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Fuel characteristics of rehabilitated bauxite mines in Western Australia

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USE OF THESIS

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ABSTRACT

This investigation assessed the fuel characteristics of Alcoa of Australia's rehabilitated bauxite mines in the south-west of Western Australia. The study determined the fuel loads, their composition and structure. The characteristics of fuel were determined, their relationship with time ascertained, and the similarity of these characteristics to the jarrah forest ecosystems that they have replaced was discussed. Pits aged from four to twenty years since rehabilitation were assessed. Predictive models were developed to allow the rapid assessment of fuel. The fuel characteristics in two controlled burn areas were also assessed to how much fuel would burn in a fire and what factors were effecting this consumption.

Fuel quantities increased with age since rehabilitation from 7.19t/ha in a 5 year-old pit to 68.23t/ha in a 17 year-old pit. This is up 6 times higher than the maximum levels suggested for the surrounding jarrah forest. The composition and structure of fuels changed over time from predominantly standing material in the young rehabilitation areas to litter in the older sites. Young sites (4-7 year-old) were characterised by live standing material and had little standing dead or litter material. Sites aged in the 8-11 year range had large quantities of standing live and litter fuel with an increasing proportion of standing dead fuel. Twelve to 15 year-old rehabilitated pits had large loads of litter and standing dead fuel while in the oldest sites (16-20 year-old) the fuel was mostly in the litter layer. The quantity of litter was very strongly correlated with age since rehabilitation. Litter depth and age of pits can be used to predict total average fuel.

The method used in each year of rehabilitation, and particularly the species in the understorey seed mix, effected the characteristics of the fuel. The effects of variations in the rehabilitation methods were particularly obvious in the older rehabilitated pits (aged over 15 years). It may be of benefit to exclude these older pits from further monitoring programmes.

The distribution of fuels was very heterogeneous in nearly all sites. It was much more variable than in the surrounding jarrah forest. For example, fuel loads sampled in a 15 year-old site, ranged from approximately 20t/ha to 120t/ha. This uneven fuel distribution will influence fire behaviour and intensity during controlled burns.

Measurement of fuel consumption showed that a spring burn of moderate to high intensity consumed more fuel than an autumn burn of lower intensity. The higher moisture content of the autumn burn area contributed to the lower consumption of fuel as moisture inhibits combustion. More than 88% of standing fuel was consumed in the burns. Research data suggests that fire is carried in this standing fuel component. This differs from the jarrah forest where fire is carried in the litter layer. This implies that measurements of moisture content in soils and litter, which are used in other models to predict fire behaviour, would be of limited use in the rehabilitation areas under 15 years of age which have a significant proportion of standing fuel.

Although many other factors need to be considered in relation to the controlled burning of rehabilitated areas, the findings of this study have important implications. The fuel characteristics in 4 to 20 year-old rehabilitated areas are different to the jarrah forest ecosystem that they have replaced. At this stage the areas need to be treated differently in the development of a fire management programme.

DECLARATION

I certify that this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any situation of higher education; and that to the best of my knowledge and belief it does not contain any material previously published or written by an person except where due reference is made in the text.

ACKNOWLEDGEMENTS

I would like to express my great appreciation to my supervisors Dr John Koch, of Alcoa and Mr Eddie Van Etten of Edith Cowan University, without whom I would not have survived to finish this research. They provided me with their knowledge, support, help and poked me when I needed it.

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CHAPTER ONE

GENERAL INTRODUCTION

1.1 Thesis Introduction

Fire is an indelible part of the Australian bush. It is evident as an environmental factor in almost all Australian vegetation types, and much of the biota has adapted to fire via seed germination requirements, fire resistance, and many other morphological and behavioural characteristics (Kemp, 1981; Singh *et al.*, 1981; Luke *et al.*, 1986; Pyne, 1991; Bond *et al.*, 1996). *Banksia* for example, require intense fire to open their woody follicles for seed dispersal (Kemp, 1981; Bell *et al.*, 1989; Bradstock *et al.*, 1992). Eucalypt species have also developed a number of characteristics that are directly related to their fire prone environment. These characteristics include epicormic buds that sprout after a fire and thick bark to insulate the vascular cambium against the heat created (Bell *et al.*, 1989). Fire then, can be described as natural kin to the Australian environment. It has been helping to shape this land ever since it's introduction millions of years ago through natural mediums like lightning strikes and has continued to shape the environment more vigorously since the arrival of humans (Pyne, 1991; Flannery, 1994).

Australian Aboriginals have been using fire as a management tool for tens of thousands of years in what are described as 'fire stick' farming practices (Gill, 1981; Nicholson, 1981; Pyne, 1991). These nomadic people used fire, to extract from the natural environment, elements critical for their existence (Pyne, 1991). The arrival of Europeans into the land brought a halt to much of the fire management practices carried out by Aboriginal people. Although some settlers recognised that the environment changed after the halt of burning, fire was generally considered to be destructive and best excluded from the forests for fear of its damaging effects (Gill, 1981; Shea *et al.*, 1981; Burrows, 1985; McCaw, 1989; Pyne, 1991). Fire management was not re-established until a number of catastrophic wildfires had swept through forests and towns making people recognise that fire was a natural factor of the Australian environment that needed to be addressed (Gill, 1981; Shea *et al.*, 1981). It is now

a tool, called controlled burning, that is utilised for the management of many ecosystems by various controlling agencies, the Department of Conservation and Land Management (CALM) in Western Australia for example (Luke *et al.*, 1986). These agencies routinely use fire management for a number of reasons including sustaining rare and endangered species, species selection, and maintenance of forest fuels (live and dead plant material) at a level that will not facilitate a wildfire (uncontrollable fire) (Christensen *et al.*, 1981; Burrows, 1994).

Fire management is an area that is also becoming important to the mining industry. Significant tracts of land on the Australian continent are held in mining tenements, with approximately 37,185,200 ha in Western Australia alone (Department of Minerals and Energy, 1994). After mining, companies are now required to rehabilitate public land to standards set by governing agencies of the state and nation. These standards require that the rehabilitation activities are consistent with maintaining or restoring ecosystem integrity (Bartle *et al.*, 1989; Nichols *et al.*, 1985; Bright, 1995). Often, governments want the land to be restored to its pre-mining state. However, mining operations generally alter the mineral composition of the soils by removing the desired minerals, and current knowledge of ecosystem development is incomplete. Consequently, complete restoration is, rarely, if at all achievable (Bright, 1995). Ecosystems that are developed through mining rehabilitation processes are therefore of significance to fire management studies, as the new ecosystems that are being developed may not have the same characteristics as the ecosystems that they are replacing (Bright, 1995; Grant *et al.*, 1996a). Ultimately, these differences could manifest in divergent fire characteristics which may need specifically tailored fire management (Grant *et al.*, 1996a). These ecosystems, are important as they may make up a significant proportion of the landscape.

