Native Forest Silviculture

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Silvicultural Use and Effects of Fire

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PART A: **Guidelines for the Silvicultural Use of Fire and for the Management of Forests Damaged by Wildfire**

PART A: Guidelines for the Silvicultural Use of Fire and for the Management of Forests Damaged by Wildfire

1. INTRODUCTION

This bulletin reviews the impact of fire on the silvicultural management of Tasmania's native forests.

Part A provides guidelines for the silvicultural use of fire for site preparation and fuel reduction and for the management of forests damaged by fire. Part B contains a summary of some of the ecological effects of fire in Tasmania's forests. A comprehensive review of the literature is provided as Part C.

Operational instructions relating to the use of fire as a fuel management and silvicultural tool are contained in the Fire Management Manual (Forestry Commission 1992).

2. USE OF FIRE FOR SITE PREPARATION

Eucalypts require a seedbed clear of shade and undecomposed litter for seedling establishment. In nature, receptive seedbed is created by wildfire which removes the vegetation and litter layers and enhances early growth through the "ash-bed" effect. This growth stimulation is due to soil-heating and appears to be greater in wet, dense understorey forests than in dry, open understorey forests.

In managed forests, seedbed can be created by one or a combination of the following:

* *fire* - planned burning of logging slash and litter;

* *mechanical treatment* - physical displacement of slash and litter by logging disturbance or machine scarification.

The use of fire to prepare seedbed for the establishment of regeneration is determined by a number of factors. These factors are summarised below.

Forest type - Fire is generally the most effective means of exposing receptive seedbed in forests with dense understorey, thick litter or organic layers. Mechanical preparation of seedbed, by logging disturbance or scarification, is more feasible in forests with an open, sparse understorey.

Ground conditions and slope - Clearing of slash layers by mechanical methods may be unacceptable for environmental, logistical or economic reasons on sites which are steep, very rocky or have soils which are susceptible to erosion, compaction, displacement or inversion.

◀ **Photo 1:** *Heavy slash layers following logging in wet eucalypt forest. The slash is a barrier to eucalypt regeneration and is a serious fire risk.*

t **Photo 2:** *Heaping of slash to create seedbed and/or facilitate top disposal burning is an appropriate technique in partially logged open understorey forests. However, in dense understorey forests heaping is very expensive, much of the potential seedbed remains covered by heaps and suitable conditions for safe burning are extremely limited.*

Retained growing stock - The use of high intensity planned burns is restricted to clearfell systems where there is insufficient growing stock suitable for retention. Low intensity broadcast burns and top disposal burns may be possible in partially logged open forests although the opportunities for such burns in partially logged wet forests are often very limited because of heavier fuel loads and poor fuel moisture differentials between standing fuels and slash. The fire resistance of eucalypts increases with increasing age, height growth and bark thickness. Young growing stock such as seedlings and saplings are likely to be killed if totally scorched or burnt. Older growing stock such as poles and mature stems are killed by high intensity fire but may survive lower intensity fire. However, the wood quality of fire-damaged trees is often down-graded due to crown die-back, proliferation of stem epicormics and the spread of decay organisms from fire scars. Careful selection of burning regime is also required where mature trees are retained for specific purposes such as the provision of seed, shelter, landscape, soil conservation or habitat value.

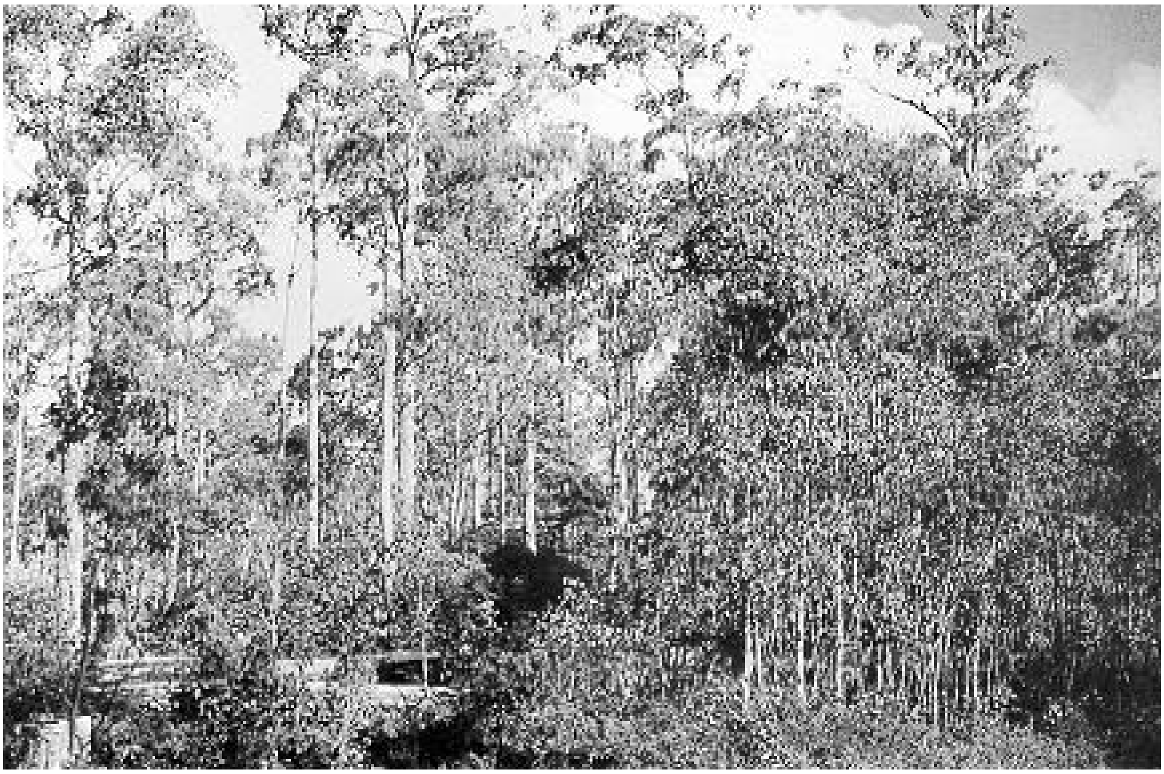


Photo 3: *Young advance growth in open E. delegatensis forest. Broadcast burning is not necessary for seedbed preparation and would damage the advance growth. Careful logging and heaping of slash will allow top disposal burning to be undertaken if necessary for fire protection purposes.*

Safety of planned burns - High intensity burning involves two elements of risk:

* the risk of a poor burn resulting in inadequate seedbed and an unacceptable standard of regeneration establishment;

* the risk of an escaped burn causing damage to adjoining values.

Both risks must be minimised by careful planning and conduct of the burn as detailed in the Fire Management Manual.

Particular priority must be given to ensuring **safe burning boundaries** with respect to the coupe shape, topographic configuration, fire-breaks and adjoining vegetation.

Special consideration is required where logged coupes are near the following areas:

* fire-sensitive communities such as rainforest, alpine and sub-alpine vegetation;

* fire-shadow sites such as rocky slopes, knolls and deep gullies which may contain rare plant communities;

* isolated communities such as patches of relict rainforest and riparian strips.

Economics - Burning may be uneconomic where high levels of cull felling or coupe perimeter works are required. Logging disturbance and mechanical scarification may be lower cost alternatives to burning on suitable sites. However, where volumes of residues are high or ground conditions are difficult, mechanical seedbed preparation is on average three to ten times the cost of planned burning.

Fuel management - The reduction of logging slash will help to protect the new growing stock from future wildfire. The priority for fuel reduction burning will depend upon the forest type, magnitude and longevity of fuel fractions, adjacent vegetation and land-use, and risk of ignition sources. Priorities for fuel reduction burning should be identified in fire management plans (refer to Fire Management Manual 1992).

Site fertility - Nutrient losses from slash burning on high rainfall, fertile sites are believed to be minimal and can be replaced by natural inputs within 20 years. However, on lower fertility sites the retention of unburnt slash may be important for the conservation of site fertility.

Flora, fauna or cultural conservation values - Burning or mechanical clearing operations should be modified to protect special flora, fauna or cultural values (refer to Forest Practices Code (1993) and associated manuals).

Logistics and resources - The choice of burning regime will be constrained by factors such as the size and number of burns, limited number of suitable days for burning, and the availability of sufficient resources for ignition, patrol and suppression activities.

"Ash-bed" effect - The initial growth of eucalypts is superior on seedbeds prepared by intense soil heating.

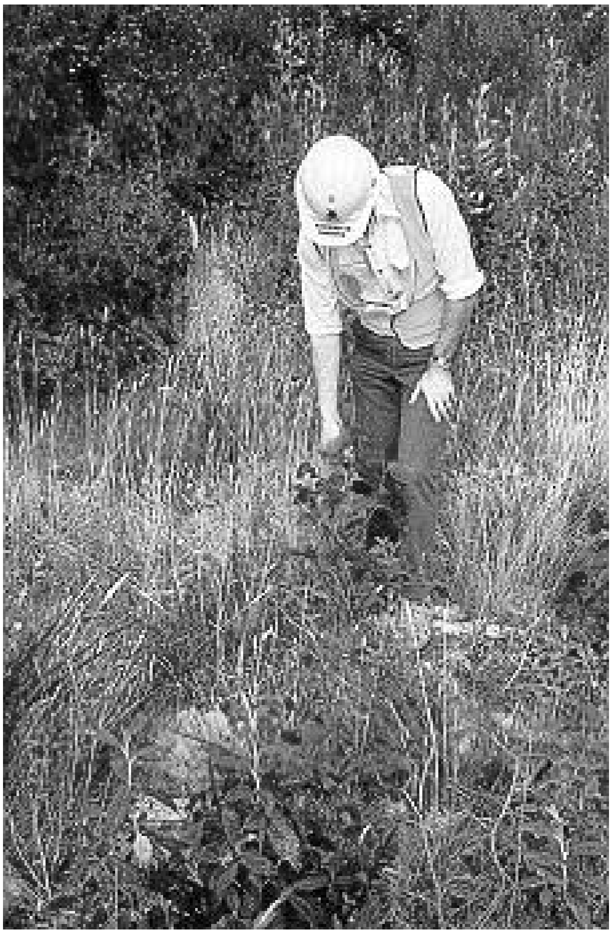


Photo 4 ▲ Photo 5 ▲

Growth of E. obliqua seedlings at age 2 years on unburnt seedbed (Photo 4, left) *compared to adjacent high intensity burn seedbed* (Photo 5, right). *Wet forest, Christmas Hills, north-west Tasmania.*

The intensity of planned burns will be determined by the quantity and moisture content of fuels and by the prevailing weather conditions, as influenced by topography. Recommended burning intensity for various forest types is as follows:

High intensity slash burns are prescribed for wet, dense understorey forests in order to ensure the removal of slash and organic layers to expose maximum seedbed and optimise the soil-heating effect. High intensity burns can only be conducted in clearfelled areas where the retention of growing stock is not required.

Moderate to low intensity slash burns are prescribed for dry, open understorey forests where slash and litter levels are low. These burns are generally conducted in clearfelled areas, although mild burns may also be carried out in seedtree and shelterwood retention areas where damage to retained trees can be avoided.

Top Disposal burns are prescribed for partially logged forests where burning is restricted to slash heaps away from sensitive growing stock.

Burning should be undertaken in late summer (mid February to late March) to ensure :

* the successful removal of fuels whilst soils are dry (to maximise the soil-heating effect);

* seedbed receptivity is optimised for subsequent sowing and autumn establishment.

In partially logged forests, burning can stimulate seedfall, thus synchronising the preparation of seedbed and natural seeding.

The relationship between burning intensity and forest type is indicated in Figure 1.

Guidelines for the use of fire for the establishment of regeneration are provided in Figure 2.

3. USE OF FIRE FOR FUEL HAZARD REDUCTION

Properly planned and conducted fuel reduction programmes have many benefits for forest management. Potential impacts of planned burns will depend upon the forest type and the extent, intensity and frequency of burning. When planning a hazard reduction programme, the following silvicultural factors should be considered:

3.1 Forest Type

The Fire Management Manual (1992) provides details on vegetation types and suitability for fuel reduction burning as follows:

Figure 1: Relationship between forest type and fire intensity appropriate for site preparation after logging.

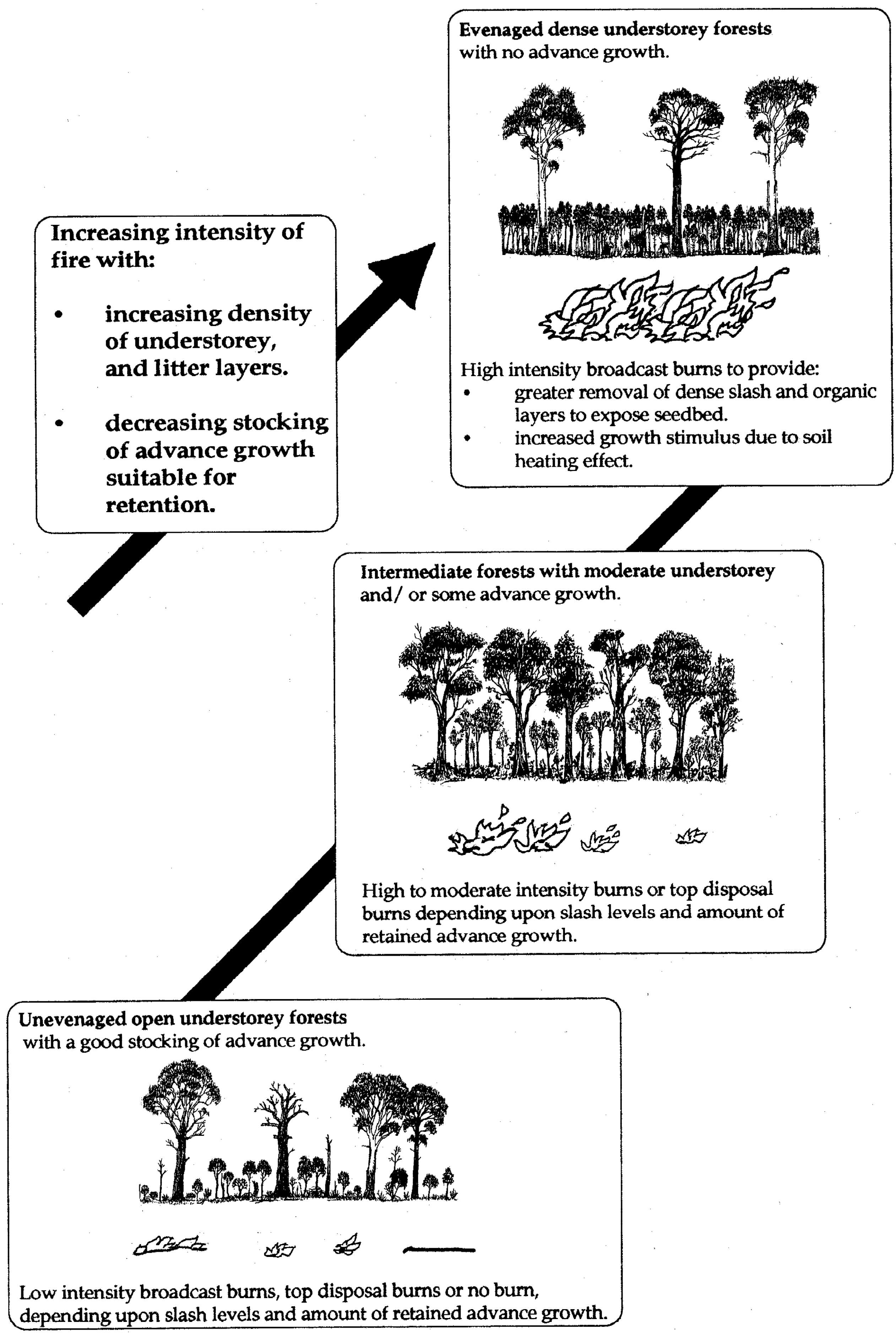
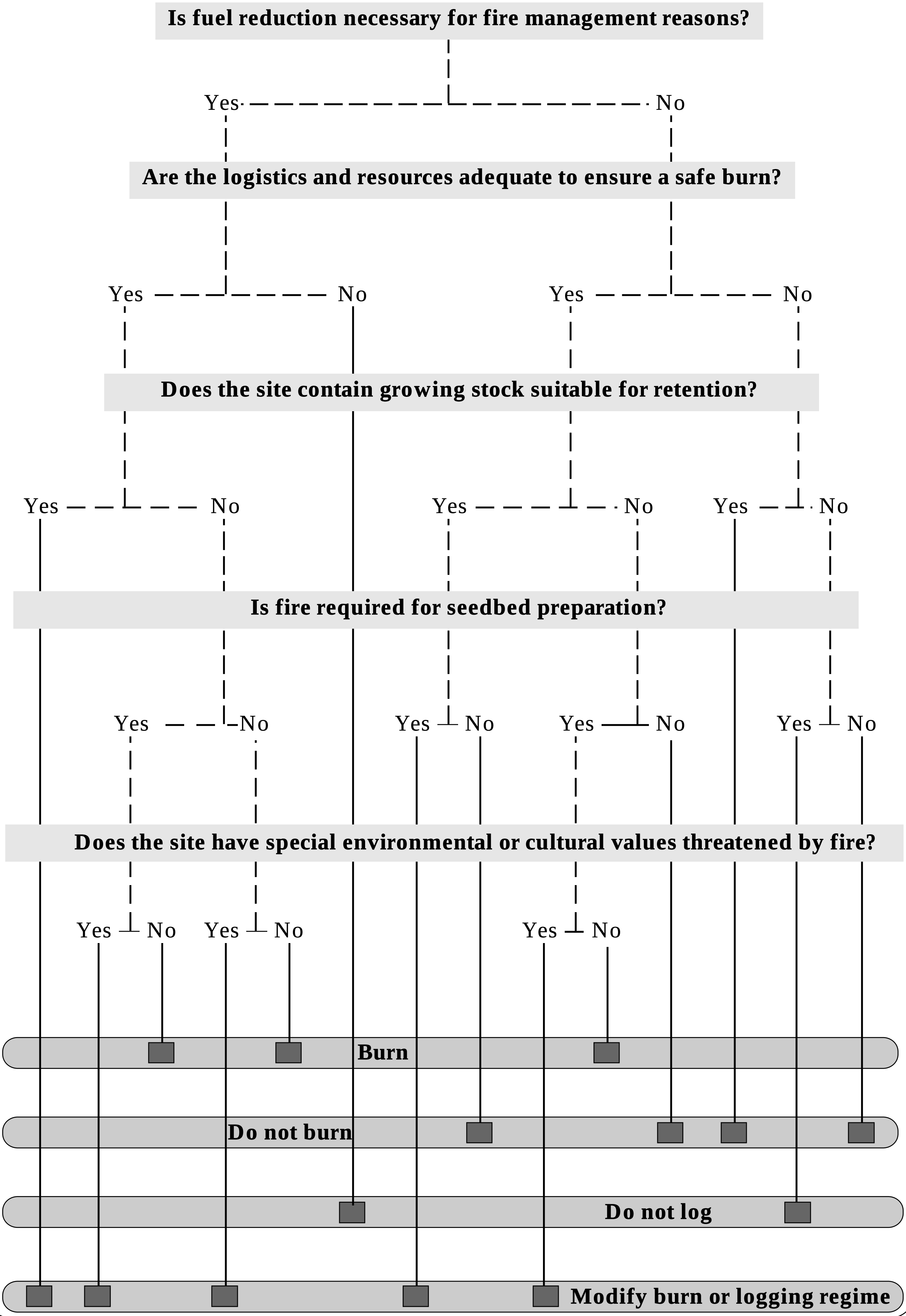


