret fire intensity. A limitation with calculating fire intensity is knowing what fuel and how much of it is involved in the flaming combustion zone. This, and the fact that Van Wagner's relationship was developed from experiments in a different fuel and forest type, probably explains the differences between the models graphed in Figure 3. The best approach is to set some rules which apply for a specific fuel type. For example, for jarrah forest litter bed fuels I assume that the quantity (before fire minus after fire) of dead surface fuel <6 mm and live fuel <4 mm (up to flame height) is burnt in the flaming zone. Rough barked trees such as jarrah can become discrete fuel entities (fuel rods), especially under conditions of high fire danger. Flames will spread in bark up the tree bole, releasing heat close to the tree crowns. This contribution cannot be simply added to the intensity of the surface fire for correlating with crown scorch. I have not been able to devise a sensible mechanism which accounts for this other than to observe that it occurs most frequently when the Soil Dryness Index (Mount 1972; Burrows 1987) is high, fuels are dry (<10 per cent moisture content) and winds are stronger than about 10-15 km h^{-1}. I accept it as part of the unexplained variability of the scorch height-intensity relationship shown in Figure 3. The difficulty with calculating intensity probably explains why the various empirically derived relationships between intensity and scorch height have different coefficients (Fig. 3).

The seasonal differences between the scorch height-flame height relationship (Fig. 4) reflects differences in ambient temperature and moisture conditions and differences in the physiological status of the vegetation.

Impact Zone in the Flames

Plants are killed either by defoliation (incineration) or by stem girdling at or near ground level. Defoliation height is about the height of the flames when flame height is less than the height of the vegetation. Most understorey species in the jarrah forest have paper-thin bark and are readily girdled and killed to ground level by even the mildest of fires (most re-sprout from subterranean organs). Trees and tall shrubs which develop thick protective bark are more resistant to death by thermal girdling. Stem mortality will depend on bark thickness, bark moisture content, and the temperatures and duration of heating experienced at the bark surface.

During laboratory fires (Burrows 1994), exposed thermocouple maximum temperatures reached in the flames at a fixed distance (10 cm) above the fuel bed related reasonably well to flame length and fire intensity until a certain flame thickness (emissivity) was reached when maximum temperature saturated. Heat load, or the duration of heating, was independent of intensity but related reasonably well to the quantity of fuel consumed, and to flame residence time. During the same experiments, thermocouples inserted into the cambium of *Banksia grandis* stem sections (near ground level) showed that temperatures experienced during low intensity laboratory fires were largely dependent on bark thickness and on the quantity of fuel consumed and were independent of flame rate of spread.

In contrast to laboratory studies, field studies showed that the mortality rate of *Banksia grandis* and cambial damage to jarrah is affected by bark thickness and fire intensity classes (Burrows 1985). That is, controlling for bark thickness and the quantity of fuel

TABLE 1

Impact zone, impacts, quantifying impacts, descriptors of heat output and factors affecting heat transfer.

	IMPACT ZONES			
	ABOVE FLAMES	IN FLAMES	BELOW FLAMES	BEHIND FLAMES
Impacts	Scorch and death of leaves, twigs, fruits leading to defoliation seedfall, cover reduction.	Defoliation, mortaility cambial damage, bark loss, soil exposure, seedbed preparation, seedfall, seed mortaility.	Soil heating, seed germination, soil chemical and strucutral changes, micro-organisms.	Super-heating of soil, allbed, chemical and structural changes, removal/ replacement of hollows, stem damage, tree fall.
Measure of impacts	Scorch height, scorch area, cover, density, quanity of seedfall.	Defoliation height, area defoliated, mortality by species, area of cambium damaged, cover, structure, depth of burn quantity of fuel burnt.	Soil temperatures, chemical changes, bulk density, colour soil seed germination.	Area cambial damage, damage, number logs removed, number logs created, trees downed, area of ashbed.
Descriptors of heat output	Flame height, flame length, Byram intensity.	Flame height, flame depth, flame residence, time intensity, combustion rate, fuel consumed.	Fuel consumed, fuel size, fuel moisture, flame residence time.	Coarse fuel consumed, consumed, burn out tiem, fuel moisture, drought index.
Factors affecting transfer	Temperature, wind speed, height above flames.	Bark thickness, stem size, plant moisture content, bark moisture ambient temperature, drought index.	Soil moisture content, soil bulk density, drought, index.	Soil moisture, soil heat structure, drought index, distance from fuel to tree stem.