Fuel fundamentally effects fire behaviour and its impacts on the ecosystem (Cheney, 1981; Burrows, 1985; Luke *et al.*, 1986; Simmons *et al.*, 1986; Gill, 1987; Burrows, 1994; Bond *et al.*, 1996). Fuel was described by Gill *et al.* (1987) as being the major determinant as to whether a fire would be controllable and uncontrollable. Of the three main influences on fire behaviour, these being fuel, weather and topography, fuel is the only parameter affecting fire spread that can be directly manipulated by man (Luke *et al.*, 1986; Gill *et al.*, 1987; Burrows, 1994). An understanding of fuel characteristics is therefore essential for a fire management program. In this study, fuel characteristics in an ecosystem developed through mining

rehabilitation have been examined. Alcoa of Australia, which has bauxite mine operations in the region, provided this opportunity (Figure 2.1). The jarrah forest surrounding Alcoa's mining operations is managed using a rotational burn programme. Alcoa must develop a fire management programme to enable the integration of rehabilitated land into this forest system. An understanding of fuels in the rehabilitated areas will be important in the development of this programme. The overall aim of this study was to determine the fuel characteristics of ecosystems rehabilitated after bauxite mining. To achieve this aim a number of specific objectives were developed and the information gathered for each objective was compared with features of the surrounding native jarrah forest. The objectives were to determine:-

i) fuel loads, their composition and structure in rehabilitated areas aged between 4 and 20 years;

ii) how these characteristics of fuel were related to time, and whether the rehabilitation methods implemented by Alcoa had influenced this relationship;

iii) the proportions of these fuels that could be expected to burn in a controlled burn; and

iv) methods of fuel prediction that would allow the estimation of fuel characteristics without intensive sampling.

1.2 Thesis structure

This thesis has been split into 7 chapters including this introductory chapter. Information has been appended in 3 appendixes. Appendix 1 provides information about the controlled burns study carried out for this study. Appendix 2 is a compilation of the data collected from the individual sites and statistical information that is relevant to this study.

Chapter 2 details studies that have been undertaken for the determination of fuel characteristics, and the relevance of these studies to Alcoa's rehabilitation areas. It also describes the study area, the rehabilitation procedures used by Alcoa, and selection procedures for study sites.

Chapters 3 and 4 are an assessment of the fuel loads, their composition and structure, and relationships with time and the different rehabilitation strategies that had been implemented over the time period. A comparison was made between the fuel characteristics of the rehabilitated areas and those of the northern jarrah forest, the natural ecosystem that has been replaced by these rehabilitated forests.

Chapter 5 provides a synthesis of the way that the fuel characteristics of the rehabilitated forests respond to fire. This chapter assesses the proportion of fuel that is available to burn in a controlled situation and suggests factors that may influence the availability of these fuels.

Chapter 6 develops predictive models to estimate fuel characteristics. It discusses the relevance of these models to the development of a controlled burn programme and the suitability of using models that have been developed for the northern jarrah forest.

Chapter 7 is an overview and synthesis of the findings of this study. It assesses the relevance of this research both scientifically and for the development of a fire management program in Alcoa's rehabilitation areas. Limitations of this study are identified and suggestions made for further study in this area.

CHAPTER TWO

BACKGROUND

2.1 STUDIES OF FUEL CHARACTERISTICS

Recurrent fires are an integral feature of sclerophyll ecosystems in all Mediterranean climates throughout the world (Bell *et al.*, 1989; Bond *et al.*, 1996) and a large amount of literature exists on the topic of fuel characteristics in these communities. In Australia alone, a plethora of research papers exist, many of which are narrowly focused on particular ecosystems. For example, Ashton (1975) studied litter dynamics in *Eucalyptus regnans* forest near Melbourne, Birk (1979) and Birk *et al.* (1989) concentrated on wet sclerophyll ecosystems in Queensland, Bowman *et al.* (1988) investigated coastal monsoonal forests in the Northern Territory and studies by Peet (1971), McCaw (1986); and Burrows (1994) studied *Eucalyptus marginata* and *E diversicolor* forests in the south-west of Western Australia. Although the findings of all these studies are specific to the different forest types, they all agree on the importance of fuel in forest fire potential and attempt to predict fuel levels over time. Particularly important is the study by Burrows (1994) which made a detailed investigation of standard jarrah forest fuels for the development of fire behaviour and fire impact models. Burrows (1994) study was important because it was undertaken in the northern jarrah forest where Alcoa mines bauxite. The jarrah forest is the ecosystem that current rehabilitation techniques are attempting to replicate (Koch *et al.* 1994).

Although studies of fuels in natural sclerophyll ecosystems are relevant to the bauxite mine situation, they cannot be applied directly to the forest ecosystems that have formed in Alcoa's bauxite rehabilitation areas. This is because the literature that exists on the topic of fuel characteristics in sclerophyll forests pertains to 'mature' ecosystems whereas the bauxite areas are 'immature' sites. The distinction lies in the fact that mature ecosystems have long established existing flora and fauna. Rehabilitated sites on the other hand, are building completely new ecosystems, after the areas have been cleared of vegetation and mined for the desired minerals which alters the soil structure (Nichols *et al.*, 1985; Bartle *et al.*, 1989; Bright, 1995). Furthermore, Alcoa's rehabilitation areas are different because the

combinations of rehabilitation strategies implemented over time have produced a mosaic of unique forest communities which cannot always be found in the natural environment. Species that do not occur together naturally are sometimes found in the same rehabilitation sites (Koch *et al.*, 1993). This is particularly obvious in those older rehabilitation areas which used combinations of exotic species.