Figure 2: Guidelines for the use of fire for the establishment of regeneration.



i) Types **not suitable** for fuel reduction burning -

Alpine vegetation - fire must be excluded because of very slow recovery or loss of fire-sensitive communities.

Wet forests - Wet forests with dense understorey are not suitable for burning due to low flammability of fuels (other than under severe fire weather conditions) and the potential for the development of a bracken understorey with repeated fires.

Wet forests with dense tall bracken and cutting grass understoreys - these highly flammable understoreys may reflect the occurrence of wildfire at intervals of between 4 and 20 years. In the absence of fire these species may be shaded out by the development of a tall shrub understorey.

Intermediate forests - forests intermediate between wet and dry forest types usually have a shrubby understorey associated with fire-free intervals of 20-40 years. More frequent fires may simplify the understorey to open grass or bracken.

ii) Types **which may be suitable** for fuel reduction burning:

Dry forests and woodlands - open understorey mature forests are suitable for burning at intervals between 4-20 years.

Some non-forest communities of heathland, buttongrass moorland, and grassland may be suitable (more detailed advice should be sought from Forest Practices specialists).

3.2 Forest Structure

In unevenaged forests frequent fires may destroy young growing stock and prevent regeneration from establishing to a stage capable of tolerating low intensity burns. Associated with this may be changes in the understorey (such as the proliferation of grass or bracken) which further inhibit seedling regeneration. The absence of young growing stock may restrict silvicultural options for logging, particularly on harsh sites where seedling regeneration is difficult to obtain or slow to establish. The timing and frequency of burns should therefore be scheduled to protect young growing stock which has value for regeneration purposes.

3.3 Wood Quality

A single low intensity planned burn is unlikely to cause widespread wood damage but localised hot spots may result in cambium damage which causes kino veins or provides an entry point for decay organisms. Repeated burns may exacerbate this problem, resulting in scar tissue which eventually develops into butt hollows. Such major physical defects and associated levels of decay, seriously degrade the quality of wood and may lead to structural instability and collapse of the tree.

Fuel reduction planning should ensure that the intensity and frequency of burns does not result in high damage levels to future crop trees.

3.4 Seed Crops

Fires hot enough to cause crown scorch may kill flower primordia, resulting in lighter flowering and lower seed crops. The intensity of planned burns should therefore be such that crown scorch is minimised when seed collection or natural regeneration regimes are planned.

3.5 Forest Productivity

Low intensity fires which do not scorch growing tips are unlikely to result in significant growth losses. Regular burning at low intensity does not appear to affect nitrogen status of soils which are relatively fertile and not prone to severe leaching. However, site productivity may be reduced on inherently infertile sites. Advice on soil effects should be obtained from a soils specialist during the planning stages of hazard reduction programmes.

3.6 Conservation Values

The ecological effects of burning depend upon the forest type and the intensity, frequency and season of burning (refer to Part B). Substantial species changes may occur if the natural fire regime is highly modified by increased or decreased frequency of fires. Advice on burning effects should be sought from relevant specialists particularly in areas with special conservation values.

3.7 Fuel Management

Procedures for planning and conducting fuel reduction programmes are detailed in the Fire Management Manual (1992).

4. MANAGEMENT OF FOREST AREAS FOLLOWING WILDFIRE

Eucalypts are generally well adapted to survive even high intensity fire. Recovery occurs from crown epicormics, stem epicormics or basal shoots, depending upon fire intensity, species and tree age. However, although individual trees may recover from wildfire, wood quality may be seriously downgraded as a result of:

* poor form due to the growth of stem epicormics;

* wood decay due to the entry of decay organisms into fire wounds.

Some guidelines for the future management of fire-damaged forests are presented below.

4.1 Regeneration Stands

A guide to the likely survival and recovery of young *Eucalyptus obliqua* regeneration following wildfire is presented as Figure 3. The recommended treatments for fire-damaged regeneration are detailed below (from Wilkinson and Jennings 1993).

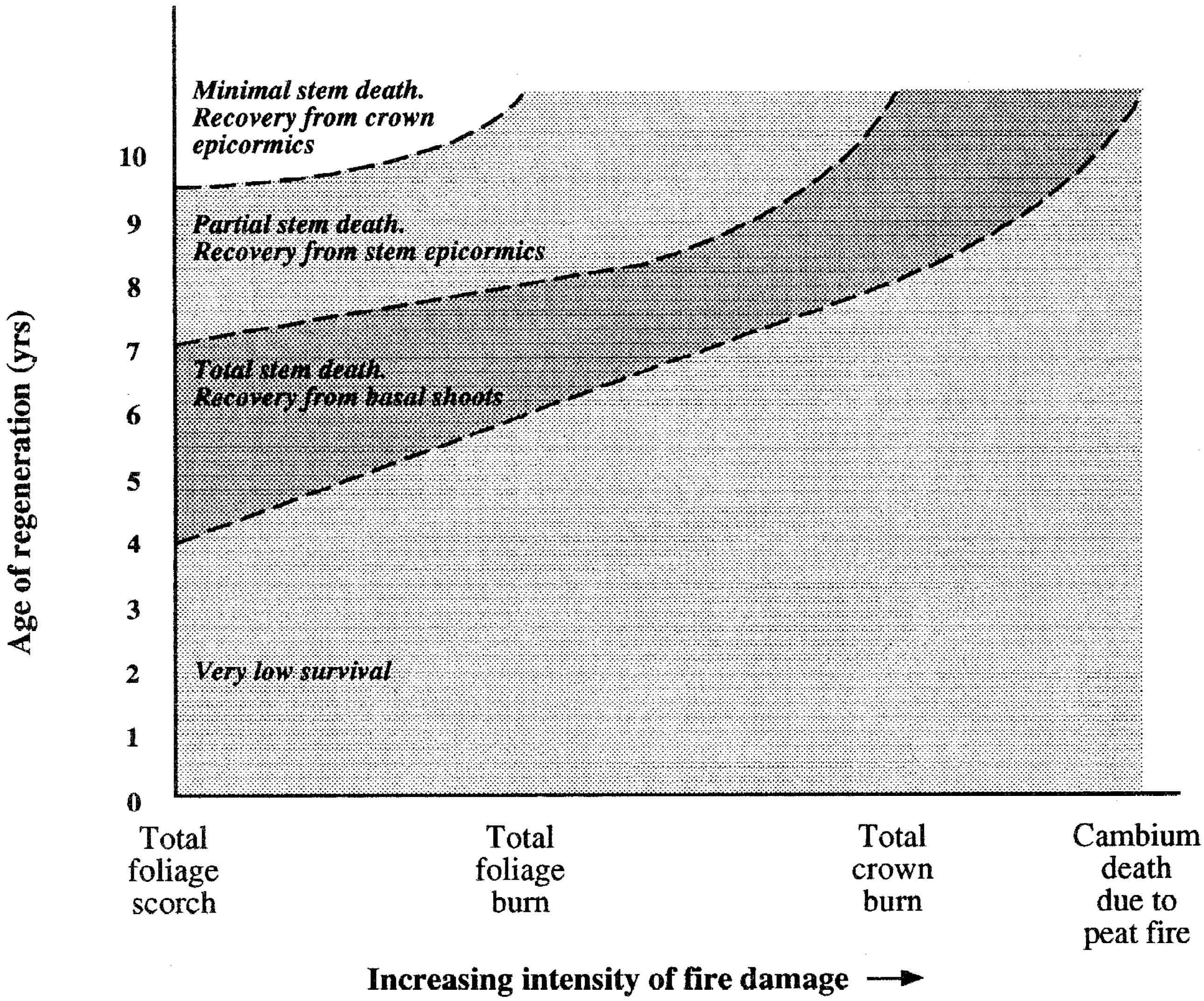
a) Post Fire Assessment

* *Colour aerial photography* of the wildfire area at 1:10,000 scale should be taken as soon as possible after the fire when smoke has dissipated and whilst dead leaves remain on trees. Damage classes to be mapped include: total crown burn; total foliage burn; total foliage scorch; and partial foliage scorch.

* *Ground inspections* should be undertaken to verify damage classes mapped on photographs.

* *Ground assessment* will be necessary after shoot recovery (6 - 8 weeks after the fire) to confirm the correlation between damage level and expected recovery (Figure 3).

Figure 3. A guide to the likely survival and recovery of young ***E. obliqua*** regeneration following wildfire (from Wilkinson and Jennings, 1993).



b) Future Management

The remedial treatment of young regeneration to increase future productivity is not economically justified unless large increases in productivity or value can be assured (Technical Bulletin No. 7). Recommendations for remedial treatments are detailed below.

* *Fire-killed regeneration*: re-sow in early autumn whilst receptive seedbed remains; control animal browsing.

* *Stem-killed regeneration with basal shoots*: no further treatment is justified where survival is adequate. A high proportion of multi-stemmed shoots should eventually thin to a single stem but total stand sawlog production is likely to be decreased. Understocked areas should be re-sown in early autumn. Animal browsing must be controlled.

* *Dead-topped regeneration with stem epicormics:* treatment may be justified where the following criteria apply:

  - high quality site;

  - machine clearing can be carried out at reasonable cost and without environmental damage;

  - management priority is for the production of high quality sawlogs and / or priority for pulpwood production is low;

  - funds are available for investment in remedial treatment.

Where treatment is justified, clearing must be completed before suitable conditions for seed germination are lost. Plantation establishment may be an option on approved sites (Neilsen 1990). However, on most sites remedial treatment will not be justified and recommended action is:

* continue to monitor wood quality as the stand matures;
* provisionally plan for sawlog yields to be significantly reduced;
* re-schedule burnt areas to short rotation pulpwood crop if high defect levels preclude sawlog production.

4.2 Mature Stands

Dry, open forests usually recover well from wildfires because the species are highly fire-tolerant and fuel loads may be relatively low, particularly in areas subjected to regular hazard reduction burns. In contrast, wildfire in wet forests is usually catastrophic due to the greater fire-sensitivity of some species, heavier fuel loads and more extreme fire weather and drought conditions necessary to sustain the fire.

The following guidelines are provided for mature stands damaged by wildfire.

a) Post-fire assessment

* In wet forest types, colour aerial photography and ground assessments should be undertaken as detailed in 4.1(a) above. In dry forest types where high mortality is not expected a field survey of epicormic growth several weeks after the fire will generally provide an adequate indication of likely damage levels and recovery.

b) Future Management

* *Fire-killed stands:* salvage logging should be carried out within one year if possible and no longer than four years (regrowth) or six years (older stands) after the fire.

* *Stands with a high proportion of crown-death and stem epicormics:* salvage logging as above. If this is not possible the stand will recover but will contain high levels of defect and future sawlog recovery may be significantly lowered.

* *Stands with crown epicormics:* the more severely damaged stands should be scheduled for logging within a 10-15 year period. Lightly to moderately affected stands can be retained although growth rates may be depressed for four to six years and defect levels may be higher than usual.

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Part B: Ecological effects of fire in Tasmanian forests

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Part B: Ecological effects of fire in Tasmanian forests

1. INTRODUCTION

The ecological effects of fire depend upon the forest type, intensity, frequency and season of burning. Ecological changes occur within forest ecosystems as part of normal successional processes, as modified by natural fire regimes. Different ecological impacts are likely to result if the long-term pattern of fire frequencies is altered by substantially increased or decreased frequency of fires.

Complex interactions between fire and specific ecological factors are widely reported in the scientific literature. However, information on the relative impacts of various fire regimes is very limited for many species and sites. In ecosystems which are adapted to the periodic occurrence of fire (such as the eucalypt forests) there is no single fire regime which will be optimum for all ecological factors.

The following sections have been prepared to provide field staff with a short summary of some of the ecological effects of fire in Tasmanian forests. The summary contains general information on major effects but does not provide the detail necessary for a comprehensive understanding of the subject. The reader should refer to the literature review and references cited in Part C of this bulletin for a more complete coverage of the topic.

2. PREHISTORY OF FIRE

* Fossil charcoal in Victorian brown coal deposits indicates the presence of fire in vegetation for at least 60 million years.

* Eucalypt forest types evolved over 10 million years ago into an environment subjected to periodic fire.

* The natural regeneration of eucalypts depends upon the regular occurrence of fire. Characteristic fire frequencies for the three main eucalypt forest types have been postulated to be:

  - 80 to 400 years for mixed forests;
  - 20 to 80 years for wet sclerophyll forests;
  - 4 to 20 years for dry sclerophyll forests.

3. EUCALYPT FIRE ECOLOGY

3.1 Adaptations to fire

* Eucalypts not only depend upon fire for regeneration, but actually promote fire as a means of maintaining site occupancy. Factors which appear to increase the rate of spread and intensity of fire include the following:

- highly flammable leaves which contain volatile oils and have a slow rate of decomposition;

- prolific branch and bark shedding, leading to high fuel loads and rapid fire spread due to the spotting of ignited stringybark or long ribbons of gum bark;

- open canopy of many forests allowing the periodic drying out of fuels;

- pendulous orientation of leaves which may maximise the convective flow of air when fires occur.

* Features which allow eucalypts to survive fires include:

  - lignotubers, the below ground dormant buds which are protected from fire by the insulation of soil;

  - effective insulation against heat provided by thick bark which protects the dormant buds along the stem and branches. These buds can produce copious epicormic growth to replace foliage destroyed by fire;

  - protection of seed in woody capsules and the stimulation of seedfall onto receptive seedbed following fire.

3.2 Natural regeneration

* The successful regeneration of eucalypts depends upon adequate access to light, moisture and nutrients. Generally this requires the removal of overstorey, understorey and undecomposed litter layers. In nature, suitable conditions for regeneration are provided by wildfire.

* Wildfires in wet forests are infrequent because their fuels are moist and the environment is rarely conducive to fire. Intense, infrequent fires may develop under severe drought and fire weather conditions. These fires tend to be catastrophic, killing all or most of the overstorey trees and resulting in the perpetuation of evenaged strata of regeneration. Many wet forests are single-aged in structure, although successive fires not intense to kill all existing trees may result in two, three (or rarely more) ages of regeneration.

* Wildfires in dry forests are more frequent than in wet forests. Fire intensity is usually variable, with locally intense fires corresponding to fallen crowns or previously unburnt patches of fuel. Forest structure is generally unevenaged, with cohorts of regeneration corresponding to previous fires. New seedlings and existing lignotubers may remain suppressed by the surviving overstorey. Death of overstorey trees, as a result of old age, windthrow or structural collapse following fire, creates gaps for the release of seedlings and lignotubers.

