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Measuring Forest Fires For Ecological Studies

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1. Introduction

Forest fires are described variously depending on the level of interest and knowledge of the observer. For example, a news journalist is apt to report "a devastating bushfire"; fire ecologists have often described fire as a disturbance event. Fire managers and behaviour scientists commonly describe fire in terms which 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. There is an abundance of literature which defines, models, and describes ways of measuring or calculating these variables (see texts e.g., Davis 1959, Luke and McArthur 1978, Gill *et al.* 1981, Chandler *et al.* 1983, Johnson 1992) so it is not my intention to repeat that here.

When studying the ecological responses or effects caused by fire, it is important to identify, understand and measure characteristics of the fire, the environment in which it is burning and factors affecting the heat transfer process which give rise to the various effects. Fire ecologists have generally shown a surprising lack of curiosity about how fires actually produce their ecological effects (e.g., see 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. Alexander was critical of the lack of adequate description of fires by fire ecologists. He defined fire variables commonly used by fire behaviourists, especially Byram's intensity (Byram 1959), which in spite of its limitations, is a meaningful description of a fire's potential to damage vegetation.

Understanding fire-induced ecological responses cannot be achieved by simply measuring the fire behaviour variables described above. Firstly, it is important to understand the heat transfer process as distinct from the fire's behaviour. Combustion, fire spread and heat transfer are complex processes which are not well understood from first principals. We will probably be dependent on empirical or semi-empirical models in the absence of a universal physical model for some time into the future. This means specific models will have to be developed or validated for each vegetation type or fuel complex. Secondly, there is limited information linking fire behaviour variables with biotic impacts, an exception being the linkage between fire intensity, flame dimensions and scorch height (e.g. Van Wagner 1973, Luke and McArthur 1978, Cheney *et al.* 1992). Thirdly, ecosystem responses will depend on numerous other

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interrelating factors including climate, landform and soils, the fire regime, (Gill 1977 and 1981), fire size, patchiness, the ecological and biological characteristics of the ecosystem (e.g., life cycles, regeneration and re-colonisation strategies, adaptive traits expressed by organisms), and precedent and antecedent weather.

What and how fire ecologists measure fires will depend largely on the purpose of the study. There is no universal framework and the approaches are, and will be, as varied as nature itself. I present a framework for gathering information pertinent to describing fire and the fire environment for ecological studies which I have found useful for interpreting fire effects in the jarrah forest. This framework is shown in Figure 1 attached.

I am going to skip the first two tiers of the framework. Ecologists are familiar with these parameters and concepts and I'm sure they will be addressed by other speakers. I will focus my discussion on i) identifying some meaningful "fire intensity" or "fire behaviour" variables which cause immediate physical impact on the vegetation and soil, ii) identifying factors likely to influence heat transfer and iii) linking these variables with some physical impacts of fire.

2. Fire Intensity and Impact zones

Immediate physical impacts of a forest fire include i) removal of live and dead vegetation resulting in changes in cover and structure ii) plant and animal death and injury and iii) soil heating and exposure. Physical impact on the vegetation translates to an almost instantaneous change in habitat (food and shelter). The impact on animals will depend on their habitat requirements and on the extent to which these have been affected by the fire. Therefore, measuring the impact of fire on vegetation is the key to interpreting impact on wildlife.

The extent of physical impact will depend, by and large, on the amount and rate of heat energy given off by the flames (fire intensity) and the amount of heat transferred 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 in terms which best reflect or characterise the temperature histories experienced by plant tissue and the soil at critical locations. Byram's intensity is a very useful measure of intensity and of the impact of fire on vegetation above the flames (see Alexander 1982). Some ecologists have attempted to measure temperature histories in the field to characterise fire intensity but this has met with mixed success mainly because of the high degree of temporal and spatial variation in temperature (e.g., Hobbs and Atkins 1988). 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. Having identified which fire descriptors best characterise heat energy distribution, the next step is to link these descriptors to physical impacts.

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

To study physical impact of fire, I find it convenient to recognise four strata or "Impact Zones", as summarised in Table 1 attached.

2.1 Impact zone A: Above the flames

This zone is affected by hot (but not burning) turbulent gasses 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 but in other forests plants may be killed outright by full crown scorch (e.g. *Pinus radiata*). The result is a reduction in cover and density of vegetation and often massive and synchronised 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). An empirically derived relationship between flame height and crown scorch height for jarrah forest fuels is shown in Figure 2 attached.