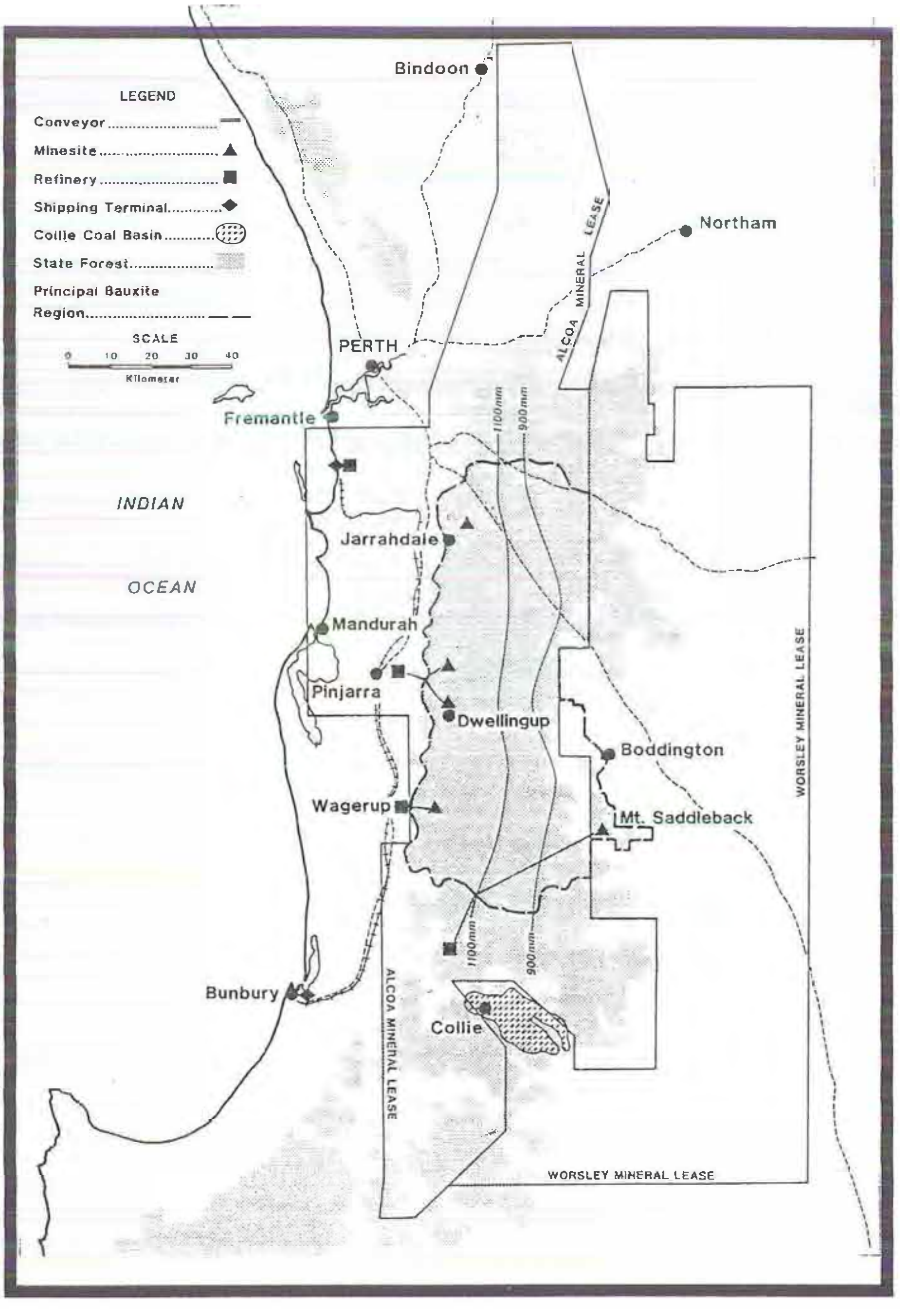
The unique quality of Alcoa's rehabilitation areas are exemplified by the high fuel quantities that characterise them. A study by Ward *et al.*, (1991), for example, yielded results of up to 42.0 t/ha biomass and 19.75 t/ha of litter in 10 year-old rehabilitation with a mixed eucalypt overstorey. These results suggest that Burrows (1994) estimation of a constant mean level of litter accumulation in jarrah forest after about 15 years at approximately 16.0 t/ha of litter may not apply to Alcoa's rehabilitation areas.

A number of studies that have been conducted in Alcoa's rehabilitation areas have incorporated an assessment of fuel characteristics (Koch *et al.*, 1987; Ward *et al.*, 1991; Grant *et al.*, 1996a; Ward *et al.*, 1996). These studies address the fuel characteristics of specific aged sites as peripheral information to the main aim of their research. Ward *et al.* (1991) for example, carried out a study about the effect of controlled burns on nitrogen and phosphorous levels. They assessed fuel loads at two sites that were aged 4 and 14 years since rehabilitation as part of this study. No study carried out in the rehabilitated ecosystems has specifically addressed the fuel characteristics of a number of different aged pits. A detailed study of fuel characteristics over a span of different aged pits was therefore regarded as important. It would answer questions about the fuel characteristics of Alcoa's rehabilitated areas and the relationship between these characteristics with time. Such a study would also indicate the relationship between the fuel characteristics of the rehabilitated areas and the natural ecosystem that has been replaced.

2.2 ALCOA'S REHABILITATION AND IT'S HISTORY

It is important to have an understanding of Alcoa's rehabilitation history. The rehabilitation methods applied over time have had a direct influence on the ecosystems, and may therefore have influenced the fuel characteristics assessed in this study.

Figure 2.1 : The location of bauxite mine operations in the south-west of Western Australia



(Cited in Bartle *et al.*, 1989)

Alcoa commenced mining in the northern jarrah forest of south-western Australia in 1963 and implemented its first rehabilitation program in 1966 (Elliot *et al.*, 1996). *Pinus* and exotic *Eucalyptus* species were chosen for their timber potential, fast growth and resistance to jarrah dieback disease (Tacey, 1979; Elliot *et al.*, 1996). By 1971 it became apparent that the areas being mined annually were small in terms of the amount of timber production possible, and that pine plantations had fire management problems (Tacey, 1979). In order to reduce these problems, the objective of timber production was diminished in importance, and other methods of rehabilitation were investigated. These involved the implementation of an understorey and using exotic and native *Eucalyptus* species in the overstorey. Through these investigations, it was recognised that the first 100 mm of soil, called the topsoil, are important as they contain the bulk of biologically active components (Bartle *et al.*, 1989). These investigations also showed the importance of immediate topsoil return for the re-establishment of native seed stored in the soil (Ward *et al.*, 1993). This is because seed viability was found to decrease significantly with the stockpiling of soil. It was also found that deep ripping of the compacted kaolinitic pit floor for better root penetration and erosion control had a large impact on the survival and growth of plants (Ward *et al.*, 1993). These findings formed the basis of rehabilitation methods that were implemented by Alcoa from that time onwards.