3.3 Silvicultural regeneration

* Well planned and conducted slash burning programmes allow forest managers to effectively use fire as a means of creating receptive seedbed and reducing fuel loads following logging.

* Mechanical clearing of slash and litter layers by logging disturbance or scarification, may also provide receptive seedbed on sites which have suitable soils, slope, ground conditions and low risk of wildfire damage.

3.4 Growth

* The growth of eucalypt seedlings is enhanced on sites subjected to a high intensity burn. The "ashbed effect" may be greater in wetter forest types than in drier forests.

* The "ashbed effect" is due to changes in the soil brought about by **soil-heating**. The beneficial changes for the growth of eucalypt seedlings may result from one or a combination of the following:

  - modified spectrum of soil microflora;

  - removal of leachates or other toxins;

  - increased availability of nutrients, particularly nitrogen and phosphorus;

  - reduced competition from other vegetation due to the reduction of soil-stored seed.

3.5 Damage

* The thick bark of eucalypts protects the cambium from fire damage. Bark thickness increases with age and diameter growth. The relative resistance of a tree to fire damage will therefore depend on its age, growth rate and the height above ground of fire-susceptible thin-barked stem or branches.

* Fire may cause damage to trees in a number of ways:

  - death of stem or major branches results in the formation of epicormic growth along the living portion of stem, causing problems of stem deformation or poor branching;

  - formation of gum veins as a result of damage to the phloem;

  - damage to the cambium, resulting in fire scars which provide an entry point for decay fungi and insects.

* When trees are killed by fire, defect develops gradually as radial cracking, followed by subsequent insect damage and decay. Defect is minimal within one year of the fire but extensive losses occur within four to six years.

4. EFFECTS ON SOIL

* The impact of fire on soils is determined by many factors, including: fire intensity and duration; soil type; topographic position; effect of vegetative cover and post-fire weather.

* Severe fire which causes defoliation of vegetation and is followed by intense rainfall can accelerate soil erosion, especially where hydrophobic layers are produced in the soil by the fire.

* Fire is unlikely to cause structural changes to the soil profile since the soil-heating effects only usually penetrate to a shallow depth.

* High intensity fire may increase pH levels and increase the leaching of some nutrients. However, the concentrations of available phosphorus, potassium, calcium and magnesium are increased in the upper layers following burning.

* Significant quantities of some nutrients can be lost from organic matter during a fire by volatilisation and as particulate form in smoke, and through subsequent erosion. Total nitrogen losses of up to 60% of that stored in organic matter have been reported to occur in slash burns. Between 10-20% of phosphorus, calcium and magnesium may also be lost to the atmosphere. The magnitude and significance of such losses is dependent upon the proportion of the site nutrient capital stored in organic matter, fire intensity and frequency, the amount of fuel consumed and the climate.

* Measurements from a single slash burn on dolerite soils in wet eucalypt/rainforest have indicated an initial increase in the availability of nutrients. Furthermore, the nutrients lost from the area as particulate ash were in quantities likely to be replaced in rainfall within 15-20 years.

* Repeated low intensity burning does not appear to reduce the nitrogen status of moderate fertility soils which are not prone to leaching. However, total nitrogen losses may occur on inherently infertile sites such as heaths and moorlands.

5. EFFECTS ON WATER VALUES

* Intense fires reduce the leaf area of vegetation and thereby increase throughfall and soil moisture and surface run-off.

* Fire may increase sediment loads and turbidity as a result of decrease in vegetative cover, increased run-off and erosion.

* Low intensity fire appears to have negligible effect on water quality. High intensity fire may increase the level of nutrients in streamwater and hence increase the risk of eutrophication.

* Detrimental effects of increased run-off can be reduced if riparian vegetation remains undisturbed.

6. EFFECTS ON AIR

* Fires release the same quantities of the “green house” gas, carbon dioxide, that would otherwise be released more slowly by decomposition.

* Fires also produce smoke which has an impact on air quality.

7. *EFFECTS ON VEGETATION*

* Alpine and sub-alpine communities do not require fire to regenerate and are severely damaged by fire.

* Rainforests do not require fire to regenerate. However, they appear to be able to recover their former structure and composition following a single fire, although some particularly fire-sensitive species such as *Diselma*, *Athrotaxis* and *Nothofagus gunnii* may be lost or severely restricted in distribution.

* Successive fires in rainforest or mixed forest are likely to eliminate the rainforest species and replace them with bracken, cutting grass or sclerophyllous species.

* Dry sclerophyll communities generally recover rapidly following wildfire.

* The effects of regular hazard reduction burns will be determined by the extent, season, frequency and intensity of the burns and the vegetation type burnt. If burns are varied in season as much as possible they are unlikely to have serious effects on the vegetation. Very high fire frequencies will encourage the development of a fire-promoting understorey (e.g. bracken or grass). Poor timing of burns in particular may result in the depletion of the soil seed bank and reduce species which regenerate primarily from seed.

8. *EFFECTS ON FAUNA*

* A single fire causes an initial reduction in the populations of invertebrates. Post-fire recovery will depend on the initial community structure, fire intensity, percentage of area and substrate burnt, and season of burning. Populations of some species appear to recover within a few years. The recovery of other species will depend upon the longer term recovery of specific habitats, food sources etc.

* High intensity fire generally has a greater impact on fauna than low intensity fire due to more severe effects on habitat and fewer refuges from which re-colonisation can occur.

* Impacts on vertebrate animals will depend upon the longer term effects of changes to vegetation and habitat following fire.

* Vertebrates respond in various ways to fire, depending upon their preferred habitats and food requirements. No single fire regime will encourage all species within an ecosystem.

PART C: Literature Review

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PART C: Literature Review

Part C of this bulletin contains a review of the literature relevant to the ecological effects of fire in Tasmanian forests. This review is provided as the information upon which Part A (prescriptions) and Part B (summary of ecological effects) is based.

1. THE PREHISTORY OF FIRE IN TASMANIA

Evidence of fires in vegetation appears as specks of charcoal in coal deposits over 60 million years old (Mount 1979; Kemp 1981)) indicating that fire occurred millions of years before the eucalypts dominated Australia's forests.

Present vegetation types, including the eucalypt forests, have been recognised in fossils more than 10 million years old (Kemp 1981) and were widespread two million years ago (Hope, in press; Kershaw *et al.*, in press).

Most eucalypt forests appear to depend on fire for their long-term health and regeneration requirements and to die out in its prolonged absence. The maximum limits to fire frequency can be inferred by the longevity of the plants and seed. For mixed forest eucalypts this appears to be less than 500 years (Mount 1966) and for dry forest shrubs is probably of the order of 100 years. The average interval is likely to be less than half these maxima. Gilbert (1959), Jackson (1968) and Mount (1966, 1979) concluded that eucalypt forest types had characteristic average fire frequencies of 80-400 years (mixed forest), 20-80 years (wet sclerophyll forest) and 4-20 years (dry sclerophyll forest).

There is palynological (pollen analysis) evidence from mainland Australia of an increase in sclerophyll vegetation and carbonaceous fragments, believed to be coincident with the arrival of Aboriginal man (Singh *et al.* 1981), and also the drying of the climate (Macphail 1981).

There appears to be evidence to suggest that Aboriginal burning was coincident with the spread of eucalypts over large parts of south-east Australia (Singh *et al.* 1981; Macphail 1984).

Aborigines have been in Tasmania for at least 30 000 years (Cosgrove 1989), and the available evidence suggests that they made wide use of fire, particularly in the last 4 500 years (Goede and Murray 1977; Macphail 1980; Kiernan *et al.* 1983; Ellis 1984, 1985).

At the height of the last glaciation so much water was held as ice on land that the sea was about 100m below today's level and Tasmania was both larger in area and connected to the mainland. The fossil record appears to suggest that what is today's Tasmanian land area was then largely unforested and that most of the forests were below today's sea level (Macphail 1980).

About 10,000 years ago the climate warmed and the glaciers began to retreat. The sea gradually rose and Tasmania again became an island. The forests spread uphill on to all but the most infertile or poorly drained soils. This spread occurred despite the continuing presence of aboriginal burning. The fossil pollen evidence (Macphail 1980) indicates between 6,000 and 3,600 years of equilibrium (depending on altitude) between climate, vegetation, fire and people until the 1800's.

Macphail (1980) considers that climate has been the primary determinant of vegetation patterning changes in Tasmania and that fire has been a secondary factor.

Nevertheless, the interplay between man, fire, vegetation and soil fertility is considered by many workers to have been influential in the present day patterning of plant communities. (Gilbert 1959; Mount 1966; Jackson 1968; Brown and Podger 1982a; Macphail 1984; Ellis and Thomas 1988, Podger *et al*. 1988).

2. EUCALYPT FIRE ECOLOGY

2.1 Adaptations to fire

The fossil record indicates that the eucalypts evolved into an environment in which fire was already an occasional component. The selective pressure of fire in the environment has undoubtedly favoured those species best able to resist, recover and regenerate after fire. Eucalypts now possess adaptive traits which help the individual survive, and life cycle features which allow them to cope with particular fire regimes.

a) Features which promote fire

It has been suggested that eucalypt species are not just adapted to fires, but are actually fire promoting as a means of maintaining site occupancy (Mount 1964; Ashton 1981; Ingles 1985). This idea arises because eucalypts appear to exhibit a number of features which increase the rate of spread and intensity of fire, whilst themselves displaying adaptive traits to wildfire. In the absence of human intervention, the natural regeneration and continued existence of the eucalypts depends upon the recurrence of fire (Mount 1964, 1970, 1979).

The leaves of most sclerophyll plants, including eucalypt leaves, are relatively flammable, largely because of their high volatile oil content and their low nitrogen and inorganic matter levels, especially when dead (King and Vines 1969). The dead leaves typically have a slow decomposition rate (Hatch 1959; McArthur 1967; Peet 1971). The open canopy frequently associated with eucalypts allows the periodic drying out of fuels further inhibiting decomposition (Mount 1964, 1970) and the prolific branch and bark shedding characteristics of the eucalypts results in high fuel loads. The spread of fire in eucalypt forest is accelerated by the spotting process associated with either loose stringybark or long ribbons of decorticating bark (Mount 1964). It has been suggested that the pendulous orientation of the leaves in the canopy promotes maximum convective flow when fires do begin (Ashton 1981).

It would be misleading to consider these factors in isolation from other more persistent environmental factors. Vertical orientation of leaves, for instance, is a feature often associated with plants reducing their incident solar radiation load in moisture limiting environments. The slow decomposition rate of litter may perhaps be ascribed to aspects of sclerophyll leaves associated with the need to maintain rigidity in drought conditions or existence in a nutrient poor environment (Beadle 1966; Noble 1986). Nevertheless, the presence of eucalypts in a forest community increases the probability of extensive fires. For instance, it is principally the presence of eucalypts in mixed forest that increases the possibility of the community burning relative to rainforest with otherwise the same species composition (Dickinson and Kirkpatrick 1985).

b) Vegetative regrowth adaptations

i) Lignotubers

Lignotubers are basal woody swellings associated with dormant buds. Lignotubers begin as small structures in the axils of the cotyledons and the first few leaves. As the plant grows the lignotuber increases in size and progressively becomes buried (Chattaway 1958; Stone and Cornwall 1968). If the above-ground parts of the eucalypt plant are destroyed or killed by fire, basal sprouting from the lignotuber may allow regeneration of the individual. Soil is a good insulator and only a small proportion of the heat from a fire will penetrate more than the first few centimetres into the soil (Packham 1971; Priestley 1959). This means that the buried parts of the plant provide valuable refuges for meristematic tissue. Because of the stored carbohydrate in the lignotuber and the undamaged root system, lignotuberous shoots often display growth rates in excess of those shown by seedling regeneration (e.g. Henry and Florence 1966), and can rapidly out-grow the danger zone close to the soil surface where fire and browsing pose significant threats. The effectiveness of lignotubers appears to be related to the age of the plant (Kyall and Gimmingham 1965), the severity of the fire (Naveh 1974), the season of burning (Doman 1968) and the frequency of burning (Grano 1970).

Among eucalypts, lignotubers are very common (Pryor and Johnson 1971) and although different species may develop them to differing degrees, only 12 - 15 species Australia-wide lack them altogether (McArthur 1968). These species are predominantly the ash species which dominate wet sclerophyll and mixed forest communities. The lack of these features in wet sclerophyll communities has been hypothesised to be related to the diversion of energy resources towards fast growth (Ashton 1981). Lignotubers are vulnerable to damage if fire burns the substrate, as in peat or duff fires, a situation that may arise in wet forests but is unlikely to occur in dry forests. Those eucalypt species which range in their climate from wet to dry sites, such as *E. obliqua* and *E. viminalis* tend to show variable lignotuber development (Ladiges and Ashton 1974; Ashton 1981).

ii) Bark protection of aerial buds

When apical dominance is removed as in the case of a defoliation by fire, dormant stem buds produce clumps of shoots known as epicormic shoots (Jacobs 1955). These allow the tree to rapidly restore its photosynthetic capacity.

These buds are protected by bark which is a very effective insulator (Martin 1963). There appears to be relatively little difference in the thermal diffusivity of bark of different species (Reifsnyder *et al*. 1967). However differences in bark thickness, moisture content and bark flammability will affect the relative insulation provided by bark of different species (Cremer *et al*. 1978; Gill 1981). Bark thickness varies widely between species and between individuals within a species depending on growth rate, diameter, height above ground and stand history. It is generally presumed that gum bark provides better insulation per unit thickness than peppermint bark which in turn provides better insulation than stringybark (Gill and Ashton 1968; Vines 1968). However, other research has found that similar thicknesses of bark from stringybarks and gums have equivalent properties (McArthur 1968).

c) Seed Protection and Dehiscence

All eucalypt fruits are woody. This in itself confers protection from radiated heat or heat associated with a crown fire. It has been suggested that capsules may provide protection of enclosed seed from very high temperatures (>250^{o}C) for 4-5 minutes (Webb 1966a, Ashton 1981). Ashton (1981) hypothesises that it is the very volatility of the eucalypt crowns which leads to explosive heats for very short periods of time rather than protracted periods of heat which in part aids the survival of crown stored seed. In wet forests the vertical separation of the eucalypt canopy from the understorey may also protect the seed (Mount 1970), even though the adult trees themselves may be girdled and killed by a fire burning in the understorey.

Unlike the seed of many understorey species in both wet and dry forests, very little eucalypt seed is stored in the soil beyond twelve months, and shed seed is not resistant to fire (Gilbert 1958; Cunningham 1960; Cremer 1962b; Ashton 1981). Insect harvesting of seed has been considered to account for a large proportion of seed losses (Jacobs 1955; Ashton 1955, 1979; Cunningham 1960; Grose 1960; Cremer 1965). Ashton (1979) found that ants removed 60% of annual seedfall and that all viable seeds were lost in the warmer months. In addition burial under as little as 1cm of soil has been demonstrated to dramatically reduce percentage germination (Cremer 1962b), so it is unlikely that seed will survive fire by burial. Finally seed of some species stored for long periods in moist conditions may be susceptible to the induction of strengthened primary or secondary dormancy (Cunningham 1960; Grose 1963).

Eucalypts do, however, have the capacity to store seed on the tree for between two to four years (Cunningham 1960; Cremer 1965; Ashton 1975). Not all seed is shed as it matures in the inter-fire period, and a seed-bank is stored in the crown. Seed shed normally peaks for most Tasmanian species in autumn, and fire or drought can accelerate this process. In *E. regnans* forest seed is evenly shed throughout an average year, but more than half the year's seed shed is concentrated in autumn in a drought year. Capsule opening depends on desiccation which can only occur following severance of water supply. Fire can accelerate seed shed by: 1) death of the trees by girdling, 2) dieback of twigs and branches due to scorching by radiant heat and 3) abscission of capsules by the formation of an abscission layer in response to fire (Cremer 1962a).

The rate at which girdling affects seed shed depends to some extent on the intensity of the fire. Grose (1957) reported that girdling of the bark only of *E. delegatensis* did not affect seedshed until one year later, whereas seedtrees with their sapwood cut cast most of their seed within one to two months. Capsules on heat-killed twigs cannot be abscissed and remain aloft until eventually torn off by rot and weather, however seed shed occurs as soon as the capsules dry out (Cremer 1962a). Cunningham (1960) observed that completely scorched crowns of *E. obliqua/E. radiata* forest shed seed heavily within two days. Cremer (1962a) observed that 80% crown scorch in *E. regnans/E. obliqua* caused 95% of crown stored seed to be shed within four months of a fire with the remaining 5% shed the next spring. Christensen (1971) observed that between 15 -75% crown scorch in *E. diversicolor* caused seed shed within 2-4 weeks, whereas 5% crown scorch did not.