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) incorporate wind speed and ambient temperature as factors which effect scorch height independent of the effects of these factors on fire behaviour. The seasonal differences between the scorch height-flame height relationship (Figure 2) reflects differences in ambient conditions and differences in the physiological status of the vegetation.

Byram's fire intensity also relates reasonably well to scorch height. Theoretically it should, as it characterises the total heat output from the flames. I recommend Alexander (1982) and Cheney (1990) for details on how to calculate and interpret fire intensity. The greatest difficulty in calculating fire intensity is knowing what fuel and how much of it is involved in the combustion zone. 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 SDI > 1000, fuels are dry (< 10%) 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 (Figure 3).

2.2 Impact zone B: In the flames

Plants are killed either by defoliation 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. The extent of defoliation will be effected by factors effecting fire intensity and by the moisture content of live 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). Tree and lower tree species 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.

Studies using thermocouples have shown that exposed thermocouple maximum temperatures reached in the flames at a fixed distance above the fuel bed relates reasonably well to flame length and fire intensity until a certain flame thickness (emmisivity) is reached and temperature saturates. Heat load, or the duration of heating, is independent of intensity but related reasonably well to the quantity of fuel consumed, and to flame residence time. 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.

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. That is, controlling for bark thickness and the quantity of fuel consumed, mortality and cambial damage increased with increasing heat flux from the flame, as characterised 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 it reflects 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 rods or

slabs in a fuel bed, but are potential fuel rods in a fuel bed. A significant proportion (up to 30% of total thickness during intense fires) of bark burns on the tree, especially on the leeward side, contributing significantly to cambial damage.

2.3 Zone C: Below the flames

This zone is the top 3-4 cm of soil, including the soil surface. The level of fire-caused impact on the soil 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 (see Aston and Gill 1976). Soil heating is independent of intensity, although intensity may reflect fuel consumption. The extent to which the soil is heated will effect 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 effected. The physical process of heat transfer through soil and some effects of fire on soil are summarised by Aston and Gill (1976), Wells *et al.* (1979), and Humphreys and Craig (1981).

2.4 Zone D: Behind the flames

This is the zone behind the flaming combustion zone where larger fuel particles such as limbs, logs and old hollowbutt trees, burn away slowly, often smouldering rather than flaming. Long durations of localised heating can have considerable impact on the soil and nearby vegetation, giving rise to the "ashbed" effect, and to severe cambial injury to trees. Hollowbutt 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.

3. Summary of meaningful descriptors

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 summarised in Table 2 for each of the four impact zones.

4. Concluding remarks

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.