Between 1976 and 1988 a number of different rehabilitation strategies were employed by Alcoa (Elliot *et al.*, 1996). These changes came about as result of upgrading rehabilitation methods based on information coming from their research programmes. Different methods of seeding, planting, fertilising and species selection were used. In the overstorey for example, 50 species of eucalypt were trialled, utilising a combination of both eastern Australian and indigenous eucalypt species (Tacey, 1979). At least three species of eucalypt were typically planted at each pit in order to retain tree cover in case a tree species failed (Bartle *et al.*, 1989; Elliot *et al.*, 1996). Methods also improved in the understorey rehabilitation methods during this time period. For instance, the seed mix for the understorey was divided into major and minor mixes. The major mix contained (and still does) pioneer species that were mainly legumes characterised by vigorous growth and a relatively short lifespan. In 1976, when broadcast seeding was first introduced, the major mix consisted of 8 species, by the end of the 1980's this number had increased to 14 species (Alcoa, 1976 - 1992; Koch *et al.*, 1993). The

second type of mix, the minor mix, when first introduced in 1976 consisted of approximately 6 species and over the same time period this increased to between 60-100 species depending on availability of seeds (Alcoa, 1976 - 1992; Koch *et al.*, 1993). Between 1976 and 1978 this seed mix was applied by tractor but after this date aerial seeding methods were utilised instead (Alcoa, 1976 - 1992).

After considering the success of the rehabilitation strategies being used, in 1988 Alcoa moved to a more challenging goal of re-establishing a functioning jarrah forest ecosystem for its rehabilitation programme (Grant *et al.*, 1996c). Therefore, in the period since 1988, native *Eucalyptus marginata* (jarrah) and *E.calophylla* (marri) have been used as the main overstorey species via seeding methods. In addition to the dominant trees, the range of understorey species have also been restricted to species endemic to the region. The species being used are primarily from the Mimosaceae, Fabaceae, Myrtaceae and Proteaceae families which are the dominant taxa from the northern jarrah forest (Ward *et al.*, 1990; Koch *et al.*, 1993; Koch *et al.*, 1994). Currently, approximately 100 species are used in the major and minor seed mix. The species used and the proportion of seed varies from year to year as a result of the availability of seed and feedback from routine annual monitoring. The seed mix also changes due to input from research results for the establishment of a functioning jarrah forest ecosystem (Koch, pers comm, 1996).

The understorey, now produced in the rehabilitation areas solely by seeding and topsoil return, provides many benefits including soil stabilisation and erosion control, rapid water use, and the accumulation of plant nutrients and organic matter (Ward *et al.*, 1991). All of these are important for the land-use objectives of water catchment, timber production and Alcoa's goal of re-establishment of the jarrah forest ecosystem (Ward *et al.*, 1991). For example, Ward *et al.* (1985) concluded that the nutrients provided by the symbiotic nitrogen 'fixation' by leguminous species which are favoured in the understorey seed mix, are of major importance, as nitrogen can be a major factor limiting plant growth in rehabilitated areas.

Currently Alcoa operates three mines in the jarrah forest (Figure 2.1) where approximately 450ha of land are mined and rehabilitated annually (Koch *et al.*, 1994). The mines are subject to multiple land use pressures, including water catchment, timber production, recreation and conservation (CALM, 1992). In order to maintain access to the bauxite

resources Alcoa has developed a comprehensive plan of post mining rehabilitation with an active research program designed to minimise environmental impacts (Nichols *et al.*, 1985; Ward *et al.*, 1993).

2.3 THE IMPLEMENTATION OF A FIRE MANAGEMENT PROGRAMME BY ALCOA

Although the benefits of vigorous understorey growth are important in the rehabilitation of Alcoa's mined lands, this growth can represent a serious fire hazard in an already fire prone environment (Grant *et al.*, 1996a). This hazard takes the form of the quantity and structure of fuel produced by the leguminous species utilised in the rehabilitation areas. Due to their characteristically rapid growth and relatively short life-span, leguminous species have the potential to produce large amounts of fuel in both the litter and understorey levels of the ecosystem.

Due to a lack of knowledge of the long and short terms effects of burning in the rehabilitation areas, Alcoa has historically had a strategy of fire exclusion (Koch, pers comm, 1996). Alcoa has now mined and rehabilitated in excess of 7000 ha of land (Elliot *et al.*, 1996), and the company recognises that the species being used in the rehabilitation process could represent a fire hazard that must be addressed. Alcoa has therefore begun the process of developing a fire management plan and the company is undertaking studies of fire behaviour and its implications for rehabilitation areas. Fire management is also of importance to the company as they are currently negotiating completion criteria with CALM, the Water Authority and other governing agencies. These criteria must be satisfied before the responsibility for rehabilitated sites can be relinquished into the hands of CALM (Elliott *et al.*, 1996). The completion criteria will ensure that:

1) procedures meet land use objectives set by the governing agencies;
2) rehabilitation areas can be integrated into the natural landscape;
3) rehabilitation areas have sustained growth and development;
4) the vegetation in the rehabilitation areas is as resilient as the vegetation in the native jarrah forest; and

5) rehabilitated ecosystems can be integrated with forest management practices used by CALM (Elliott *et al.*, 1996)

A fire management programme is considered to be integral to these objectives, particularly as the jarrah forest that surrounds Alcoa's mining areas utilises a rotational fire management programme.

2.4 STUDY AREA

2.4.1 Landform and soils

The Darling Scarp is a dissected, uplifted peneplain which rises 300 - 400 m above the coastal plain. This marks the western edge of the Darling Plateau (Mulchay, 1967; cited in Nichols *et al.*, 1985). Plateau soils are ancient and are formed largely *in situ* by the weathering of Darling Range granite which laterised during the tertiary period. These soils are characterised by pisolitic or bauxite laterites over a layer of deep kaolinitic clay (Koch *et al.*, 1994).

2.4.2 Vegetation

The overstorey sclerophyll vegetation of the region is mostly dominated by jarrah (*Eucalyptus marginata* Donn ex Smith) with variable contributions of marri (*E.calophylla*) (Dell *et al.*, 1989; CALM, 1992). The second level of vegetation is dominated by *Allocasuarina, Persoonia* and *Banksia* spp, with a shrub layer containing species characterised by resprouters (i.e. k-selected species which tend to be long lived, produce little seed and have the ability to resprout from rootstock after a fire) (Tacey, 1979; Bell *et al.*, 1989; Koch *et al.*, 1994). However, species similarity comparisons made by Koch *et al.* (1994) before and after mining reflect low species correlations between the unmined forest and rehabilitation areas. Their study showed that rehabilitated areas have a predominance of r-selected species (fast growing, pioneers, annuals and biennials which concentrate on seed production and fast biomass production) instead of the k-selected species dominating in mature jarrah forests.