It is also possible that a fire which is not hot enough to have any obvious effects on the crowns of eucalypts may induce abcission of all or nearly all of the crown-stored seed, so that the whole crop is abscissed in two months, a process which normally takes two years (Cremer 1962a, 1965). No convincing evidence as to the mechanism of this sudden abcission exists, although Cremer (1962a) postulates increased moisture stress associated with damage to shallow roots as a result of any humus fire. Heavy shedding of crown-stored seed immediately after a fire may satiate the reduced predator numbers (Ashton 1979) and ensure that some seed germinates.

2.2 Natural regeneration pathways

Eucalypts possess lifecycles that allow them to survive in an environment periodically visited by fire. If one accepts the definition that an adaptive trait "is an aspect of the developmental pattern which facilitates the survival and / or reproduction of its carrier in certain successions of environments" (Dobzhansky 1956) then the ability to survive various fire regimes is an important part of the eucalypts' adaptation to their environment.

The eucalypt genus displays a range of such adaptations and perhaps is best considered by reviewing the natural regeneration pathways of wet, dry and intermediate forests.

a) Wet forests

In the wetter forests, it is generally recognised that regeneration will not succeed without the removal of the understorey and the provision of a mineral seedbed (Ashton 1956, 1962, 1981; Gilbert 1959, 1963; Cunningham 1960; Mount 1964, 1970, 1979; Jackson 1968,1981; Gilbert and Cunningham 1972; Cremer *et al.* 1978).

Whilst seed will germinate at very low light intensities, seedling survival requires at least 10 - 30% of full sunlight (Ashton 1956, 1981; Gilbert 1958; Cunningham 1960; Cremer 1962b; Ashton 1981). Intact eucalypt canopies allow at least this amount of light (30 - 40% of full sunlight normally) to penetrate through to the understorey (Ashton 1976; Bowman 1984). However, the dense understorey of wet forest intercepts most of this so that only 1 - 5% reaches the forest floor (Ashton 1956, 1976). Seedling death in these instances may be related directly to low light intensities (Cremer 1962b) or associated fungal diseases arising from damp, shady cool conditions (Ashton and MacCauley 1972). Ashton and Willis (1982) suggest that an increase in soil temperature following the creation of gaps may allow the development of a microflora favourable for healthy seedling growth. They found that the rhizosphere fungus *Cylindrocarpon destructans*, which favours cool soil of undisturbed *E. regnans* forest, is known to produce a powerful toxin which inhibits eucalypt seedling growth. Similar microbiological factors have been proposed to explain poor seedling growth in soil from *E. pilularis* forest (Florence and Crocker 1962) and in the suppression of adult eucalypts by rainforest understorey (Ellis 1984, 1985). Inhibitory substances from the understorey or overstorey trees have also been suggested as possible factors in regeneration inhibition (Florence and Crocker 1962; del Moral and Muller 1969; 1970; del Moral *et al.* 1978; May and Ash 1990). Competition for soil moisture and nutrients have generally been discounted as factors in wet forest (Cremer 1962b).

Germination has been observed to be up to 20% poorer on undisturbed seedbed than on disturbed seedbed (Cunningham 1960; Gilbert 1959; Bowman 1984). Some seed is able to germinate on undisturbed litter and duff layers however there appears to be no survival beyond the cotyledon stage (Jacobs 1955; Gilbert 1959). This has been variously ascribed to drought as a result of poor rooting in the unconsolidated substrate (Cunningham 1960; Cremer 1960; Mount 1979) and to allelotoxic effects (Ashton 1962; Mount 1970; Willis and Ashton 1978).

Predation of seed by insects and browsing of young seedlings by insects and mammals also reduce the success of regeneration. Browsing is a major factor in survival, despite the ability of eucalypts, even non-lignotuberous species, to recover from decapitation above the cotyledonary dormant bud level (Mollison 1960; Gilbert 1961; Mount 1976, 1979; Ashton 1981).

The method by which the understorey is removed and soil disturbed appears largely irrelevant to the establishment of regeneration. Gilbert (1959) cites the example of an *E. regnans* sapling growing in a 400m^2 clearing in the Styx Valley produced by the windthrow and sliding of a large mature tree. However windthrow is a relatively minor cause of forest disturbance in Tasmania's wet eucalypt forests, and this example is the only reported instance of regeneration in association with windthrow. Regeneration can also be found associated with landslides on the Mathinna series in the north-east of the state, and on Mt. Hugel and Cathedral Mountain in the west of the state. But by far the most significant natural cause of disturbance in these forests is wildfire. The presence of thousands of hectares of even-aged eucalypt forest around the State is itself strong evidence of the regenerative role of wildfire, further supported by numerous observations of prolific regeneration following wildfire events (e.g. Galbraith 1937; Gilbert 1959; Ashton 1976).

Gilbert (1959) concludes that wildfire creates favourable conditions because:-

* the understorey is destroyed;
* the forest floor receives full sunlight and the litter layer is destroyed;
* some eucalypt seed is destroyed but large numbers of capsules survive on trees and there is a heavy fall of seed soon after fire;
* there is a reduction in the number of insects which harvest seed;
* populations of browsing mammals are reduced if the fire is large enough;
* periods favourable for seed germination occur in the autumn soon after late summer wildfire.

Wildfires in wet forests are less frequent than in dry forests because their fuels are more moist and their environment is rarely conducive to fire, with perhaps two or three days per season suitable for widescale conflagration. Generally the high, reliable and evenly distributed rainfall and the protection of ground fuels from drying by the dense understorey canopy reduces the fire hazard. When there is a coincidence of ignition, severe fire weather and prolonged drought, relatively intense fires can develop which kill the overstorey and consume the understorey as relatively large volumes of accumulated fuels burn. In addition to fine fuel loads of up to 20 tonnes per hectare, wet forests in Tasmania may develop a humus layer which may provide a further 160 tonnes per hectare (Frankcombe 1966). In contrast, fires in dry, open forests are more frequent as a result of drier fuels and more rapid fuel accumulation (due to slower rates of decomposition).

It has been suggested that each community has a characteristic interval between fires (Mount 1966; Jackson 1968) For wet sclerophyll forests this has been hypothesised to be 20 - 80 years (Mount 1966) and for mixed forest 150 - 350 years (Gilbert 1959) or 80 - 400 years (Mount 1966). Evidence also suggests that for mixed forests and rainforests there is also a relatively high risk of a second fire within 20 years of the first (Mount 1966; Jackson 1968; Brown and Podger 1982a, b; Podger *et al.* 1988, Bowman *et al.* 1986, Barker 1991).

Because the wet forest eucalypts are relatively fire sensitive fire generally results in the formation of so-called evenaged regrowth. However, in some circumstances fires may not kill all the eucalypts while temporarily destroying the understorey (Ashton 1956, 1981). In the Florentine Valley Mount (1966) found up to five ages on each *E. regnans* coupe in 4,000 hectares assessed. However in the nearby Styx valley a single age was the norm for both *E. regnans* and *E. obliqua* except on relatively dry sites. With more fire resistant species such as *E. obliqua* and *E. delegatensis* the trees may recover from even a moderately severe fire so that this intimate intermixing of ages is more common (Gilbert 1959; Bowman 1984). In some other reported cases such unevenaged wet forest stands may arise from reinvasion of rainforest under mixed aged eucalypt forests which have arisen over a more open understorey (Needham 1960; Ellis 1964; Orme 1971).

Frequently the above ground parts of shrubs and small trees are destroyed by fire. Unlike the eucalypt component many of the understorey species, particularly in the family Asteraceae (e.g. *Olearia and Bedfordia*) are capable of coppicing after even moderately intense fires (Howard 1973; Ashton and Frankenberg 1976; Ashton 1981). Other species regenerate prolifically from ground-stored seed, which for some species such as *Acacia* may persist in the ground for more than 100 years (Cunningham and Cremer 1965). It has been suggested that the seed of some other species (e.g. *Pomaderris* spp.) persists in the soil for less than 100 years (Gilbert 1959). These understorey species, if they regenerate prolifically, may inhibit eucalypt growth and in some instances cause death. Floyd (1966a) observed heavy losses of *E. regnans* in Victoria and Tasmania in dense thickets of *Pomaderris* spp. up to the age of 8 years. Cunningham and Cremer (1965) found that intense root competition could adversely affect eucalypt growth, and that in some very dense and vigorous stands of *Acacia* spp. death of eucalypts eventually resulted from light stress after they failed to overtop the understorey.

The growth of wet sclerophyll eucalypts is rapid if given a favourable start and they can soon overtop the understorey. *E. regnans* has been reported to achieve half its final height in 25 - 35 years (Ashton 1967a; Jackson 1968). Within 15 to 20 years following a wildfire, the regenerating eucalypts generally produce sufficient seed to ensure that there will be a subsequent regeneration pulse should a second wildfire occur (Jackson 1968; Gilbert 1959). Fires at shorter intervals may result in the conversion of eucalypt dominated sites to scrub or bracken, or in the case of mixed species stands may result in the removal of the more fire sensitive species (e.g. *E. regnans*) and the selection of the more fire tolerant species (e.g. *E. obliqua*) (Ashton 1981).

b) Dry forests

Dry sclerophyll communities in Tasmania are usually unevenaged (Duncan and Brown 1985). It has been hypothesised that in these forests regeneration depends largely on recruitment of lignotuberous seedlings into the overstorey (Jacobs 1955) and that seedling regeneration is mostly associated with very intense fire, often on a local scale within a larger less intense fire. Most mature trees survive fire and usually recover well (Purdie and Slatyer 1976; Christensen *et al*. 1981; Bowman 1984). Unlike the dominants of the wet eucalypt forests, most trees in dry eucalypt forests are relatively thick barked, fire resistant and lignotuberous. Intense fires associated with fallen limbs or other fuel accumulated next to the boles of trees may give rise to fire scars where cambial tissue has been killed and repeated burning may ultimately fell the tree (Mount 1979). Insect attack, especially *Porotermes* (Elliott and Bashford 1984) stemming from a fire scar may also weaken trees and pre-dispose them to windthrow. Felled trees may give rise to a local accumulation of fuel, which during the next fire will lead to a locally intense fire with a long residence time, generating an ashbed (Jacobs 1955; Vines 1968; Mount 1979) and to good growing conditions for seedlings (Pryor 1960; Attiwill 1962; Renbus 1968). The combined stimulus of the ashbed and the canopy gap arising from the felled tree may lead to the recruitment into the canopy of new germinants, or the release of nearby suppressed lignotuberous seedlings. Accession to the lignotuber pool depends upon suitable environmental and biotic factors following the disturbance that causes the regeneration event (Mount 1979), particularly a lack of browsing (Mount 1976) and occurrence of adequate rainfall (Bowman 1984; Henry and Florence 1966). Consequently, while regeneration cohorts correspond to previous fires, not every fire gives rise to a regeneration cohort (Bowman 1984). Seedlings and lignotubers in the interfire interval are suppressed by the existing overstorey (Henry and Florence 1966; Opie 1968; Gill and Ashton 1971; Incoll 1979; Schuster 1980; Bowman 1984; Kellas *et al*. 1982, 1987). This effect has been ascribed to allelopathy (May and Ash 1990; Florence and Crocker 1962) and to competition for soil water (Bowman and Kirkpatrick 1986; Battaglia and Wilson 1990).

Fire thus aids regeneration by exposing seedbed, removes any allelotoxic chemicals and by temporarily destroying the canopy, thus reducing the evapotranspirative demand. The lignotuberous pool of regeneration is quite hardy and may persist for long periods of time; depletion of their numbers is generally a slow process (Henry and Florence 1966). Stems suppressed for even long periods of time (>20 years) show considerable capacity to respond to release. Repeated burning, particularly if associated with browsing (the worst case being grazing by stock) may remove or severely deplete this lignotuberous pool (Bryant 1971; Heigh and Holgate 1979).

c) Intermediate forest

The two situations described so far, the 'wet' and the 'dry' forest types, refer to the extremes of eucalypt forest types. Between the two extremes there is a range of forest types with variable structure and understorey. Forests with shrubby understorey tend to occur on relatively moist sites with infrequent fires. More open understorey reflects a drier site and / or a higher frequency of fire.

2.3 Requirements for silvicultural regeneration

Whilst natural regeneration events are predominantly triggered by fire, regeneration after logging does not require the occurrence of fire. The requisites for regeneration are : 1) a mineral seedbed, 2) viable seed, 3) suitable weather, 4) relative freedom from browsing and insect attack, 5) release from both overstorey and understorey competition.

Gilbert (1958) working in the Florentine Valley found that the establishment of eucalypt seedlings on disturbed mineral soil was at least equal to that where slash had been burnt. Similarly, Cunningham (1960) working with *E. regnans* in the Ada Valley, Victoria obtained prolific regeneration on disturbed ground. Florence (1964) found that an autumn slash burn in a summer rainfall area gave very poor regeneration compared with disturbed mineral soil. In high elevation mixed species forest in East Gippsland, Victoria, Fagg (1981) found that sowings on disturbed mineral soil had a significantly higher seedling per cent (three times as high) three to four years after sowing, than they did on burnt seedbed. In some instances very high intensity burns have given superior germination. Grose (1957) found that ashbeds had a significantly better seedling percent after fourteen months than did disturbed seedbed. Campbell and Bray (1987) found that seedbed type (high intensity burn, moderate intensity burn, and disturbance only) had no effect on total observed germination in *E. regnans* in Victoria.

For the wet forest types Cremer (1962b) estimates that in the logging without burning treatments he examined, only 20% mineral soil exposure resulted. Other studies suggest that much of this disturbed soil is usually compacted (Shea *et al*. 1981). Cremer(1962b) concludes "Extensive regeneration surveys in the felled *E. regnans* forests of Victoria and Tasmania have shown that adequate regeneration is not the normal result of logging for logging's sake. Regeneration was successful only where logging was so selective as to leave an adequate number of useless standing trees as a seed source, and provided that a fire destroyed the remaining understorey and slash." Modern logging standards to smaller diameter specification and utilisation of minor species probably result in greater than 20% ground disturbance. The use of modern machinery reduces compaction and sowing overcomes the necessity for incidental seeding from cull trees. Even so regeneration without additional seedbed preparation must be considered uncertain.

In the drier forests of Tasmania burning is not considered necessary for the establishment of regeneration after logging (Felton and Cunningham 1971; Gilbert and Cunningham 1972). However, the forest regenerated without slash burning has an increased risk of wildfire damage. According to Dickinson (1985) the level of fine fuel on unburnt sites is greater than on burnt sites for at least eight to nine years. Studies by Beck (1993) indicate that the increased fuel loads may persist on some sites for up to 16 years.