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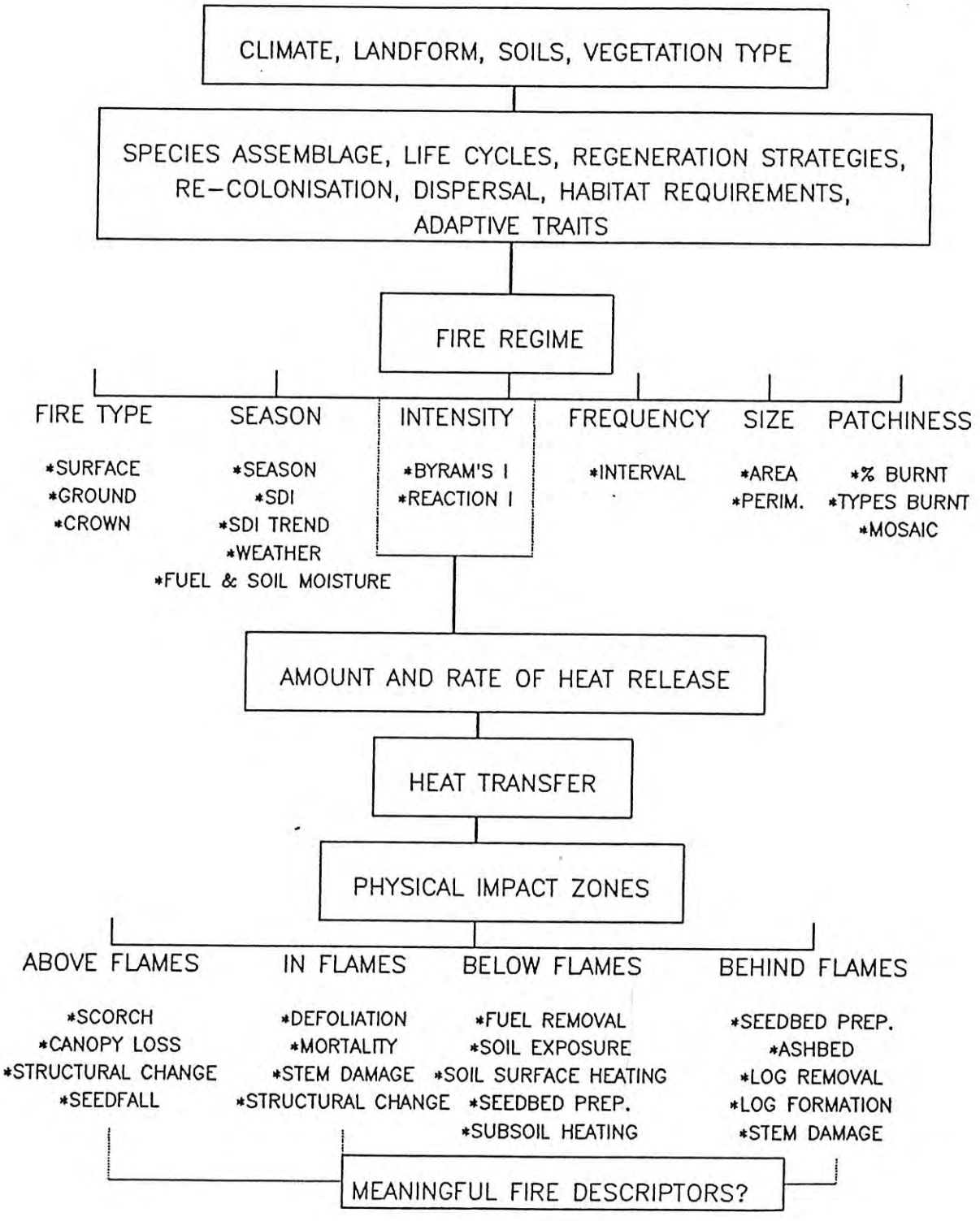
FIGURE 1: A FRAMEWORK FOR GATHERING INFORMATION ABOUT FIRES FOR FIRE ECOLOGY STUDIES



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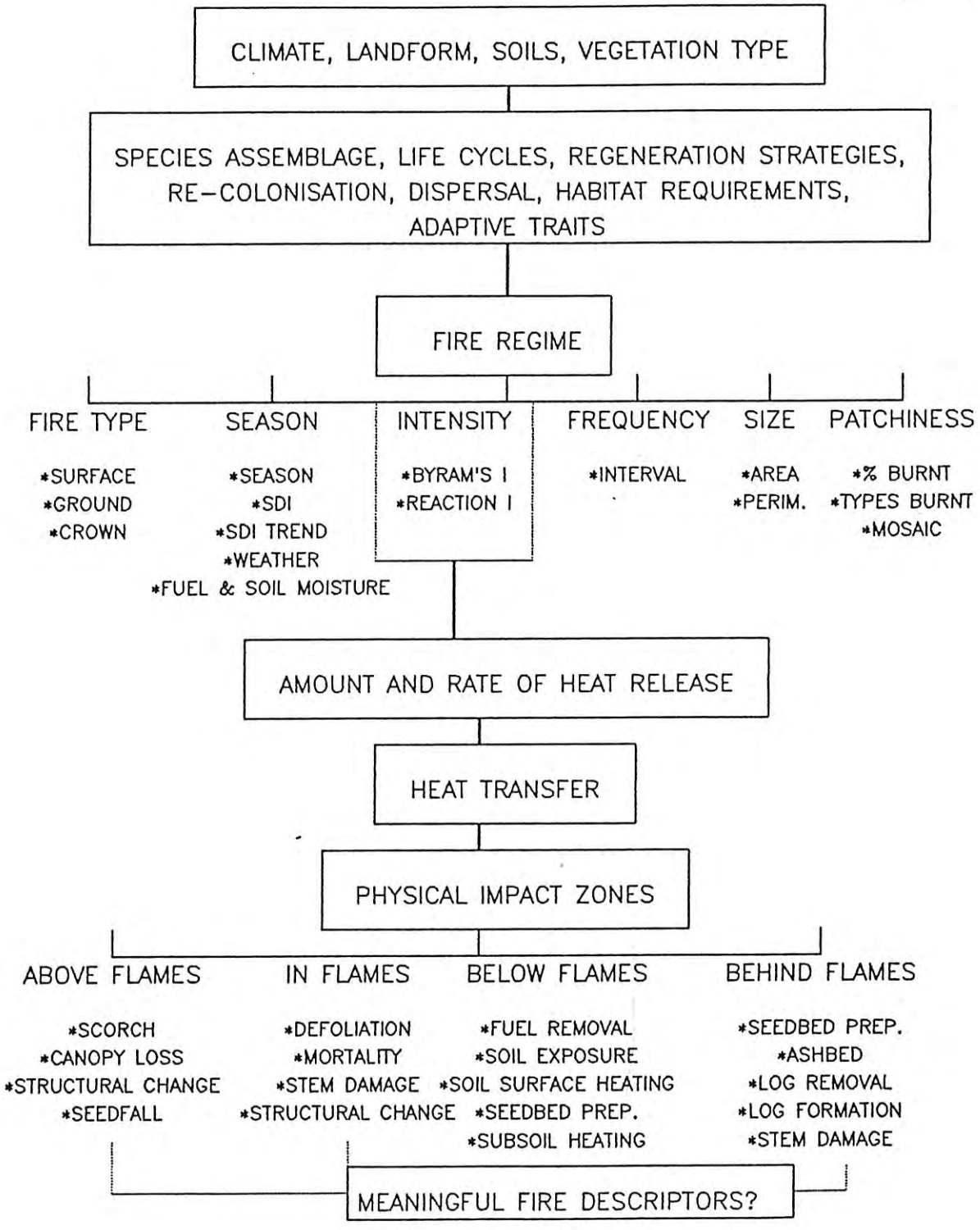