2.4.3 Climate

The climate of the area is Mediterranean, characterised by cool wet winters and hot dry summers (Gentilli, 1989). Annual rainfall averages 1100 - 1400 mm in the region (1216 mm

in Jarrahdale) (Koch *et al.*, 1994), reflecting the orographic effect of the escarpment (CALM, 1992). Most rainfall occurs in the winter months from May to September (Tacey, 1979). Seasonal summer drought for 4 - 6 months is common (Gentilli, 1989). Average daily temperatures range between 15 - 30 °C in the summer months of January and February, and range between 6 - 15 °C in the coldest winter month of August (Koch *et al.*, 1994).

2.5 STUDY SITES

Sixteen sites were selected from pits at the Jarrahdale mine which is approximately 45km SSE of Perth, Western Australia (Figure 2.1). The pits were rehabilitated between 1976 (20 year-old) and 1992 (4 year-old). This age range was chosen because pits rehabilitated earlier than 1976 have little or no understorey and therefore have different fuel characteristics to all sites rehabilitated since then (Ward *et al.*, 1993). Pits rehabilitated later than 1992 were also excluded because they are very young in terms of plant growth and vegetation structure and did not have sufficient dry fuel to be assessable. The Jarrahdale mine was used for most of the study in order to reduce possible variation due to soil, climate, and other site differences that could occur if all three mines were used (Figure 2.1). Jarrahdale is also the oldest of the three mines and therefore has a wider range of rehabilitation areas.

In order to obtain representative data, the pits chosen were of a reasonable size (~ 10ha) to limit edge effects, and represented a number of different rehabilitation methods used over the years. The pits were aged 4 - 18, and 20 years since rehabilitation. Visual assessment was undertaken of a number of pits from each age by Dr John Koch, Environmental Research Scientist from Alcoa, Carl Grant, a Ph.D. student studying fire ecology in the rehabilitated areas and myself. This enabled the selection of one pit to be representative of each age of rehabilitation that was to be assessed.

Two 15 year-old sites were assessed, one of which was an additional site used to assess fuel consumption in a controlled burn. This fire pit was situated at the Huntly mine site, located approximately 10km north of Dwellingup (Figure 2.1). A study of fire impacts is being carried out on this site by Carl Grant, a Ph.D. student from University of Western Australia, whose thesis is entitled 'Fire Ecology in rehabilitated bauxite mines in the south-west of

W.A.'. It was appropriate to take advantage of the burn at the Huntly site as a study site, particularly as no burns were planned at the Jarrahdale mine. This site was assessed to determine the amount of fuel that was consumed in an Autumn burn.

The most important part of this study was to determine the trends in fuel quantities, composition and structure over time. Sampling for each pit, and sorting of these samples was a time consuming process taking approximately 40 hours for two people. Therefore, decisions had to be made about the feasibility of sampling a large number of pits in the limited time span of an honours project. In rehabilitation areas, each pit of the same age is considered to have comparable characteristics. This is because for each year the same methods of rehabilitation are used. These methods include site preparation, planting, fertilising, and seeding. Other studies in rehabilitation areas have not replicated because of this assumption (Sawada, 1996; Ward *et al.*, 1991; Bright, 1995; Elliot, 1996; Ward *et al.*, 1996). For these reasons it was decided to study a chronosequence (a range of ages of rehabilitation) rather than study many pits of the same age to enable replication

A pilot study was carried out in preparation for the main project. The study was made at the site of a moderate intensity controlled burn which was carried out in spring 1995. The site was adjacent to the pit used for the autumn burn. This assessment provided preliminary data and gave indications of fuel consumption and fire behaviour in rehabilitated pits.

CHAPTER THREE

FUEL LOADS AND FUEL COMPOSITION

3.1 INTRODUCTION

Fuel quantities are very important for fire management because they have a large influence on the intensity of a fire and its rate of spread (Gill *et al.*, 1987; O'Connell, 1987; Burrows, 1994). The Department of Land Management (CALM) for example, controls the quantities of fuels in many of the forests that it manages in order to maintain a level of influence over the forest in terms of fire management (Burrows *et al.*, 1990). It is important therefore, to study the quantities of fuel in an ecosystem before preparing a fire management plan (Woods *et al.*, 1983; Gill *et al.*, 1987; O'Connell, 1987).

For fuel to be accurately quantified, the proportions of different components present should be specified (McCaw, 1991). This is because the different fuel components have differing flammability characteristics due to their specific attributes of size, shape and density. These attributes have a direct influence on heat transfer and combustion (McCaw, 1991). Burrows (1994) for example, found distinct differences in the time period that different components of fuels in the jarrah forest take to combust. The composition of fuel is therefore also of interest in fire management plans. Estimations of fuel quantity and combustibility provide the basic information for the development of predictors for fire management. The objective of this chapter is to ascertain if a relationship exists between fuel loads and time. The change in composition of fuel will also be assessed in relation to time. Both of these factors will be analysed to determine if the range of rehabilitation methods used have produced different fuel accumulation characteristics. In addition, fuel measurements reported in this chapter are used as a basis to assess the ability of alternative measures to predict fuel loads in the rehabilitation areas (this is undertaken in chapter 5).

3.2 METHODS

3.2.1 Data Collection

Fuel usually consists of litter, and live and dead standing material. To measure fuel loads and fuel composition in the rehabilitation area, fuel was collected and assessed using quadrat sampling. This is a form of destructive sampling which is considered to be the most accurate way to estimate litter (Catchpole *et al.*, 1992; Burrows, *et al.*, 1986). The methods have been split into litter sampling and standing fuel sampling as the procedures are different for these two components.

Litter Fuel loads

Quadrats were used to obtain representative data from the 17 rehabilitated pits chosen for assessment. Within each pit, litter was collected from 10 quadrats. Following Chambers *et al.* (1983), this method involved the use of a baseline along the edge of the sampling area. Points along this line were spaced in a pre-determined and equal distance apart. These points were chosen by determining the length of the perimeter and dividing that length by five (to the nearest metre). From the five starting points, at a 90 ° angle from the perimeter, a quadrat was placed 50m and another quadrat at 100m from the perimeter (Figure 3.1).

The method of sampling used may be termed 'semi-random' as the locations of the first starting point was randomly determined. As the pits varied in size, quadrat placement using 50 and 100m distances resulted in different parts of the pits being sampled. This perimeter method for the determination of quadrat placement was used because of the difficult access to many pits. This difficulty was due to the dense understorey growth that is characteristic of rehabilitation areas. Use of the pit perimeter allowed more efficient use of time. It also reduced inaccurate quadrat placement due to direction disorientation caused by manoeuvring around understorey growth. Even though it utilises systematic methods, this type of semi-random sampling is considered to be an efficient method of locating sampling points that still allows valid calculation of the variance (Chambers *et al.*, 1983).