2.4 Fire and growth

a) The "ashbed" effect

Major aspects of the "ashbed" effect are summarised below.

i) Pryor (1960) drew attention to the accelerated growth of pines where windrowed logs had been burnt and called this phenomenon the "ashbed" effect. Although he also showed this effect was due to soil heating rather than to ash the misnomer has remained.

ii) The depth of heated soil depends on the duration and intensity of the fire and especially on the moisture content of the soil. Soil moisture influences the moisture content of the fuels above it before the fire and provides both a heat sink in the latent heat of evaporation and a continuous supply of steam to dampen the surface fire. These processes reduce the rate of combustion and hence the fire intensity. This means that the greatest quantity of "ashbed" soil occurs where there is a more or less continuous cover of heavy fuel (e.g. logging slash or a deep dry organic layer) over the very dry soils.

iii) Cromer (1967) showed that similar growth responses could be established by sterilising the soil with radiation, but that this tended to be less dramatic and of shorter duration compared to those produced by soil heating.

iv) Renbus (1968) showed that after sufficient heating the fungal-dominated assemblage of soil micro organisms was replaced for about a year by one dominated by bacteria and actinomycetes. Pines or eucalypts established in that year had superior growth to those established on unheated soil and the advantage continued for at least 15 years. The effect could not be obtained for plants established more than 15 months after the burn.

v) Attiwill (1962) showed that the stimulated growth effect could be produced by either heating to 300^{o}C or by heating to 150^{o}C plus leaching of a powerful toxin produced by the lesser heating. In the field there is a spatial mosaic of degrees of soil heating, even on the driest soil, and a reduction of heating with depth. This means that Attiwill's toxic effect is probably present as a layer wherever the soil was heated. This may help to account for the poor establishment of *E. obliqua* and *E. regnans* associated with spring regeneration burns over wet soil. On the other hand most bushfires and most current high intensity slash burns occur at the end of the dry season, when soils are dry, with germination not occurring until after the soil is thoroughly re-wetted and any toxic layer removed.

vi) In both wet and dry forest soils such ashbeds, as opposed to merely burnt seedbeds, have generally been reported to increase early mortality relative to soils subjected to a moderate intensity burn or disturbed soils. (Gilbert 1958; Floyd 1962; Christensen and Schuster 1979; Fagg 1981). This has been attributed to various causes including the effect of high soil/air interface temperatures resulting in necrosis of stem tissue (Dexter 1967; Fagg 1981), *Phytophthora* and *Pythium* spp. (Marks and Kassaby 1974), drought resulting from a water repellant soil layer (De Bano and Rice 1973) and possibly an increase in frost heave due to a loss of soil structure. In contrast to growth on burns of light or moderate intensity which show little or no growth improvement relative to disturbed soil (Cremer 1962c, Floyd 1962; Fagg 1981), growth of surviving seedlings in ashbeds is generally concluded to be much improved (Pryor 1960, 1963; Cremer 1962c, Attiwill 1962; Hatch 1960; Grose 1957; Loneragan and Loneragan 1964; Humphreys and Lambert 1965; Lockett and Candy 1984; Renbus *et al*. 1973). These effects can be quite marked. Grose (1957) reported for *E. delegatensis* two years after seedbed preparation a mean height of 244cm on ashbed soils compared to 42cm on disturbed soil; Fagg (1981) reports 269cm versus 128cm for *E. fastigata* after 3 years; and Cremer (1962b) reports 55cm versus 12.5 cm for *E. regnans* after one year. These growth increases have been attributed to changes in available nutrients, particularly available nitrogen and phosphorus (Attiwill 1962; Hatch 1960; Loneragan and Loneragan 1964; Humphreys and Lambert 1965) and soil sterilization and alterations in the soil microflora (Renbus 1968, 1973).

vii) Cremer (1962c) suggests for *E. regnans* in the Florentine Valley that the stimulatory effect of fire is most important during the first years after the fire, and that whilst the boost in height growth increases the chance of survival it may be of little value in terms of mean annual growth when the trees are harvested. Hatch (1960) however implies that the residual ashbed effect may last 20 years. Lockett and Candy (1984) found that early growth rate differences existed between burnt and unburnt plots in a range of forest types. Lockett (pers. comm.) now concludes on the basis of this research that the effects are variable depending on forest type, varying from no effect in
the driest forest types to a growth rate difference which lasts for more than 10 years in wet forest. He estimates that whilst the decision to burn or not will have no effect on the rotation length in dry forests, burning has the potential to reduce 10 years or more the rotation length in wet forest.

viii) The hottest burns on dry soil generally destroy all ground stored seed and give eucalypts a relatively competition free period of growth (Floyd 1966a; Fagg 1981). Burns of lower intensity however encourage the development of mat-forming herbs and grasses which can quickly kill young eucalypts (Gilbert 1958; Cremer and Mount 1965; Fagg 1981). Similarly regeneration of taller understorey species is generally more prolific on burnt seedbeds (Floyd 1966, Cunningham and Cremer 1972, Fagg 1981). Whilst germination of taller understorey species is generally less on burns of high intensity than on lower intensity burns or disturbed ground, total biomass increment can be higher due to vigorous growth (Fagg 1981).

ix) In general it can be expected that no more than 10% of any burnt coupe will be an ashbed (Fagg 1981), and with improved utilisation standards this figure is likely to fall, particularly for drier forest types. It is likely that only a small number of regenerating eucalypts in any one coupe will benefit from the growth stimulation of an ashbed. However given that up to 100,000 seedlings per hectare may be present immediately after the regeneration burn, and that perhaps only 100 will be present at rotations end, the initial ashbed effect may have a strong influence in enabling the final crop trees to out-compete the understorey and other eucalypts. In the wetter forests it appears that it is possible that the decision to burn or not may markedly affect rotation length. Furthermore, unless an adequate stocking of regeneration can be achieved without burning, the effects on productivity will be much greater still.

b) Later age growth

The literature on the effects of fire on growth of older trees is conflicting, hardly surprising given the range of fires, soil types, forest types and the different measurement intervals used. Wallace (1965) notes that growth of jarrah was stimulated following the Dwellingup wildfire in January 1961, but not until crowns reshot in the summer of 1962. Shea *et al*. (1981) report that one year after a moderately intense fire with complete crown scorch, the growth of jarrah poles was four times that of those in unburnt plots or plots subject to mild spring burns. Nicholls (1974) however reported an initial decrease in diameter increment in the same forest type following an intense fire, although a mild fire had no effect. Abbott and Loneragan (1983) found no consistent effects of high intensity fire on jarrah diameter increment, and they concluded that low intensity fire had no long term (30-50 years) or short term (10 years) effects on diameter increment. Peet and McCormick (1971) found that a low intensity burn had no effect on the girth increment of jarrah, karri or maritime pine for 4 years after the burns. Byrne (1977) found that in *E. maculata/E. fibrosa/E. drepanophylla* forest in Queensland that there was an annual increase in diameter increment for the first three years following a burn and then a return to the pre-fire growth rate. Incoll (1981) in *E. obliqua/E. sieberi* forest found a growth reduction of between 50 - 80% following moderate to severe wildfires, with no evidence to suggest that the lost growth is ever recovered. Curtin (1966) concluded that in *E. maculata* forest in northern New South Wales low intensity burns were having little or no effect on growth rates. Wright and Grose (1970) found that volume increment in *E. obliqua* was only 30% of the pre-fire level in the second year after a fire which completely defoliated the trees. Four years after the fire the increment had increased but was still below its pre-fire level. The cases where the diameter increment has been stimulated may be due to a rejuvenated crown or even an increased crown volume associated with epicormic growth (Webb 1966b) and a reduction in seed production.

The effect of fire on younger trees is more pronounced because death of the thin barked stem cambium often results in partial or complete stem die-back. Following stem die-back, one or more stem epicormics will eventually reach the pre-burn stem height and enable positive height increment to be resumed. Wilkinson and Jennings (1993) calculated growth losses of at least seven years before height growth recovered to pre-burn levels in 7.5 to 9.5 year old *E. obliqua* regeneration following the total scorching or burning of the foliage. The total burning of the crown, resulting in complete stem death and regeneration from basal shoots, caused estimated growth losses of at least 11 to 13 years.

After millions of years of fire the effects of natural fire frequencies on long term site productivity are likely to be negligible.

2.5 Fire exclusion effects

The health of eucalypts during their lifetimes may in some instances be related to the periodic occurrence of fire. Ellis (1964) showed the "dieback" and death of *E. delegatensis* at Mt Maurice, Tasmania was associated with a cessation of frequent burning some 80 years previously, which has allowed the development of a dense rainforest understorey. In this instance recovery of eucalypts was observed following the removal of the understorey by felling, or felling and burning (Ellis *et al.* 1980), suggesting that allelochemical or microbiological factors were contributing to growth check. Mount (1970) postulates an hypothesis on the importance to the healthy growth of eucalypts of the removal (by fire) of plant residues or wastes.

The absence of wildfires has also been implicated in phasmatid outbreaks (Readshaw 1965; Campbell 1974) in that infrequent wildfires favour egg survival by permitting an accumulation of litter on the forest floor. In general, however, stress, including fire damage, predisposes trees to insect attack and concurrently reduces their capacity to recover from damage (Carne and Taylor 1978). For the forest manager fire without canopy scorch or stem damage seems to be a suitable compromise.

2.6 Fire and seed crops

It can be expected that very young floral primordia are at least as vulnerable as leaves to fire, and probably more so (Cremer 1962a). Any fire then that scorches the canopy can be expected to reduce part of the seed crop. It has been observed (Kimber 1978) that crown scorched trees had much lighter flowering in subsequent years.

In addition it is possible that a fire which is hot enough to scorch leaves and to kill twigs will cause death or induce dormancy amongst seeds in capsules in the crown. Cremer (1962b) estimates that a light scorch in *E. regnans* doubled seed dormancy (7% to 14%). Grose (pers. comm. cited Cremer 1962a) found that heat insufficient to discolour the leaves on slash near a fire nevertheless reduced viability of seed from 98% to 26%. However, both scorched and defoliated forests do regenerate from seed if it is present before the fire, so it is clear that sufficient can survive even greater heating than Grose describes.

2.7 Fire damage and death

Mature trees of dry sclerophyll eucalypt species with little or no butt-scarring are rarely killed by fire (Purdie and Slatyer 1976; Christensen *et al*. 1981; Incoll 1981; Bowman 1984). Branch tips and leaves are generally the most susceptible to damage. Death of these in a fire results in the production of epicormic shoots over the remaining living stem and branches. If the entire upper shoot is killed shoots are produced from lignotubers or coppice from the stump. Repeated burning may eventually enlarge fire scars to the point where the trees are destabilised (Mount 1979) and are windthrown, or are killed by associated insect attack. Bowman (1984) found that following a severe wildfire in which no crown escaped undamaged, only 6% of trees were killed, and all of the stems over 40 cm in diameter that were killed were killed by stem failure. Christensen *et al*. (1981) provide the following relationship between fire intensity and damage:

fire intensity (kWm^{-1})	
20-500	(prescribed burning range) - little physical damage to the forest as a whole with little or no crown scorch.
500-1700	small trees defoliated; branchlets of taller trees damaged; formation of isolated fire scars.
1700-3500	(moderate fire) eucalypts damaged enough to stimulate epicormics.
3500-7000	crown fires will develop in low forests; tree canopy usually defoliated over large areas.
> 7000	violent fire behaviour that will kill almost all above ground foliage and stems.

Since bark thickness increases with age and diameter growth, the relative resistance of a young tree to fire damage will depend on its age, growth rate and the height above ground of fire-susceptible thin-barked stem or branches. Peet and McCormick (1971) found that karri saplings less than 5.8 m tall were killed by low intensity fuel reduction burns of 69 to 104 kwm^{-1}. In contrast, 5 to 7 m tall *E. dives* trees showed 100% survival after total crown-burn although 50% of the height of the stem was killed (Gill 1978). Sixty percent of small lignotuberous seedlings of *E. dives, E. pauciflora* and *E. dalrympleana* survived an intense fire (Noble 1984). Wilkinson and Jennings (1993) recorded significant mortality of *E. obliqua* saplings up to 9 m in height following the complete burning of the crown. For all saplings up to 12 m in height, complete crown-burning caused the death of all stem tissue. The total burning of foliage resulted in the death of stem tissue above 2 m and the total scorching of foliage killed some stem tissue above 4 m in height.

Mature trees in wet sclerophyll forest are far more vulnerable to fire than those in dry forest. The severest fire is a crown fire in which the eucalypt canopy as well as that of the understorey is consumed in the fire. Such a fire generally kills all eucalypt trees. A less intense fire may kill the eucalypts by girdling at ground level or at the level of the understorey crown fire where bark of the eucalypts is thinner and highly sensitive to heat (Cremer 1962b). Species such as *E. obliqua and E. delegatensis* with thicker bark are more resistant to this kind of fire. The lowest intensity development of fire is a creeping humus (peat) fire. Peat fires typically have a long residence time in heavy sub-surface fuels (150 t/ha) and may severely injure or kill all eucalypts, including mature trees (Cremer 1962b). Death in such cases is due to death of the cambium in contact with the burning humus. Such fires may be far more damaging than those which consume the understorey but leave the humus intact (Cremer 1962b).

2.8 Fire and defect

When fire does not kill a tree and epicormic development is confined to the crown the effects on tree form are minimal (McKittrick and Hodgson 1969). But if the leading shoot is killed epicormics may develop along the whole length of the bole. Eventually one of these will take over and a stem kink will result (Incoll 1981). As the other epicormics are shed, gum veins may also result.

Low intensity fires which do not kill the cambium may still be sufficiently hot to damage the phloem of a tree and cause the formation of gum veins (Jacobs 1937; Nicholls 1974). Floyd (1966b) reported that defect was significantly higher in a 47 year old *E. pilularis* stand which had been burnt regularly in comparison to an adjacent unburnt stand. Results of most studies however have shown that a low intensity fire, which does not cause cambial death and butt scars, does not cause significant defect development later (Peet and McCormick 1971; Nicholls 1974; Nicholls and Cheney 1974).

Fires of higher intensity will kill areas of cambium. In such instances the bark will be shed and a fire scar formed (Gill 1974). Such an injury in itself rarely causes an appreciable loss of merchantable volume. However such damage exposes the wood to entry of fungi and insects which may subsequently cause widespread defect. Greaves *et al.* (1965) found that damage attributable directly to fire was small. Less than 5 per cent of the defect was due solely to fire; the other 95 per cent was due to the entry of fungi and insects as a result of fire. Wilkinson and Jennings (1993) found that decay was confined to the fire killed sections of stem in young *E. obliqua* regeneration seven years after the wildfire, with no evidence of decay or insect attack to live sections of stem. However, the breakdown of decay barriers followed by rapid spread of decay has been reported to occur in young trees approximately 15 years after the initial entry of decay organisms into wounds (White and Kile 1991).

When trees are killed by fire, defect develops gradually as radial cracking followed by subsequent insect damage and decay. Wright and Grose (1970) report little loss of wood if fire-killed stems are salvaged within one year of the fire, with extensive losses occurring within four to six years.

3. ECOLOGICAL MODELS OF VEGETATION, FIRE AND TIME

Two models have been proposed to indicate the ecological relationships between vegetation, fire and time in Tasmania.

Fire cycles - Mount (1966) suggests that most vegetation boundaries are determined by site factors. He postulates that the reason that most vegetation types fall into three broad fire-frequency classes is because of their three broad rates of fuel accumulation in an environment that contains sufficient ignition. These rates in turn are determined by the rates of production and decomposition of each site.

Ecological drift - Jackson (1968) relates the patterns of fire frequencies to the structure of the vegetation and the regeneration and flammability characteristics of the component species. He believes that the delicate balance between fire frequencies and vegetation can be changed by a more random probability of fire than the more stable frequencies proposed by Mount.

Jackson draws attention to a relatively high fuel period of 10 to 20 years after fire in the wetter vegetation types that otherwise have a low fire-frequency and suggests that, if a fire occurs in this period, the vegetation type may change to one with a higher fire-frequency. On the other hand, if a high fire-frequency class experiences a long fire-free period, a component of the vegetation may die out and be changed (ecological drift) to that of a lower class.

Although there are only minor differences between the two Tasmanian models the fire management implications are profound. For those who seek to maintain the vegetation types both models agree that the best way is to maintain past fire frequencies. For those who seek to maximise the area of “climax” forest, fire prohibition appears to be the way. However, if fuels continue to accumulate and past ignition patterns are maintained this is likely to lead to larger and more intense, dangerous and damaging fires than previously occurred. On the other hand if ignitions are sufficiently reduced many fire-dependent species may be at risk - including all the eucalypts.

4. EFFECTS OF FIRE ON OTHER ECOLOGICAL FACTORS

This section presents a summary of the major effects of fire on forest soils, water, vegetation, fauna and the atmosphere. The impacts of these factors on fire behaviour are also briefly discussed. The information contained in this section is largely drawn from the key reviews identified at the beginning of each summary and specific citations to individual sources have been omitted.

4.1 Soils

a) Key reviews

Raison (1979), Humphreys and Craig(1981), Flinn *et al.* (1983), Tomkins *et al.* (1991).

b) Physical properties

i) Many factors, such as fire intensity and duration, soil type, topographical position and post-fire weather interact to determine the nature of fire effects on the physical properties of soil.

ii) Surface temperatures may reach up to 800^{o}C beneath burning windrows and log piles, 400^{o}C under heavy slash and 100^{o}C under a low intensity burn. Except for beneath log piles the temperature of soil below 2cm is seldom raised above 100^{o}C.

iii) Heating of dry soils causes a greater rise in surface temperature, and more penetration of heat than heating of moist soils.

iv) Heat destroys organic matter relatively slowly below 200^{o}C but very rapidly by the time temperatures reach 400^{o}C. When surface temperatures are below 200^{o}C some non-destructive distillation of volatile substances and accelerated drying of organic colloids at shallow depths can be expected. Organic matter can also be lost from the upper profiles as a result of leaching due to removal of the vegetation cover.

v) Peat is a form of soil that has a very high organic matter content which can burn once sufficiently dry. This burning is usually by glowing rather than flaming combustion. Once started, a peat fire can sustain itself under quite wet conditions.

vi) Most other soils have up to 10% of organic matter tightly incorporated in their upper layers. Although this organic matter cannot carry even glowing combustion in the presence of so much mineral soil, it can be heated, with little or no colour change; charred black; or burnt out to leave orange mineral soil under log heaps or heavy slash fires.

vii) Fires may both induce and remove water repellency of soil. Temperatures achieved under slash fires may induce such effects within minutes, but such effects can also be equally rapidly removed. Removal of fire-induced water repellency by rain has also been reported.

viii) In soils with a clay proportion the breakdown of structure due to the oxidation of soil organic matter is to some extent counterbalanced by aggregation of the clay fraction. Since a soil profile is usually affected by fire to only a shallow depth, it is unlikely that such changes have major or long term effects.

ix) There is no evidence to suggest that fire, by itself, adversely affects the stability of soil surfaces. However if the vegetation is killed the binding effect of plant roots is reduced as they decay and the reduction in evapotranspiration leads to higher soil moisture contents. The combination of these may lead to an increased chance of landslips until regeneration is established.

c) Chemical Properties

i) Soil pH generally increases after fire due to the release of basic ash material (e.g. CaO_2) following the combustion of organic material. Such effects are usually restricted to the surface layer of soil, and the extent of change is related to fire intensity, soil type and the nature of fuels. In general if any pH change is recorded it is of the order of between 0.5 and 1 pH unit but may be more than 2 units for a hot slash burn.

ii) Low intensity fires are regarded as having little effect on soil pH.

iii) Fire-caused pH changes may act to increase soil nitrification and increase leaching losses as a result of the formation of bicarbonate ions in the elevated pH environment. However, the reduction in acidity reduces acid leaching and hence soil podsolisation.

iv) Generally there is a trend towards higher concentration of available phosphorus, potassium, calcium and magnesium in the upper layers of soil following burning.

v) A single slash burning on dolerite soils in wet eucalypt/ rainforest improves the availability of nutrients. Nutrients lost from the area as particulate ash are in quantities that will probably be replaced in rainfall within 15-20 years.

vi) Studies in subalpine dry sclerophyll forests suggest that *total* soil nitrogen lost as a result of repeated low intensity burning may not be completely replaced by rainfall or biological inputs. In general such losses are greater in vegetation types such as heath and moorlands which have very high *total* soil nitrogen contents and grow on inherently infertile sites. These losses in *total* soil nitrogen are temporary and, from a plant nutrition point of view, minor when compared with the marked increase in *available* nitrogen. It has generally been concluded that regular burning at low intensity does not affect the nitrogen status of other soils where fertility is higher and leaching problems less severe.

vii) Significant quantities of nutrients can be lost from organic matter during a fire by volatilisation and as particulate form in smoke, and through subsequent erosion and wind transport of ash. The magnitude and significance of such losses is dependent on the proportion of the site nutrient capital stored in organic matter, fire intensity and frequency, the amount of fuel consumed and the climate. Total nitrogen losses of up to 60% of that stored in organic matter have been reported to occur in slash burns. Volatilisation of other nutrients have also been reported with between 10 and 20% of phosphorus, calcium and magnesium in fuel lost to the atmosphere during burning.

viii) Whilst it is clear that nutrients stored in foliage constitute an important component of the nutrient cycle, uncertainty about rates of nutrient input and loss make generalisations on the effect of fire on site productivity difficult at this stage. However, the fossil record implies no detriment from fire in the long term (i.e. 10 million years) to the vegetation types that grow on these sites.