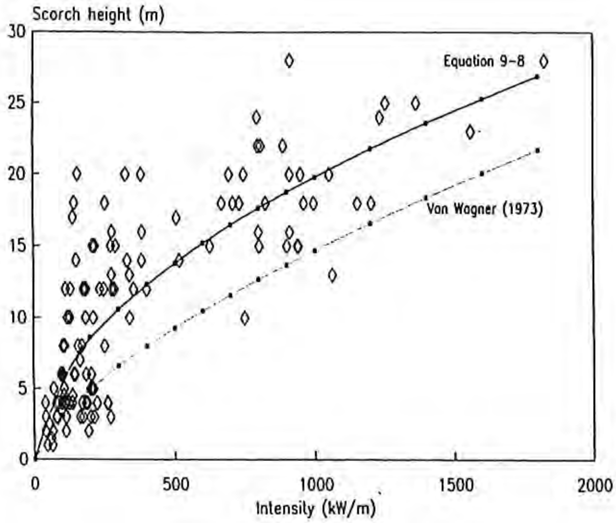

Figure 3. Crown scorch height as a function of Byram (1959) fire intensity for summer/autumn jarrah forest fires.

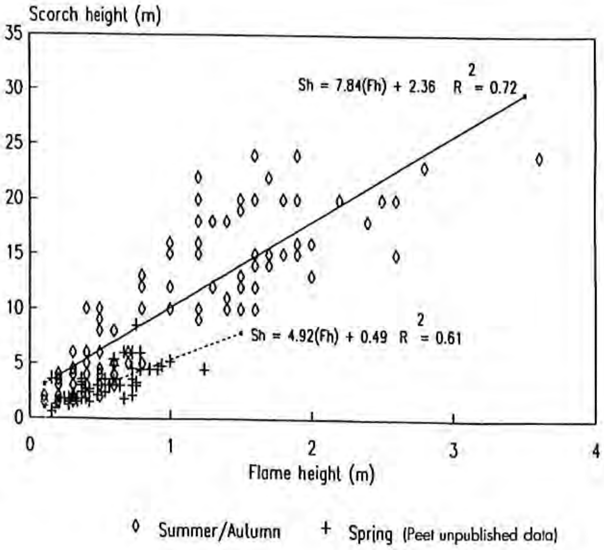

Figure 4. Crown scorch height as a function of flame height for summer/autumn and spring fires in jarrah forests.

consumed, mortality and cambial damage increased with increasing heat flux from the flame, as characterized by intensity classes. It is possible that the highly spiked nature of the heat flux experienced during very intense fires diffuses through the bark to the cambium sufficiently to heat the cells to 60-70°C. An alternative explanation is that in the field, intensity *per se* may not be accounting for increased death and injury, but reflecting burning conditions, especially fuel moisture and wind speed. Fast spreading fires are usually associated with warm, dry and windy conditions and under these conditions, other fuel sources, which may be overlooked, contribute to the heat output of the fire. These include larger diameter surface material and bark on standing trees. Rough barked trees cannot be considered as inert rods or slabs in a fuel bed, but are potential fuel rods in a fuel bed. A significant proportion (up to 30 per cent of total thickness during intense fires) of bark burns on the tree, especially on the leeward side, contributing significantly to cambial damage (Gill 1974; Tunstall *et al.* 1976; Gill *et al.* 1986).

Impact Zone Below the Flames

This zone is the top few centimetres of the soil, including the soil surface. The degree of fire-induced soil heating and subsequent changes to soil chemical and physical properties will depend on how much of the fuel resting on the soil is consumed, how dry the fuel is and the thermal properties of the soil, such as moisture content and bulk density (Aston and Gill 1976; Frandsen and Ryan 1986; Hungerford 1989; Burrows 1994). Soil heating is independent of intensity, although intensity may reflect fuel consumption. The extent to which the soil is heated will affect seed bed preparation, germination of soil stored seed, micro-organism responses and the chemistry and structure of the soil. When fuels and the soil are moist and there is only partial combustion of the litterbed, then top soil is unlikely to be affected. The physical process of heat transfer through soil and some effects of fire on soil are summarized by Aston and Gill (1976), Wells *et al.* (1979), and Humphreys and Craig (1981).

Impact Zone Behind the Flames

This is the zone behind the flaming combustion zone where larger fuel particles such as limbs, logs and old hollow-butt trees burn away slowly, often smouldering rather than flaming. Long durations of localized heating can have considerable impact on the soil and nearby vegetation, giving rise to the 'ashbed' effect, and to severe cambial injury to trees. Hollow-butt trees may burn down. The extent to which this occurs will depend on the amount and distribution of coarse fuel, fuel dryness and the intensity of the fire carried in fine fuels.

CONCLUSION

Fire impacts which are likely to be linked with ecological effects, fire descriptors which relate to these impacts, and factors influencing the heat transfer process are summarized in Table 1 for each of the four impact zones.

I have presented a framework which may be useful for gathering information about fires for ecological study. This framework is comprised of four elements:

(i) biophysical, biological and ecological information;
(ii) fire regime information;
(iii) combustion and heat transfer;
(iv) physical impacts.

Fire will impact directly on plants and animals and indirectly on animals by its impact on plants (habitat).

Fundamental processes of combustion and heat transfer are poorly understood, so local, empirical or semi-empirical models will need to be derived which link acute impacts with meaningful descriptions of heat energy output and distribution.

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