Figure 3.1 : Quadrat and levy pole placement within pits

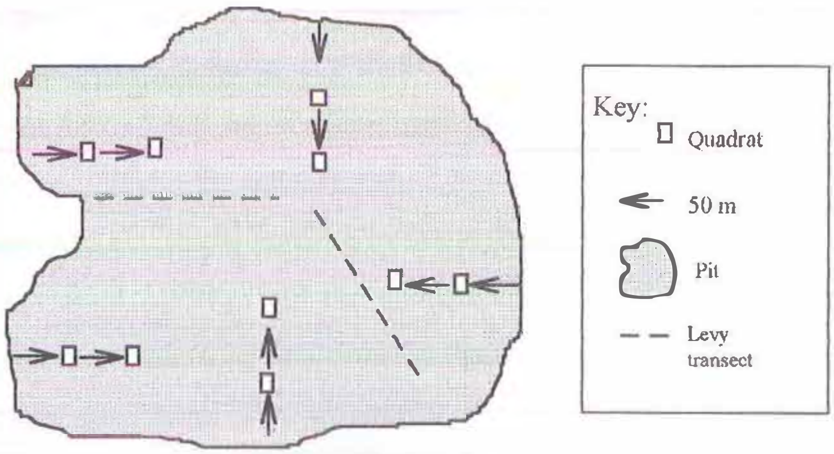
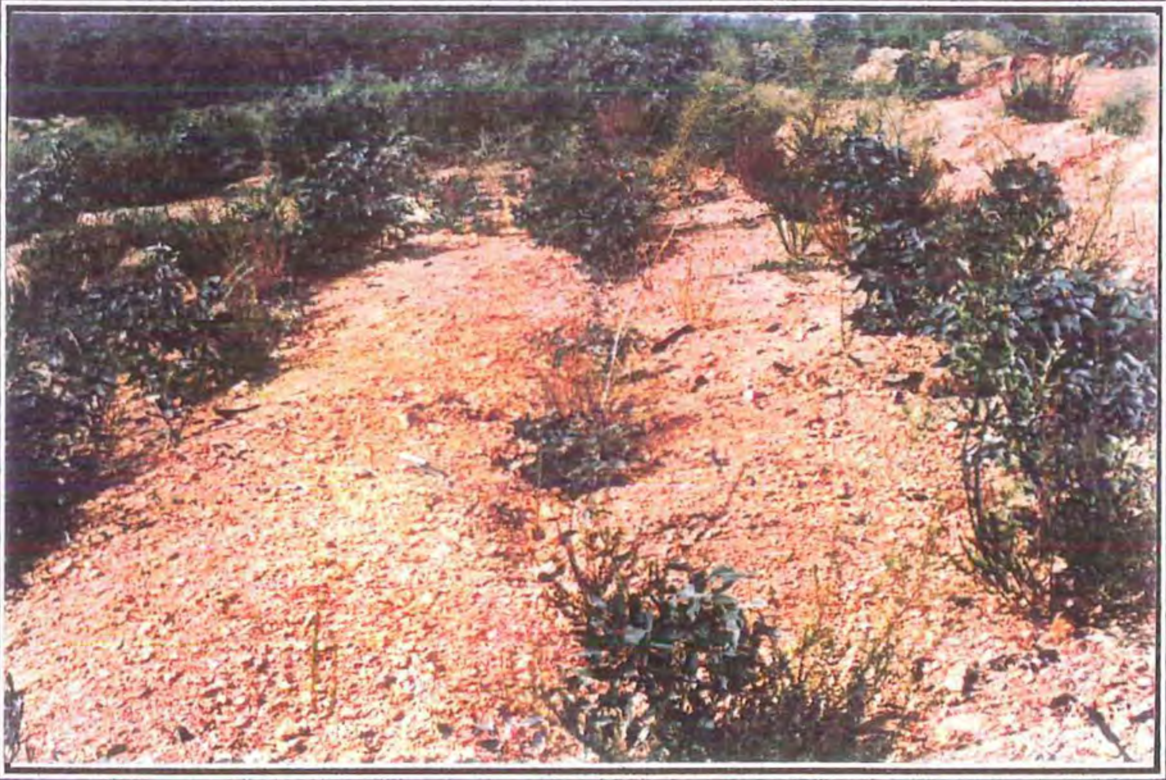


Figure 3.2 : Pit rehabilitated in 1992 at the Jarrahdale mine site. Photograph shows the rip-lines created in the rehabilitation process and the propensity of vegetation to grow at the bottom of these rips.



The deep ripping of the pit floor in the initial stages of rehabilitation of the pit causes a mounding pattern throughout the pit (Figure 3.2). These mounds are referred to as rip lines and are approximately one metre width between mound tops. Vegetation and litter often collect at the bottom of the rip lines, therefore quadrats of 1.0m x 0.5m were placed with the long axis at right angles to the rip lines and therefore included both the top and bottom of rip lines. The quadrat size was larger than fuel studies carried out by Peet (1971), Fox *et al.* (1979), O'Connell (1987), and Birk *et al.* (1989) where quadrats of $0.37m^2$ and smaller were used. The larger quadrat size and its orientation was chosen because the quadrat should be approximately the size of groupings of individuals and cut across banding in the vegetation pattern (Kershaw, 1975; Mueller-Dombois *et al.*, 1974). As the quadrat crossed high density and adjacent low density patches it effectively reduced the variance between quadrats by averaging the vegetation patterning. The rectangular shaped quadrats were also utilised as this shape is considered to be more efficient for sampling than circular or square quadrats in terms of reducing variability (Kershaw, 1975; Mueller-Dombois *et al.*, 1974).

The litter from each quadrat was collected, bagged and later sorted into the following classes :-

i) leaves ;
ii) duff (fragmented decomposing material (Burrows, 1994));
iii) bark ; and
iv) round-wood diameter classes : 0 - 15mm
16 - 30mm
31 - 45mm.

Although other studies of litter accumulation have only measured round-wood size classes < 15mm (e.g. Burrows 1994; Ashton 1975; Fox *et al.*, 1979), findings from the preliminary study at the Huntly spring burn suggested that litter level fuel of a diameter averaging 28.26mm or less will be totally consumed in a fire (see Appendix 1B). This means that more fuel is available to burn in the rehabilitated areas. A wider range of size classes than those used in other studies were therefore chosen for this research. The larger size classes caused higher estimations of fuel quantities than

would have occurred if the size classes of other studies had been used. This was because larger fuel components were collected. However, as more fuel was proven to be available to burn in the rehabilitated pits, the larger fuel estimations were considered justifiable. The reasons for choosing size classes that are appropriate for each ecosystem type is discussed further in chapter 5.