Frequent low intensity burning, however, may affect the understorey composition and so remove leguminous species which have the capacity to fix nitrogen. This biotic change due to fire regime may in theory have long term effects on the nutrient budget of the site. However, such theoretical conclusions are rarely supported by actual observation. Research in the jarrah forests of Western Australia indicates virtually no difference between the nutrient status of surface soils of regularly burnt forests and adjacent unburnt forests.

d) Soil effects on fire

The non-flammable nature of mineral soil is the basis of all dry fire-fighting in forests and moorlands. A firebreak that exposes mineral soil will stop a surface fire in litter or a ground fire in peat.

4.2 Water

a) Key Reviews:

Cheney (1978), Humphreys and Craig (1981), Flinn *et al*. (1983)

b) Catchment soil properties

i) Even after fires of high intensity, pore space and water transmission properties of soils are not adversely affected.

ii) Following intense fire the reduction in the leaf area of vegetation and in the depth of litter decreases the amount of interception, thereby increasing throughfall and soil moisture. Low intensity fires, because they do not remove tree crowns, have less effect on subsequent soil moisture levels.

iii) Removal of litter increases the impact of rain on the soil surface and may increase overland flow. The increased volume and velocity of runoff may increase erosion. Soil hydrophobic effects following fire may exacerbate this.

c) Streamflow

i) When the litter layer and the organic matter in the soil are burned, or when soil exposure accelerates the oxidation of organic matter, catchments become more sensitive to precipitation events due to a reduction in catchment buffering capacity.

ii) Summer baseflow increases substantially following an intense fire that burns a large proportion of a catchment, and the diurnal pattern in baseflow commonly observed in forested catchments ceases.

iii) Generally intense fire will produce a water yield increase varying from small to substantial, the variation being dependent on post-fire rainfall pattern and the rate of recovery of catchment vegetation.

iv) Low intensity fire generally has little effect on streamflow.

d) Water quality

i) The magnitude and duration of streamwater quality changes after fire depends upon the fire intensity the proportion of the catchment burnt, the post-fire rainfall pattern, soil properties and the rate of vegetation recovery.

ii) Increases in sediment load and turbidity are the most important water quality changes associated with fire. Fire affects these qualities by increasing overland flow and erosion, channel scouring due to increased streamflow, dry creep and mass erosion. Following intense fire it appears that increased sediment loads can be expected for between 18 months (if only part of the catchment is burnt) and up to at least 4 years (if the whole of the catchment is burnt). Low intensity fires appear to cause negligible changes in water quality and recovery occurs within 6 to 12 months.

iii) An increase in the concentration of various nutrients in streamwater may result from fire. The bicarbonate concentrations in soil solution may increase as oxides of magnesium, calcium and potassium in ash react with atmospheric carbon dioxide and water to form bicarbonate salts. Bicarbonate is the principal carrier of cations in the soil solution and may aid the transport of cations in overland flow. Conditions may also become more favourable for the mineralisation of soil organic matter, which may be subsequently transported in overland flow. Nutrients of particular concern in streamwater are nitrate and phosphate as increases in the concentration of these anions can cause eutrophication.

iv) The results of studies of nutrients in streamwater following fire have been varied. Although few studies report significant increases in nitrates following wildfire, some studies have reported significant increases in the concentration of phosphate. It is generally concluded that low intensity fires have little or no influence on streamwater chemical quality.

v) Moderate rises in streamwater temperature have been reported following the removal of streamside vegetation by wildfire. The effect of such a temperature rise on dissolved oxygen concentration has not been studied, although it is known that the concentration of dissolved oxygen is inversely proportional to water temperature.

vi) In general the effect of low intensity prescribed burning on streamwater quality is likely to be insignificant provided riparian vegetation remains unburnt.

vii) High intensity fire may increase organic matter deposition in overland flow. Thus potential exists for large increases in biological oxygen demand following fire, and hence of eutrophication. The likelihood of low intensity fire causing eutrophication is far less.

e) Water effects on fire

Water affects fire directly as in rain cooling and extinguishing flaming or glowing combustion. It wets the fuel and makes it more difficult to dry and heat to ignition temperatures. The water vapour produced also lowers the concentration of oxygen. This attack on all three sides of the “fire triangle” makes water the most commonly used forest fire-fighting material wherever it is readily available.

High moisture contents in dead plant material prevent both ignition and combustion. Marginal moisture contents can cause incomplete, smoky combustion with low heat output and hence low rates of spread. The moisture content of green leaves (commonly about 100% of dry weight) must be reduced to below 20% by heating before those leaves become available fuel. Where there is not enough dry fuel to burn and produce this degree of heating the green leaves will stop or inhibit the fire spreading.

Water also affects fire indirectly in that moist dead plant material decomposes more rapidly than dry material so that fuel accumulation rates and average fire frequencies are lower on moist sites than on dry - providing that they are also well drained and given a favourable temperature regime. However, on poorly drained sites decomposition is slowed by excessive soil water and insufficient aeration so that fuel accumulation rates and fire frequencies are higher than average.

At the most fundamental level without water no plants grow so there is no fuel to burn. In a drought situation, less fuel is grown but more green plants may die to become fuel. In wet summers decomposition rates are high and fuel accumulates slowly. With wet winters and dry summers there is maximum moisture for spring growth and minimum moisture for summer decomposition. It is therefore not surprising that the 5% of the world that has both a winter rainfall bias and enough of it to grow forests also has the highest forest fire frequencies. This 5% occurs around the Mediterranean, on the west coast of North America, in small parts of Chile and South Africa and throughout the southern half of Australia.

4.3 Air

a) The effects of fire on the atmosphere

One on the main products of fire is carbon dioxide - one of the “greenhouse” gasses. Plant products either burn rapidly or decompose slowly and both processes produce the same amount of carbon dioxide. Where the burn is undertaken for the establishment of vigorous new forest and the wood produced is turned into houses or other long-lasting products, a net reduction in carbon dioxide in the atmosphere may be achieved in spite of the initial peak produced by the burn. However, a net increase in atmospheric carbon dioxide will occur if forests are converted to products which decay or are burned in the short term.

The most obvious effect of fire on the atmosphere is that of smoke which is usually regarded as man-made and therefore pollution. However, fire and smoke are both natural and ancient phenomena. Along with wind-bourne dust, volcanoes and sea-spray, smoke re-charges the supply of atmospheric nutrients and provides nuclei for the formation of rain droplets. However, smoke pollution is an important issue where forests are close to rural or urban populations. Planned burning is often conducted during autumn and spring, under weather conditions when inversions are likely to occur and exacerbate problems of smoke pollution. Careful planning is necessary to prevent unacceptable impact on air quality.

The other main product of combustion is water vapour. Major fires produce thousands of tonnes of water vapour which rise with the smoke. Usually this condenses to form clouds and sometimes even rain.

b) Atmospheric effects on fire

Direct atmosphere effects on fire include the wind that carries the sparks to start spot fires, fans the flames by speeding the delivery of oxygen and the removal of carbon dioxide and water vapour, and bends the flames towards fuels on the ground and so speeds their drying and heating. Vertical atmospheric instability may substantially increase fire behaviour by stimulating the “fire wind” effect via increased convection.

Fuels dry quickly and are easy to ignite when the air is dry (low relative humidity) and warm (high temperature).

Flames and scorch are higher, suppression more difficult and damage greater on dry, hot and windy days than on cool, moist and still days. These are the vital differences that make fuel reduction burning possible.

Increases in relative humidity, decreases in temperature and rain are all atmospheric effects that depress combustion.

In the long term the atmosphere affects fire through its effects on plant growth, death and decomposition that in turn determine the rate of fuel accumulation. In the short term relative humidity and recent rain determine the ignitability and combustibility of that fuel.

4.4 Vegetation

a) Key Reviews: Neyland (1986), Duncan (1985)

b) High intensity fire effects

i) Alpine and subalpine communities are severely affected by fire. Some of the dominant shrubs (e.g. *Diselma*, *Athrotaxis* and *Nothofagus gunnii*) are easily killed and their poor seed dispersal restricts recolonisation following fire. There is no evidence that any species or community in the alpine zone requires fire to regenerate.

ii) Under extreme fire weather conditions extensive areas of rainforest have been killed by wildfire. Generally rainforest areas can be presumed to be able to recover their former structure and floristic composition following fire (see Barker 1991). However, another fire within a short time period may eliminate many rainforest species, and the community may revert to dense tall bracken, cutting grass or 'wet scrub'. The occurrence of a single fire may promote the establishment or increase in cover of more inflammable species. This may lead to the creation of more open conditions than existed before the fire, increasing the risk of a second fire for a period following the first fire. Attrition of rainforest at its margins due to successive fires has been documented.

iii) If successive wildfires occur in mixed forest, the rainforest species are likely to be eliminated for a long period of time, and replaced by dense tall bracken or cutting grass plus some sclerophyllous species.

iv) Recovery of dry sclerophyllous communities after fire is usually rapid as many of the component species are adapted to a regime of relatively frequent fires.

v) Fires of high intensity in dry sclerophyll vegetation generally results in prolific growth of woody understorey species, determined by the pre-fire composition and the soil seed bank.

vi) Following logging in dry forest, re-establishment is fastest and species composition is least altered when no burn occurs and most altered on sites subjected to prolonged high intensity burning. Generally understorey species diversity can be expected to recover within 2 years of a slash burn, although not all species may be present even 3 years after burning.

c) Low intensity fire effects

i) The ecological consequences of fuel reduction burning will be determined primarily by the extent, season frequency and intensity of the burn and the vegetation type burnt.

ii) Most fuel reduction programmes are limited to fire tolerant vegetation types, and if varied in season as much as possible, are unlikely to have serious consequences on survival of the biota.

iii) In eucalypt forests repeated low intensity burning encourages the development of an understorey which is fire promoting (e.g. bracken or cutting grass) and which is adapted to a high fire frequency. Species which recover rapidly by vegetative means dominate the understorey, while species which regenerate primarily by seed may be reduced in abundance and cover.

iv) Well managed fuel reduction burning of flammable moorlands is only carried out while the underlying peat is too wet to burn. In these conditions burning at 4 to 12 year intervals does not appear to erode the peat. However, if the interval between burns is too long excessive fuel quantities may accumulate and the upper peat layer may burn under drought conditions.

v) The principal limiting factor for the expression of pathogenicity of the root rot fungus *Phytopthora cinnamomi* in high rainfall environments is probably soil temperature. Fuel reduction burning, by reducing the foliage cover and enabling direct sunlight to warm the soil, is suspected of aiding the expression of pathogenicity of the fungus.

vi) Research in Victoria has suggested that in dry sclerophyll forest, spring fires are less favourable to herbs, particularly those with underground organs of perennation, if their foliage is removed when storage organs are depleted of reserves. Herbs and summer dormant perennials are believed to benefit from autumn fires.

vii) Consideration of the season of seed set and age of reproductive maturity is important for the survival of understorey species. Repeated or poorly timed burns may deplete soil seed banks and prevent the regeneration of some species.

d) Vegetation effects on fire

Vegetation provides the fuel for fire. Its spatial distribution interacts with fire weather and topography to determine the intensity, rate of spread, damage and difficulty of suppression of fire. Fire frequency and intensity are determined by the rate of accumulation of vegetation and the ignition source.

Different plants have different flammabilities due to differences in physical and chemical composition as well as in moisture contents. These differences occur in both the green and the dead plant. Leaves with high surface to volume ratios such as the fine grasses are more readily heated, killed and dried by fire than large-leaved plants. Oils in leaves may contribute to combustion especially in crown fires. Leaves with high mineral and nitrogen contents are relatively non-flammable when alive and decompose rapidly when dead. Those dead leaves low in nutrient and high in lignins and tannins, such as the eucalypts, provide poor substrates for insects and micro-organisms, take a long time to decompose, accumulate rapidly and are ready to burn whenever they dry out.

Trees with fibrous barks or which shed bark in long streamers have a major effect on the distribution of fire. They provide a fuel link from the ground to the tree canopy, sparks for short-distance mass spotfire and tubes of flame for long-distance ones.

4.5 Fauna

a) Key Reviews:

Campbell and Tanton (1981), Catling and Newsome (1981), Suckling and Macfarlane (1983), Michaelis (1984), Neyland (1986), Taylor (1991)

b) Invertebrates

i) Most studies of invertebrates have found that a single fire, even of low intensity, will lead to a reduction in the density of all major invertebrate groups. However, recovery is usually rapid to near pre-burn levels. The cooler and more patchy the burn the less the impact is likely to be on soil and litter fauna. Fauna in deep layers of the soil are less affected by fire than those in the surface soil. Up to 90% of the invertebrates in the litter layer can be killed by fire.

ii) Beside their direct effects fires also affect invertebrate populations by changing light, temperature and soil moisture levels.

iii) The invertebrate orders least affected by fire show high mobility or adaptations to conserve water and resist high ambient temperatures and seasonally dry habitats.

iv) Post-fire recovery will depend on the initial community structure, the intensity of the fire, the percentage of the area burnt and the season of burning. Most species seem to be represented in post-fire communities. However, changes to ambient conditions result in changes in relative abundance and community structure. Recovery of populations from intense

fire is usually slower than from low intensity fire, because the former leaves fewer and smaller refuges from which recolonisation can take place, and because its impact on conditions under the canopy are likely to be more severe.

v) Most fire effects are removed within a couple of years although in some instances it has been shown that populations may remain depleted for up to 5-7 years following burning. Whilst statements of this kind are relevant to broad groups, the rates of recovery of particular species or functional groups remains unclear. Long term changes in the composition and development of the litter layer will delay the recovery of some groups This may partly account for slower rates of decomposition in litter following burning than in undisturbed litter.

vi) Studies have shown that invertebrate numbers recover following prescribed burning. However, data on the long term effect of repeated fuel reduction burning are not available.

vii) The charring of logs in particular may be detrimental. Logs in middle to late stages of decay support a highly endemic invertebrate fauna, but once burnt their habitat value is reduced. Fuel reduction burning will have less severe effects in this regard if it is undertaken when soils or rotten logs are too wet for the logs to burn.

viii) Whilst most soil bacteria and fungi are resistant to fire, particularly if the soil is dry, soil nitrifying bacteria are less resistant, and even relatively low intensity fires may cause reductions in populations.

ix) It is generally considered that the season of burning modifies fire effects. Variation in seasonal effects is likely to be associated with activity and ability to escape fire, ability to rapidly reproduce, timing in relation to predator activity and timing of breeding.

c) Aquatic Fauna

i) Fires may affect aquatic fauna by increasing water yields, organic sediment and nutrient inputs into streams and increasing water temperature as a result of the loss of streambank vegetation. Such effects are likely to be greatly influenced by the pattern of post-fire rainfall and the proportion of the catchment burnt. Generally the effects of fire on aquatic fauna remains unspecified.