Figure 2: Flame height and scorch height for spring and summer fires in jarrah.

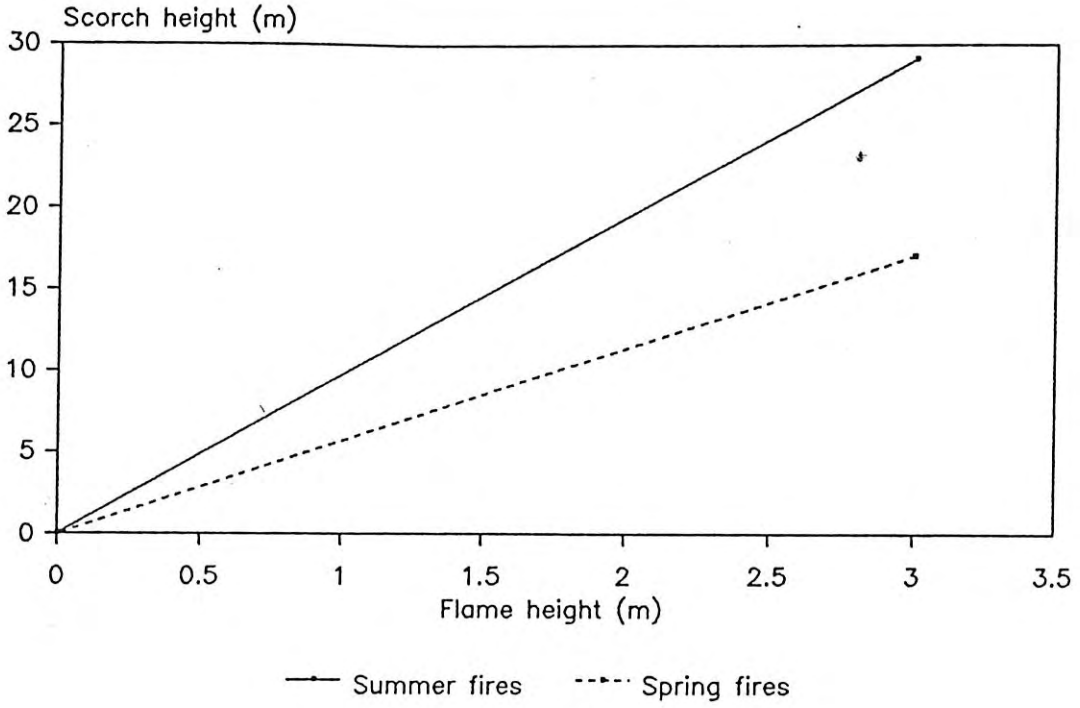
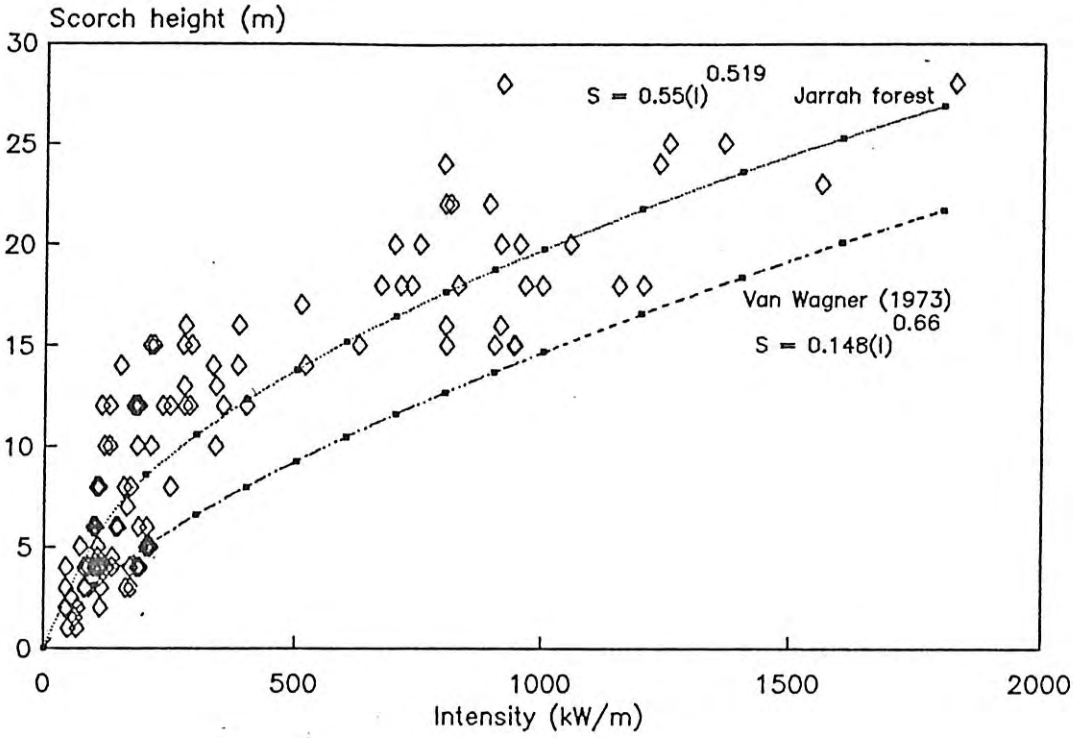