Standing Fuel

The aerated standing fuel, which is made up of live and dead standing vegetation, was harvested from each of the 10 quadrats placed in the 17 pits that were assessed. The standing material was collected in a three-dimensional shape 1.0m long x 0.5m wide x 3.9m high. The fuel was sorted into :-

i) live ; and

ii) trash (dead standing vegetation).

For average intensity burns in the jarrah forest Burrows (1994) estimated that combustible aerial fuel has a round-wood diameter of less than 4mm for live material and less than 6mm for dead material. Grant *et al.* (1996a) found that larger diameter round wood is consumed in average rehabilitation burns due to the high fuel loads which create higher intensity burns. The preliminary study also indicated that larger diameter aerial fuel is consumed at a rehabilitation site (see Appendix 1: Pilot studies). All live and dead material less than 45mm in diameter was therefore collected from the understorey to accommodate for the larger diameter fuel consumption that occurs.

3.2.2 Data Analysis

Dry weights

Each fuel sample collected in the field was sorted, weighed then oven dried at approximately 80 ° C for 4 days. The samples were then re-weighed to determine oven dried weight and moisture content[§] (% oven dry weight or %ODW). Dry weight was converted to tonnes per hectare (t/ha). This parameter was used as it is the unit of measurement employed by Australian fire researchers and managers (McCaw, 1991; Burrows *et al.*, 1986). Oven dry weight was used to estimate the average

[§] Chapter 5 discusses the use of moisture content to predict fuel combustibility

weight and proportion of each fuel component. Total fuel loads, averages and standard errors for each pit were also determined.

Statistical analysis

The data was assessed in two main ways. It was assessed to see if fuel loads and fuel composition changed with time since rehabilitation. Multivariate analysis was also used to explore overall patterns in the data.

a) Age class assessment

The 17 sites were grouped into age classes, 4-7, 8-11,12-15 and 16-20 years-old. The individual sites were also assessed to see if fuel loads increased on a time continuum. The age classes were used to determine if fuel loads and fuel composition were better described in age blocks than as separate yearly intervals. Age classes also provided repeat samples for replication purposes instead of using each year as a separate entity. Each age in a class therefore represented four replications for that class (except 11-15 year class which had two sites aged 15 years and therefore had 5 replicates).

Pearsons correlation was applied to the data to measure the degree of association between the variables (Blackmore, 1994). The variables tested were age, age class, the major fuel categories (litter, standing fuel, and total average fuel) and the separate fuel components (standing live material, standing dead material, leaves bark, duff, and round-wood). As a large number of variables were assessed in this study the correlations helped to clarify where relationships existed in the data and gave direction for further assessment. The 'coefficient of determination' (r^2), an indicator of the associated variance, was determined from the correlations to indicate how much one variable could be used to explain another (Blackmore, 1994). Where correlations did not exist, a scattergraph or line graph was made to see if the relationship was linear or non-linear. This was done because Pearsons correlations compares the data linearly. It will therefore not always, except by chance, indicate a significant correlation where a non-linear relationship exists.

Analysis of Variance (ANOVA) was used to determine if the age class categories were significantly different from each other. One-way completely randomised

ANOVA was applied because each group was considered to be separated from the others (Blackmore, 1994; Kinnear *et al.*, 1994). Tukeys b test was used as a post-hoc test to determine which of the classes were significantly different from each other (Blackmore, 1994). ANOVA was not applied to the individual sites because there was no replication in this category.

b) Multivariate analysis

Multivariate analysis, a form of cluster analysis, has the aim of grouping a set of individuals into classes on the basis of pattern and order within a data set (Belbin, 1991). Unweighted Paired Group ArithMetic Averaging (UPGMA), a hierarchical analysis from the PATN software package, was selected to provide an unbiased view of group structure (Belbin, 1991). It was used to identify any flaws in the age class categories. It also provided indications of where more accurate grouping may be developed as it used all of the fuel variables of the data set to find similarities. This was possible because UPGMA provides a means of summary, hypotheses formation, testing and prediction (Faith, 1991). It is considered to be robust as it avoids unwarranted assumptions about the nature of the underlying pattern, and it also recovers good cluster structure in the presence of data 'noise' (Williams *et al.*, 1987; Faith, 1991; Belbin, 1991; Belbin, 1993).

The UPGMA process of assessment can be explained relatively simply. The following summary has been adapted from Williams *et al.* (1987). The process begins with the creation of an association matrix of the pits which is a measurement of the similarity or dis-similarity between all of the variables of each pit. The Gower Metric association measure was used for the development of this matrix because it employs a standardising range. This standardises the variables so that equal differences in scale between variables have the same weighting regardless of scale differences. This means, for example, that the difference between samples A and B which have a weight of 5 and 10t/ha is regarded the same as the difference between samples C and D which weigh 60 and 65t/ha. Gower Metric assigns values to the variables according to their level of association. This ranges from 0 for identical samples to 1 for variables that have maximum degrees of dissimilarity. The next step in the process is the fusion of the two samples that have the smallest value of

association into a group. The values of this group are then averaged. This method of fusing the two closest samples or groups of samples, then recalculating the associations is repeated until a single group containing all the samples remains.

A dendrogram is used to display the results of the hierarchical clustering. The structure of the dendrogram illustrates the steps in the fusion process. It also shows the nested arrangement of the groups at various levels in the structure (Williams *et al.*, 1987). The base of the dendrogram is the complete set of sites, and the tiered levels of the dendrogram show the degrees of association between the variables.

The age classes were rearranged according to the findings of the multivariate analysis into classification groups. This grouping was made according to the major clusters interpreted from the dendrogram. As the UPGMA programme is designed to look for differences (and similarities) between groups ANOVA can be expected to find differences between the dendrogram groups. One-way completely randomised ANOVA was applied to the newly defined groupings to see if these categories were statistically different from each other as expected. Post hoc analysis was not carried out. The classification groups defined by the dendrogram were used in the analysis of fuel undertaken in a number of subsequent chapters of this study. It provided a contrast of the usefulness of using either individual sites or age class categories to represent the fuel in rehabilitated bauxite areas.

3.2.3 Study of forest sites

A comparative study was carried out in two areas of the northern jarrah forest that fall within Alcoa's mining lease. These areas were aged 43 years and 6 years since last burn. This study was carried out because it was considered important to compare fuel quantities and variability between the rehabilitation areas and the northern jarrah forest. The methods of data collection used for this pilot study replicated those carried out in the rehabilitated areas.