ii) In Tasmania the retention of riparian vegetation either side of a recognised stream helps to minimise changes in the fauna of streams occurs following logging (Forest Practices Code 1993). Fire intrusions into riparian strips may be presumed to produce similar, though less pronounced, effects.

d) Reptiles and amphibians

i) Very little is known about the effects of given fire regimes on these groups.

ii) Reptiles and amphibians seem to be able to survive even quite intense fires by sheltering in refuges.

iii) Although initial survival may be high, so may subsequent mortality due to lack of food and shelter.

iv) Successional changes associated with changes in habitat following fire may occur.

e) Birds

i) Few birds perish in low intensity fires in sclerophyll forest but subsequent mortality due to starvation and predation can be high.

ii) High intensity fires accompanied by fire storms can result in substantial initial mortality, with even strong fliers, such as goshawks, killed by heat and suffocation. Survivors of high intensity fire are generally those individuals living in moist habitats.

iii) Changes to vegetation structure following fire may have long term implications on bird diversity. Such effects will vary between taxa, being related to food and shelter requirements.

iv) Because of the importance of habitat, recovery of bird populations is more rapid following low intensity fire than high intensity fire.

v) In shrubby understorey forest the absence of fire leads to a decline in the total number of individual birds (but not species) in the lower strata as the forest ages.

vi) It is unlikely that fires of even low intensity in early spring, the time of peak nesting, have the potential to disrupt reproduction of birds.

vii) Response of birds to understorey fires are variable. Some species require periodic burning of vegetation to maintain suitable habitat, whilst others can not survive frequent understorey fires and are restricted to older stands.

viii) Whilst a single fire may not be particularly disruptive to birds in general, a succession of fires at frequent intervals may have long term implications because of changes to the nature of the understorey vegetation itself. A multi-layered understorey can become converted to a single layer open understorey with reduced bird diversity.

f) Mammals

i) Most native mammals can survive low intensity fires either by moving to escape the advancing fire edge or by sheltering. There may be considerable mortality of some species after low intensity fire due to predation.

ii) High intensity fires directly kill many individual mammals. Predation of small mammals following intense fire may be significant.

iii) Wildfire does not generally eliminate any species of mammal from a region.

iv) The long term effects of fire intensity are complex, affecting mammal populations by interactions with habitat composition and variability, age class structure and the plant species abundance.

v) Mammals respond in various ways to fire, depending on their preferred habitats and their food requirements. No single fire regime will encourage maximum populations of all mammal species of an ecosystem.

vi) The speed of return of species after fire may be a function of diet and cover requirements.

vii) Fire undoubtedly aids the development of hollows, important for nesting, in eucalypts. It has been suggested that intense fires may reduce the availability of log material for shelter, however this may be rapidly remedied by windthrow of weakened trees.

viii) Timing of fire in relation to breeding is probably important and is likely to vary from species to species, but little information is available .

ix) Arboreal mammals are probably not affected by low intensity fuel reduction burning as the canopy is little affected. However, mammals which utilise both canopy and understorey habitat (such as the pygmy possum) may be affected.

g) Fauna effects on fire

Fauna affect the quantity and distribution of fuels. Heavy grazing by domestic stock in particular has a substantial effect on the type and rate of fuel accumulation.

With native fauna and fuels the effect is more subtle. Where moisture and nutrients are not limiting, micro-organisms, invertebrates and their predators are actively contributing to the breakdown of dead plant material and reducing the fuel accumulation rate. Such sites also have better growth and produce more dead plant material than drier and poorer sites. However, they accumulate fuels at a slower rate because the rate of decomposition more nearly equals that of growth. The result is that fires are either less frequent or less intense on wet sites than on dry, infertile ones.

REFERENCES

Abbott, I. and Loneragon, O. (1983) Influence of fire on growth rate, mortality and butt damage in Mediterranean forest of Western Australia. *For. Ecol. Management* 6: 139-153.

Ashton, D.H. (1955) Some problems concerning the regeneration of mountain ash in Victoria. Paper presented to Section 161, ANZAAS Conference, Melbourne.

Ashton, D.H. (1956) Studies on the autoecology of *Eucalyptus regnans* Ph.D. thesis. University of Melbourne.

Ashton, D.H. (1962) Some aspects of root competition in *E. regnans* Paper presented at 3rd Gen. Conf. Inst. Foresters Aust., Melbourne.

Ashton, D.H. (1975) Studies of flowering behaviour in *Eucalyptus regnans* F. Muell. *Aust. J. Bot*. 23: 413-433.

Ashton, D.H. (1976) The development of even-aged stands in *Eucalyptus regnans* F.Muell in central Victoria. *Aust. J. Bot*. 24: 397-414.

Ashton, D.H. (1979) Seed harvesting in central Victoria. *Aust. J. Ecol*. 4: 265-277.

Ashton, D.H. (1981) Fire in tall open-forests (wet sclerophyll forests) Chapter 14 339-363 In: A.M. Gill, R.H. Grove, and I.R. Noble (eds.) *Fire and the Australian Biota.* Aust. Acad. of Sci. Canberra Aust. 1988.

Ashton, D.H. and Frankenburg, J. (1976) Ecological studies of *Acmena smithii* (Poir) Merrill and Perry with special reference to Wilson's Promontory. *Aust. J. Bot.* 24: 453-458.

Ashton, D.H. and MacCauley, B.J. (1972) Winter leaf spot disease of seedlings of *Eucalyptus regnans* and its relation to forest litter. *Trans. Br. Myc. Soc.* 58: 377-386.

Ashton, D.H. and Willis, E.J. (1982) Antagonisms in the regeneration of *Eucalyptus regnans* in the native forest. In E.I. Newman (ed.) *The plant community as a working mechanism. British Ecological Society Special Publication, No. 1* 113-128.

Attiwill, P.M. (1962) The effects of heat pre-treatment of soil on the growth of *E. obliqua* seedlings. Paper presented at 3rd Gen. Conf. Inst. Foresters Aust., Melbourne.

Barker, M.J. (1991) The Effect of Fire on West Coast Lowland Rainforest, Tasmanian NRCP Report No. 7, Forestry Commission, Tasmania and Department of the Arts, Sport, the Environment, Tourism and the Territories, Canberra.

Battaglia, M. and Wilson, L.P. (1990) Effects of shelterwoods on stocking and growth of regeneration in dry high altitude *Eucalyptus delegatensis* forests. *Aust. For*. 53 : 259-265.

Beadle, N.C. (1966) Soil phosphate and its role in moulding segments of the Australian flora and vegetation, with special reference to xeromorphy and sclerophyll. *Ecology* 47: 992-1007.

Beck, J.A. (1993) A preliminary study of fire behaviour and effects in the dry sclerophyll regrowth forests of Tasmania. Unpub. Rep. Forestry Commission, Tasmania.

Bowman, D.M.J.S. (1984) The Ecology and Silviculture of *Eucalyptus delegatensis* R.T Barker on Dolerite in Tasmania Ph.D. Thesis, University of Tasmania, Hobart 1984.

Bowman, D.M.J.S., Maclean, A.R. and Crowden, P.K. (1986) Vegetation - soil relations in the lowlands of southwest Tasmania. *Aust. J. Ecol.* 11: 141-153.

Bowman, D.M.J.S. and Kirkpatrick, J. (1986) Establishment, suppression and growth of *Eucalyptus delegatensis*. Part 3. Intra specific alleopathy, competition between adult and juvenile for moisture and nutrient and frost damage to seedlings. *Aust. J. Bot*. 34: 81-94.

Brown, M.J. and Podger, F.D. (1982a) On the apparent anomaly between observed and predicted vegetation types in South-west Tasmania. *Aust. J. Ecol.* 7: 203-205.

Brown, M.J. and Podger, F.D. (1982b) Floristics and fire regimes of a vegetation sequence from sedgeland heath to rainforest at Bathurst Harbour, Tasmania. *Aust. J. Bot*. 30: 659-676.

Bryant, W.G. (1971) Grazing, burning and regeneration of tree seedlings in *Eucalyptus pauciflora* woodlands. *Journ. of Soil Con. Service of N.S.W.* 27: 121-134.

Byrne, P.J. (1977) Prescribed burning in Australia; the state of the art. Paper presented to 5th Meeting of Australian Forestry Council Research Working Group No. 6 Melbourne.

Campbell, R.G. (1974) Factors limiting the distribution and abundance of the three species of phasmatid (Phasmatidea : Phasmatidae) which occur in plague numbers in forests of south-eastern Australia. *J. Ent. Soc. Aust. (N.S.W.)* 8: 3-6.

Campbell, A.J. and Tanton, M.T.. (1981) Effects of fire on the invertebrate fauna of soil and litter of a eucalypt forest Ch 10. In: A.M Gill, R.H. Groves and I.R. Noble (eds.) *Fire and the Australian Biota.* Aust. Acad. Sci., Canberra 243-272.

Campbell, R.G. and Bray, P.C. (1987) Regeneration of Mountain Ash following clearfelling of a regrowth stand. Research Paper No. 327, Dept. C.F.L. Vic. (unpub).

Catling, P.C. and Newsome, A.E. (1981) Response of the Australian vertebrate fauna to fire: an evolutionary approach. Ch 12: In A.M Gill, R.H. Groves and I.R. Noble (eds.) *Fire and the Australian Biota.* Aust. Acad. Sci. Canberra 243-272.

Chattaway, M.M. (1958) Bud development and lignotuber formation in eucalypts. *Aust. J. Bot.* 6: 103-115.

Cheney, N.P. (1978) Guidelines for fire management on forested watersheds, based on Australian experience. FAO Conservation guide No. 4. Special Readings in Conservation Series 1978.

Christensen, P.E. (1971) Stimulation of seedfall in karri. *Aust. For*. 35: 182-190.

Christensen, P.E. and Schuster, C.J. (1979) Some factors affecting the germination of karri (*Eucalyptus diversicolour*)seed. West Aust. For. Dep. Res. Pap. No. 50.

Christensen, P.E., Recher, H.F. and Hoare, J. (1981) Responses of open forests (dry sclerophyll forests to fire regimes. In: A.M. Cull, R.H. Groves and I.R. Noble (eds.). *Fire and the Australian Biota.* Aust. Acad. Sci. Canberra 367-394.

Cosgrove, R. (1989) Thirty thousand years of human colonization in Tasmania - new Pleistocene dates. *Science* 243: 1706-1708.

Carne, P.B. and Taylor, K.L. (1978) Insect Pests. In: W.E. Hillis and A.G. Brown (eds.) *Eucalypts for wood production.* CSIRO Australia.

Cremer, K.W. (1960) Problems of eucalypt regeneration in the Florentine Valley. *Appita* 14: 71-78.

Cremer, K.W. (1962a) The effect of fire in eucalypts reserved for seeding. *Aust. For*. 26: 129-154.

Cremer, K.W. (1962b) Studies on the problem of regeneration of *Eucalypts regnans* in Tasmania. Report on the work done under ANM Forestry Research Fellowship.

Cremer, K.W. (1962c) The effects of burnt soil on the growth rate of Eucalypt seedlings. *Institute For. Aust. Newsletter* 3(3): 2-6.

Cremer, K.W. (1965) Effects of fire in seed shed from *Eucalyptus regnans*. *Aust. For*. 29: 252-262.

Cremer, K.W. and Mount, A.B. (1965) Early stages of plant succession following complete felling and burning of *Eucalyptus regnans* forest in the Florentine Valley, Tasmania. *Aust. J. Bot*. 13: 303-327.

Cremer, K.W., Cromer, R.N. and Florence, R.G. (1978) Stand establishment Ch 4. In: W.E. Hills and A.G. Brown (eds.) *Eucalypts for wood production* CSIRO Australia.

Cromer, R.N. (1967) Significance of the "ashbed effect" in *Pinus radiata* plantations. *Appita* 20(4): 104-112.

Cunningham, T.M. (1960) The natural regeneration of *Eucalyptus regnans*. Sch. For. Univ. Melbourne, Bull. No. 1.

Cunningham, T.M. and Cremer, K.W. (1965) Control of the understorey in wet eucalypt forests. *Aust. For*. 29: 4-14.

Curtin, R.N. (1966) The effects of fire on tree health and growth. For. Comm N.S.W. Tech Pap. No. 13.

del Moral, R. and Muller, C.H. (1969) Fog drip : a mechanism of toxin transport from *Eucalyptus globulus*. *Bulletin of the Torrey Botanical Club* 96: 417-475.

del Moral, R. and Muller, C.H. (1970) The allopathic effects of *Eucalyptus camaldulensis* . *The American Midland Naturalist* 83: 254-282.

del Moral, R., Willis, R.J. and Ashton, D.H. (1978) Suppression of coastal vegetation by *Eucalyptus baxteri*. *Aust. J. Bot*. 26: 203-219.

De Bano, L.F. and Rice, R.M. (1973) Water repellent soils : their implications in forestry. *J. For*. 71: 220-223.

Dexter, B.D. (1967) Flooding and regeneration of river red gum, *Eucalyptus camaldulensis*. For. Comm. Vic. Bull. No. 20, 35 pp.

Dickinson, K.J.M. (1985) Vegetation and fuel dynamics following clearfelling of dry eucalypt forests on dolerite in south eastern Tasmania with special reference to the use of fire in forest regeneration. Ph.D. Thesis, Univ. of Tas.

Dickinson, K.J.M and Kirkpatrick, J.B. (1985) The flammability and energy content of some important plant species and fuel components in the forests of south-eastern Tasmania. *J. Biology* 12: 121-134.

Dobzhansky, J. (1956) What is an adaptive trait? *Amer. Natur*. 90: 337-347.

Doman, E.R. (1968) Prescribed burning and brush type conversion in California National Forests. *Proc. Tall Timbers Fire Ecol. Conf*. 7: 225-233.

Duncan, F. (1985) Tasmanian Vegetation and its response to forest operations. Working paper No,. 6. Environmental Impact Statement on Tasmanian Woodchip Exports Beyond 1988, Forestry Commission, Tasmania.

Duncan F. and Brown M.J. (1985) Dry Sclerophyll vegetation on Tasmania : extent and conservation status of the communities. Wildlife Division Technical Report 85/1. N.P.W.S. Tasmania.

Elliott, H.J and Bashford, R. (1984) Incidence and effect of the dampwood termite, *Porotermes adamsoni*, in two Tasmanian east coast forests. *Aust. For*. 47: 11-15.

Ellis, R.C. (1964) Dieback of alpine ash in north-eastern Tasmania. *Aust. For*. 28: 75-90.

Ellis, R.C., Mount, A.B. and Mattay, J.P. (1980) Recovery of Eu*calyptus delegatensis* from high altitude dieback after felling and burning the understorey. *Aust. For*. 43: 29-35.

Ellis, R.C. and Thomas, I. (1988) Pre-settlement and post settlement vegetational change and probable Aboriginal influences in a highland forested area in Tasmania. In: K.J. Frawley and N. Semple (eds.) *Australia's ever changing Forests. Proc. 1st Nat. Conf. on Aust. Forest History*, 9-11 May 1988 pp 199-216.

Ellis, R.C. (1984) Aboriginal influences on vegetation in the north-east highlands. *Tas. Nat*. 76: 7-8.

Ellis, R.C. (1985) The relationship among eucalypt forest, grasslands and rainforest in a highland area in north-east Tasmania. *Aust. J. Ecol*. 10: 297-314.

Fagg, P. (1981) Regeneration of high elevation mixed species eucalypt forests in east Gippsland. FCV Res Branch Report No. 175, 75 pp (unpub).

Felton, K.C. and Cunningham, T.M. (1971) Woodchip exports and pulpwood forestry in Eastern Tasmania. Paper presented 6th IFA Conference, Thredbo.

Flinn,D.W., Farrel, P.W., Stewart, H.T.L, Leitch, C.J. and Hopmans, P. (1983) The effects of fire in eucalypt forests on soils, nutrient cycling, tree growth and catchment hydrology: a review with particular reference to fuel reduction burning. pp129-146 In: E.H.M. Ealey (ed.). *Fighting Fire with Fire: proceedings of symposium on fuel reduction burning*. Monash University September 17-18, 1983.

Florence, R.G. and Crocker, R.C. (1962) Analysis of blackbutt *Eucalyptus pilularis* Sm seedling growth on blackbutt forest soil. *Ecology* 43: 670-679.

Florence, R.G. (1964) Edaphic control of vegetational pattern in east coast forests. *Proc. Linn. Soc. N.S.W*. 89: 171-190.

Floyd, A.G. (1962) Investigation into the natural regeneration of blackbutt - *E. pilularis*. For. Comm. N.S.W. Res. Note 10, 32 pp.

Floyd, A.G. (1966a) Effect of fire upon weed seeds in wet sclerophyll forests of northern New South Wales. *Aust. J. Bot*. 14: 233-256.

Floyd, A.G. (1966b) The effects of control burning on forests. For. Comm. N.S.W. Tech. Pap. No. 13.