Figure 3: Scorch height with intensity.
Jarrah data are from summer fires.



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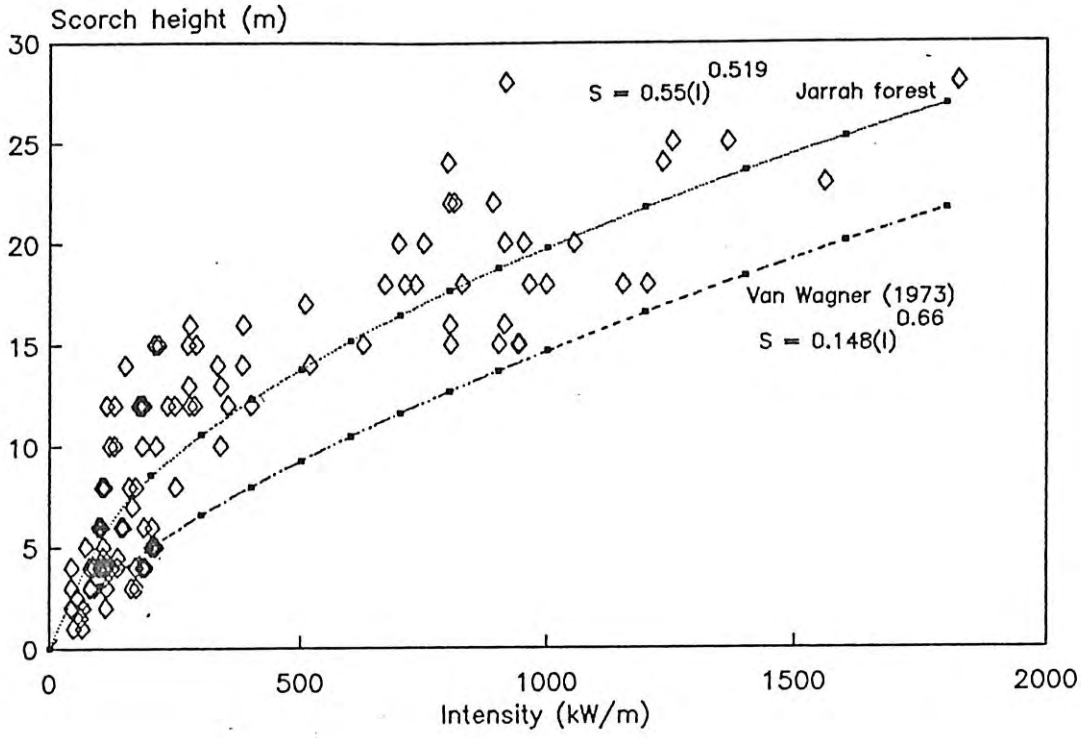