Forestry Commission (1992) Fire Management Manual, Forestry Commission, Tasmania.

Forestry Commission (1993) Forest Practices Code, Forestry Commission, Tasmania.

Frankcombe, D.W. (1966) The regeneration burn. *Appita* 19: 127-132.

Galbraith, A.V. (1937) Mountain Ash (*Eucalyptus regnans* T.V.M.) a general treatise on its silviculture, management and utilization. Govt. Printer, Melbourne.

Gilbert, J.M. (1958) Eucalypt-rainforest relationships and the regeneration of the eucalypts. Rep. ANM For. Fellowship 1955-58.

Gilbert, J.M. (1959) Forest succession in the Florentine Valley, Tasmania. *Pap. Proc. Roy. Soc. Tas*. 93: 129-151.

Gilbert, J.M. (1961) The effects of browsing by native animals on the establishment of seedlings of *Eucalyptus regnans* in the Florentine Valley, Tasmania. *Aust. For*. 25: 116-121.

Gilbert, J.M. (1963) Fire as a factor in the development of vegetational types. *Aust. For*. 27: 67-70.

Gilbert, J.M. and Cunningham, T.M. (1972) Regeneration of harvested forests. State forests in Tasmania. *Appita* 26: 43-46.

Gill, A.M. (1974) Toward an understanding of fire scar formation : field observation and laboratory simulation. *For. Sci.* 20: 198-205.

Gill, A.M. (1978) Crown recovery of *Eucalyptus dives* following wildfire. *Aust. For*. 41: 207-214.

Gill, A.M. (1981) Adaptive responses of Australian vascular plant species to fire. In: A.M Gill, R.H. Groves and I.R. Noble (eds.) *Fire and the Australian Biota*. Aust. Acad. Sci. Canberra pp 243-272.

Gill, A.M and Ashton, D.H. (1968) The role of the bark type in relative tolerance to fire in three central Victorian eucalypts. *Aust. J. Bot*. 16: 491-498.

Gill, A. M. and Ashton, D.H. (1971) The vegetation and the environment of a multi-aged eucalypt forest near Virglake West, Victoria, Australia. *Proc. Roy. Soc. of Vic*. 84: 159-172.

Greaves, T., McInnes, R.S. and Dowse, J.E. (1965) Timber losses caused by termites, decay and fire in alpine forest in N.S.W. *Aust. For*. 29: 161-174.

Goede, A. and Murray, P. (1977) Pleistocene man in southern central Tasmania : evidence from a cave site in the Florentine Valley. *Mankind* 11: 2-10.

Grano, C.X. (1970) Eradicating understorey hardwoods by repeated prescribed burning. *USDA For. Serv. Res. Pap. SO-6.*

Grose, R.J. (1957) A study of some factors associated with the natural regeneration of *Eucalyptus delegatensis* For. Com. Vic. Bull. No. 4.

Grose, R.J. (1960) Effective seed supply for the natural regeneration of *Eucalyptus delegatensis*, R.T Barker syn. *Eucalyptus gigaitea* Hook.f. *Appita* 13: 141-147.

Grose, R.J. (1963) Silviculture of *Eucalyptus delegatensis*. Pt. 1 Germination and seed dormancy. Sch. For. Univ. Melb. Bull. No. 2.

Hatch, A.B. (1959) The effects of frequent burning on the jarrah (*Eucalyptus marginata*) forests soils of Western Australia. *J. Roy. Soc. W. Aust.* 42: 97-100.

Hatch, A.B. (1960) Ashbed effects in Western Australia forest soils. For. Dept. West Aust. Bull. No. 64.

Hope, G.S. (in press) Quaternary vegetation. In: R.S. Hill (ed.) *Australian Vegetation History, Cretaceous to Recent*, Cambridge University Press, Cambridge.

Howard, T.M. (1973) Studies in the ecology of No*thofagus cunninghamii* Oerst.I. Natural regeneration on the Mt. Donna Buang massif, Victoria. *Aust. J. Bot*. 21: 67-78.

Henry, N.B. and Florence, R.G. (1966) Establishment and regeneration in spotted gum - ironbark forests. *Aust. For*. 30: 304-316.

Humphreys, F.R. and Lambert, M.J. (1965) An examination of a forest site which has exhibited an ash-bed effect. *Aust. J. Soil Res.* 3: 81-94.

Humphreys, F.R. and Craig, F.C. (1981) Effects of fire on soil chemical, structural and hydrological properties. Ch 8. In: A.M Gill, R.H. Groves and I.R. Noble (eds.) *Fire and the Australian Biota.* Aust. Acad. Sci. Canberra pp 243-272.

Incoll, W.D. (1979) Effect of overwood trees on growth of young stands of *Eucalyptus sieberi*. *Aust. For*. 42: 110-116.

Incoll, W.D. (1981) Effects of wildfire on survival, growth and defect in *Eucalyptus obliqua* and *Eucalyptus sieberi* forests. F.C.V. research branch report No. 180.

Ingles, A. (1985) Fire. Working Paper 2. Environmental Impact Statement of Tasmanian Woodchip Exports beyond 1988. Forestry Commission, Tasmania 44 pp.

Jackson, W.D. (1968) Fire, air, water and earth : An elemental ecology of Tasmania. *Proc. Ecol. Soc. Aust*. 3: 9-16.

Jackson, W.D. (1981) Fire patterned vegetation. In: W.D. Jackson (ed.) *The vegetation of Tasmania*. Univ. of Tas., Hobart, pp 17-35.

Jacobs, M.R. (1937) Field studies on the gum veins of the eucalypts. *Comm. For. Timb. Bur. Bull.* 20: 36 pp.

Jacobs, M.R. (1955) *Growth Habits of the Eucalypts.* Comm. Aust. For. Timb. Bureau, Canberra.

Kemp, E.M. (1981) Pre-Quaternary fire in Australia. In: A.M Gill, R.H. Groves and I.R. Noble (eds.) *Fire and the Australian Biota.* Aust. Acad. Sci. Canberra, pp 3-22.

Kershaw, A.P., Martin, H.A. and McEwen-Mason, J.R.C. (in press). The Neogene - A period of transition. In: R.S. Hill (ed) *Australian Vegetation History*. *Cretaceous to Recent*, Cambridge University Press, Cambridge.

Kellas, T.D., Owen, J.V. and Squire, R.O. (1982) Response of Euca*lyptus sideroxylon* to release from competition in an irregular stand. For. Comm. Vic. *For Tech. Pap.* 29: 33-36.

Kellas, T.D., Edgar, J.G. and Squire, R.O. (1987) Response of messmate stringybark regrowth to release in irregular stands of mixed eucalypts. *Aust. For*. 50: 253-259.

Kiernan, K., Jones, R. and Ranson, D. (1983) New evidence from Fraser cave for glacial age man in south-west Tasmania. *Nature* 301: 28-31.

Kimber, P. (1978) Increased girth associated with crown scorch in jarrah. W. Aust. For. Dept. Res. Pap. No. 37.

King, N.K. and Vines, R.G. (1969) Variation in the flammability of the leaves of some Australian forest species. CSIRO Div. App. and Chem. Rep.

Kyall, A.J. and Gimmingham, C.H. (1965) Vegetative regeneration of Calluna v*ulgaris* after fire. *J. Ecol*. 53: 729-734.

Ladiges, P.Y. and Ashton, D.H. (1974) Variation in some central Victoria populations of *Eucalyptus viminalis* Labill. *Aust. J. Bot*. 22: 81-102.

Leigh, J.H. and Holgate, M.D. (1979) The responses of the understorey of forests and woodlands of the Southern Tablelands to grazing and burning. *Aust. J. Ecol*. 4: 25-45.

Lockett, E.J. and Candy, S.G. (1984) Growth of eucalypt regeneration established with and without slash burns in Tasmania. *Aust. For.* 47: 119-125.

Loneragon, O.W. and Loneragon, J.F. (1964) Ash-bed and nutrients in the growth of seedlings of karri (*Eucalyptus diversicolor* F. Muell.). *J. Roy. Soc. West. Aust*. 47: 75-80.

McArthur, A.G. (1967) The influence of fire on the productivity of hardwood forests in Australia. *Aust. For. Res*. 3: 24-35.

McArthur, A.G. (1968) The fire resistance of eucalypts. *Proc. Ecol. Soc. Aust.* 37: 83-90.

McKittrick, D.J. and Hodgson, A. (1969) Fires in mixed species eucalypts. *F.C.V. Research Activity* 69: 47-48.

Macphail, M.K. (1980) Regeneration process in Tasmanian forests : A long term perspective based on pollen analysis. *Search* 11: 184-190.

Macphail, M.K. (1981) A history of fire in the forest. In: J.B. Kirkpatrick (ed.) *Fire and Forest Management in Tasmania*. Tas. Cons. Trust, Hobart, pp 15-22.

Macphail, M.K. (1984) Small scale dymanics in an early Holocene wet sclerophyll forest in Tasmania. *New Phytol*. 96: 131-147.

Marks, G.G. and Kassaby, F.G. (1974) Pathogenicity of *Pythium* spp. and *Phytophthora direchsleri* and *Eucalyptus* spp. *Aust. J. Bot*. 22: 661-668.

Martin, R.E. (1963) A basic approach to fire injury of tree stems. *Proc. Tall Timbers Fire Ecol. Conf*. 2: 151-162.

May, F.E. and Ash, J.E. (1990) An assessment of the alleopathic potential of Eucalyptus. *Aust. J. Bot*. 38: 245-254.

Mollison, B.C. (1960) Progress report on the ecology and control of marsupials in the Florentine Valley. *Appita* 14: 21-27.

Mount, A.B. (1964) The interdependence of the eucalypts and forest fires in southern Australia. *Aust. For*. 28: 166-172.

Mount, A.B. (1966) Three studies in forest ecology. M.Sc. thesis. Univ. of Tas.

Mount, A.B. (1970) Eucalypt ecology as related to fire. *Proc. Tall Timbers Fire Ecol. Conf.* 75-108.

Mount, A.B. (1976) Some problems associated with small coupes. *Search* 7: 462.

Mount, A.B. (1979) Natural regeneration processes in Tasmanian Forest. *Search* 10: 180-186.

Michaelis, F.B. (1984) Aquatic Flora and Fauna in Tasmanian Forests: Possible Effects of Forest Operations. (Unpublished) Report to the Forest Ecology Research Fund.

Naveh, Z. (1974) The ecology of fire in Israel. *Proc. Tall Timbers Fire Ecol. Conf*. 13: 131-170.

Needham, R.H. (1960) Problems associated with the regeneration of *Eucalyptus gigantea* in the Surrey Hills area. *Appita* 13: 131-140.

Neilsen, W.A. (1990) Plantation Handbook, Forestry Commission, Tasmania.

Neyland, M. (1986) Fire Ecology in Western Tasmania. A review of the literature. *Wildlife Division Tech Report 86/5 NPWS Tasmania.*

Nicholls, J.W.P. (1974) Effects of prescribed burning in a forest on wood characteristics of jarrah. *Aust. For.* 36: 178-189.

Nicholls, J.W.P. and Cheney, N.P. (1974) Effects of experimental and wild fires in pine plantations on wood characteristics. *Aust. For.* 36: 164-177.

Noble, I.R. (1984) Mortality of lignotuberous seedlings of *Eucalyptus* species after an intense fire in montane forest. *Aust. J. Ecol.* 9: 47-50.

Noble, I.R. (1986) Fire. Ch. V2 In: H.R. Wallace (ed.) *The ecology of the forests and woodlands of South Australia. Handbook of the flora and fauna of South Australia.* Govt. Printer Sth Aust.

Opie, J.E. (1968) Predictability of individual tree growth using various definitions of competing basal area. *For. Sci.* 14: 314-323.

Orme, R.K. (1971) Regeneration of eucalypt forests, Surrey Hills, Tasmania. Univ. of Tas., Hobart. M.Sc. Thesis.

Packham, D.R. (1971) Heat transfer above a small ground fire. *Aust. For. Res.* 5: 19-24.

Priestley, C.H.B (1959) Heat conduction and temperature profiles in air and soil. *J. Aust. Inst. Agric. Sci.* 25: 94-107.

Peet, G.B. (1971) Litter accumulation in jarrah and karri forests. *Aust. For.* 35: 258-262.

Peet, G.B. and McCormick, J. (1971) Short term responses from controlled burning and intense fires in the forests of Western Australia. For. Dept. W. Aust. Bull. No. 79.

Podger, F.D., Bird, T. and Brown, M.J. (1988) Human activity, fire and change in the forest at Hogsback Plain, Southern Tasmania. In : K.J. Frawley and N.M. Temple (eds.) *Australia's ever changing forests*. Proc. of the first national conference on Australian Forest History, Canberra, 9-11 May 1988, pp 119-142.

Pryor, L.D. (1960) The 'ash-bed' effect in eucalypt ecology. *I.F.A. Newsletter* 2(9): 23-26.

Pryor, L.D. (1963) Ashbed growth response as a key to plantation establishment in poor sites. *Aust. For.* 27: 48-51.

Pryor, L.D. and Johnson, L.A.S. (1971) *A classification of the eucalypts*. Aust. Nat. Univ. Press, Canberra.

Purdie, R.W. and Slatyer, R.O. (1976) Vegetation succession after fire in schlerophyll woodland communities in south-eastern Australia. *Aust. J. Ecol.* 1: 223-236.

Raison, R.J. (1979) Modification of the soil environment by vegetation fires, with particular reference to nitrogen transformations: a review. *Plant and Soil* 51: 73-108.

Readshaw, J.L. (1965) A theory of phasmatid outbreak release. *Aust. J. Zool.* 13: 475-490.

Renbus, M.A. (1968) Microbial and nutrient changes associated with the 'ash-bed' effect. M.Sc. thesis ANU.

Renbus, M.A., Chilvey, G.A. and Pryor, L.D. (1973) Microbiology of an ashbed. *Proc. Linn. Soc. N.S.W.* 97: 302-311.

Reifsynder, W.E., Harrington, L.P., and Spalt, V.W. (1967) The microphysical properties of bark of short leaf, long leaf and red pine. Yale Univ. Sch. For. Bull. No. 70.

Shea, S.R., Peet, G.B. and Cheney, N.B. (1981) The role of fire in forest management. In: A.M. Gill, R.H. Groves, and I.R. Noble (eds.) *Fire and the Australian Biota*. Aust. Ac. Sci. Canberra.

Singh, G., Kershaw, A.P. and Clark, R.C. (1981) Quaternary vegetation and fire history in Australia. In: A.M. Gill, R.H. Groves and I.R. Noble (eds.) *Fire and the Australia Biota.* Aust. Acad. Sci. Canberra .

Schuster, C.T. (1980) Regeneration in a jarrah (*Eucalyptus marginata* Sm.) and marri (*Eucalyptus calophylla* R.Br.) forest following logging and burning. For. Dept. West Aust. Res. Rep. Pap. No. 64

Stone, E.L. and Cornwall, S.M. (1968) Basal bud burl in Betula populifolia. *For. Sci*. 14: 64-65.

Suckling,G.C. and Macfarlane, M.A. (1983) The effects of fire on fauna - a review. In: E.H.M. Ealey (ed.) *Fighting Fire with Fire: proceedings of symposium on fuel reduction burning.* Monash University September 17-18.

Taylor, R.J. (1991) Fauna Conservation in Production Forest in Tasmania. Forestry Commission, Tasmania.

Tomkins, I.B., Kellas, J.D., Tolhurst, K.G. and Oswin, D.A. (1991) Effects of Fire Intensity on Soil Chemistry in a Eucalypt Forest. *Aust. J. Soil Res*. 29: 25-47.

Vines, R.G. (1968) Heat transfer through bark and the resistance of trees to fire. *Aust. J. Bot*. 16: 499-514.

Wallace, W.R. (1965) Fire in the jarrah forest environment. *J. Roy. Soc. W. Aust.* 49: 33-44.

Webb, R.N. (1966a) The protection of eucalypt seed from fire by their capsules. B.Sc Hon. Thesis Univ. Melb.

Webb, A.W. (1966b) The effects of thinning on growth of mountain ash (*Eucalyptus regnans* F.V.M.) in Victoria. M.Sc. For. Thesis. Univ. Melb.

Wilkinson, G.R. and Jennings, S.M. (1993) Survival and recovery of *Eucalyptus obliqua* regeneration following wildlife. *Tasforests* Vol. 5.

Willis, R.J. and Ashton, D.H. (1978) The possible role of soil lipids in the regeneration problem of *Eucalyptus regnans* F. Muell. In: *Open Forum on Ecological Research*. Ecol. Soc. Aust. Inc. Macquarie University, May 15-18.

Wright, J.P. and Grose, R.J. (1970) Wood degrade due to fire. *Aust. For*. 34: 149-166.

White, D.A. and Kile, G.A. (1991) Thinning damage and defect in regrowth eucalyptus. In: C.M. Kerruish and W.H.M. Rawling (eds.) *The Young Eucalypt Report*, CSIRO, Australia, pp 152-77.