TABLE 1: IMPACT ZONES AND SOME IMPACTS WITHIN THESE ZONES

IMPACT ZONE	IMPACTS	MEASURES OF IMPACT
ZONE A: ABOVE FLAMES	SCORCH AND DEATH OF LEAVES, TWIGS, FRUITS LEADING TO DEFOLIATION, SEEDFALL, REDUCED COVER AND DENSITY.	HEIGHT OF SCORCH AREA SCORCHED COVER AND DENSITY QUANTITY OF SEEDFALL
ZONE B: IN FLAMES	DEFOLIATION, MORTALITY CAMBIAL DAMAGE, BARK LOSS SOIL EXPOSURE, SEEDBED PREP. SEEDFALL, SEED MORTALITY FUEL REMOVED	DEFOLIATION HEIGHT/AREA NUMBERS KILLED/ALIVE SIZES, SPECIES KILLED/ALIVE SEVERITY CAMBIAL DAMAGE COVER AND STRUCTURAL CHANGE DEPTH OF BURN, QUANTITY BURNT
ZONE C: BELOW FLAMES	SOIL HEATING CHEMICAL, STRUCTUAL CHANGES SEED AND MICR-ORGANISM HEATING LOSS OF ORGANIC MATTER	TEMPERATURE HISTORIES NUTRIENT CHANGE STRUCTURAL CHANGE SEED VIABILITY
ZONE D: BEHIND FLAMES	SUPER HEATING OF SOIL ASHBED FORMATION STRUCTURAL/CHEMICAL CHANGES HOLLOW LOG REMOVAL LOG ADDITTION STEM DAMAGE, TREE FALL	AS ABOVE

TABLE 2: SOME PHYSICAL IMPACTS AND RELATED FIRE DESCRIPTORS

PHYSICAL IMPACT ZONES

ABOVE THE FLAMES	IN THE FLAMES	BELOW THE FLAMES	BEHIND THE FLAMES
*SCORCH *CAPSULE DESSICATION AND SEEDFALL *CANOPY LOSS *STRUCTURAL CHANGES	*DEFOLIATION *MORTALITY *STEM DAMAGE *STRUCTURAL CHANGES	*FUEL REMOVAL *SOIL SURFACE HEATING *SUB-SOIL HEATING *SEEDBED PREP.	*SEEDBED PREPARATION *ASHBED *LOG REMOVAL *LOG FORMATION *STEM DAMAGE

DESCRIPTORS OF HEAT OUTPUT (FIRE DESCRIPTORS)

1. FLAME HEIGHT 2. FLAME LENGTH 3. INTENSITY	1. FLAME HEIGHT 2. FUEL CONSUMED 3. FLAME RESIDENCE TIME 4. INTENSITY 5. COMBUSTION RATE 6. CHARRING	1. FUEL CONSUMED 2. DEPTH OF BURN 3. FUEL MOISTURE	1. COARSE FUEL CONSUMED 2. BURNOUT TIME

SOME FACTORS AFFECTING HEAT TRANSFER

1. AMBIENT TEMPERATURE 2. WIND SPEED 3. CANOPY HEIGHT	1. BARK THICKNESS STEM DIAMETER 2. LIVE MOISTURE CONTENT 3. BARK MOISTURE 4. AMBIENT TEMPERATURE	1. SOIL MOISTURE 2. SOIL BULK DENSITY	1. SOIL MOISTURE 2. SOIL B.D. 3. SPACE BETWEEN FUEL AND STEM