3.3 RESULTS

3.3.1 Fuel loads

The total average fuel loads ranged from 7.19t/ha at 5 years since rehabilitation to 68.23t/ha at a 17 year-old site (Table 3.1). Total average fuel load increased with age since rehabilitation and had a significant linear correlation (r = 0.74) (Table 3.3, Figure 3.3, 3.4 & 3.6). Total average fuel load was also correlated with age using four year age intervals (r = -0.69) and classification groups determined by the multivariate analysis (r = 0.74) (Table 3.3, Figure 3.5).

Although the fuel increased with age since rehabilitation (Figure 3.4 & 3.6), the fuel loads were highly variable. This is most obvious in the period between 16 and 20 years. When the rehabilitation sites were grouped into age classes (Figure 3.6) the relationship between average fuel and age was stronger than where individual ages were used. Several sites exhibited fuel loads that were atypical for the age class. They were 6, 16 and 18 year-old pits (Figure 3.4 & Table 3.1). The dendrogram produced by the multivariate analysis showed that the fuel loads in the rehabilitated sites were generally grouped into age classes (Figure 3.5). Some sites did not fit into the time sequence. Sites aged 6, 12 and 18 years for example, were not classified into their expected age groups.

The heterogeneous nature of the fuel loads was also indicated by the large range and standard error found within sites (Table 3.1). At a 15 year-old site for example, total fuel load ranged from 23.19t/ha to 120.17t/ha (Appendix 2A : Information Tables).

There were significant differences in the total fuel loads between the age classes (Table 3.2). Tukeys b post-hoc test indicated that class 4-7 years was not significantly different to class 8-11 years, but was different from 12-15 years and 16-20 years. Litter, a sub-group of total fuel, also showed significant differences with age. Standing fuel, the other sub-group of total fuel, was not significantly different between the age classes. As expected, One-way ANOVA of the classification groups

Table 3.1 : Average fuel quantities for the study sites

Age (Yrs)	*Age Class (4 yr intervals)*	*Classification Group*	*Total Fuel (t/ha)*	*Range (t/ha)*	*Standard Error (Fuel)*
4	4 - 7	1	11.20	0.42 - 34.08	3.13
5	4 - 7	1	7.19	0.30 - 18.72	2.35
6	4 - 7	2	37.13	12.55 - 81.16	6.72
7	4 - 7	1	14.97	1.44 - 36.64	4.11
8	8 - 11	2	35.12	8.29 - 62.55	5.19
9	8 - 11	2	38.42	1.50 - 99.46	7.88
10	8 - 11	2	31.35	2.37 - 69.41	6.94
11	8 - 11	2	33.40	18.06 - 52.01	3.58
12	12 - 15	2	42.72	20.01 - 62.59	3.92
13	12 - 15	3	38.13	6.08 - 70.13	6.59
14	12 - 15	3	47.08	16.48 - 68.78	5.71
15	12 - 15	3	44.68	5.93 - 80.14	7.04
15*	12 - 15	3	52.32	23.19 - 120.17	9.54
16	16 - 20	4	20.87	5.48 - 46.94	4.62
17	16 - 20	4	68.23	41.01 - 135.75	9.53
18	16 - 20	3	30.99	11.08 - 63.92	2.89
20	16 - 20	4	63.89	38.2 - 96.01	5.20
Forest age 6	-	-	23.16	9.15-41.68	2.85
Forest age 43	-	-	30.43	16.48-39.19	2.16

* Note : Two fifteen year old sites were sampled (one at Huntly and one at Jarrahdale)

Table 3.2 : Analysis of variance results showing average fuel load (t/ha) and the relationship between variables and the 4 yearly age classes. Within columns identical letters indicate variables that were significantly different ($p < 0.05$) using Tukeys b post hoc test.

Age classes (years)	*Litter*	*Standing live*	*Standing dead*	*Total average standing material*	*Total average fuel*
4-7	6.61a	10.17	0.84a	11.01	17.62a
8-11	17.87b	9.00	7.70a	16.70	34.57
12-15	28.80a	4.68	11.53ab	16.21	45.00a
16-20	39.36ab	4.27	4.47b	8.74	48.10a
F-value	10.37	-	8.78	-	4.72

Table 3.3 : Correlation matrix of fuel components and age classifications

	AGE OF PIT	AGE CLASS	CLASSIFICATION GROUP	BARK	DUFF	LEAVES	ROUND-WOOD	TOTAL LITTER	LIVE FUEL	DEAD FUEL	TOTAL STANDING FUEL	AVERAGE TOTAL FUEL
AGE OF PIT	1.0000											
AGE CLASS	-0.9644 ✓	1.0000										
CLASSIFICATION GROUP	0.9182 ✓	-0.9249 ✓	1.0000									
BARK	0.6597 ✓	-0.7199 ✓	0.6285 ✓	1.0000								
DUFF	0.8116 ✓	-0.7547 ✓	0.7684 ✓	0.5874 ✓	1.0000							
LEAVES	0.5975 ✓	-0.5700 ✓	0.7633✓	0.3454 ✖	0.4826 ✓	1.0000						
ROUND-WOOD	0.9376 ✓	-0.885 ✓	0.8985 ✓	0.5081 ✓	0.7406 ✓	0.6174 ✓	1.0000					
TOTAL LITTER	0.8950 ✓	-0.8397 ✓	0.8674 ✓	0.6163 ✓	0.9787 ✓	0.6015 ✓	0.8535 ✓	1.0000				
LIVE FUEL	-0.4956 ✓	0.4680 ✖	-0.3993 ✖	-0.2299 ✖	-0.1567 ✖	-0.0437 ✖	-0.5794 ✓	-0.2609 ✖	1.0000			
DEAD FUEL	0.3950 ✖	-0.3494 ✖	0.3626 ✖	0.2147 ✖	0.5187 ✓	0.0889 ✖	0.3883 ✖	0.4918 ✓	-0.3756✖	1.0000		
TOTAL STANDING FUEL	-0.111 ✖	0.1253 ✖	-0.0508 ✖	-0.0241 ✖	0.3078 ✖	0.0373 ✖	-0.1937 ✖	0.1887 ✖	0.5908 ✓	0.5259 ✓	1.0000	
AVERAGE TOTAL FUEL	0.7432 ✓	-0.6899 ✓	0.7401 ✓	0.5300 ✓	0.9624 ✓	0.5385 ✓	0.6780 ✓	0.9395 ✓	0.6131 ✓	0.02.18 ✖	0.5138 ✓	1.000

Note:✓=p≤0.05,✖=p≥0.0

Figure 3.3 : Litter quantity and composition of rehabilitated mine pits aged between 4 and 20 years old

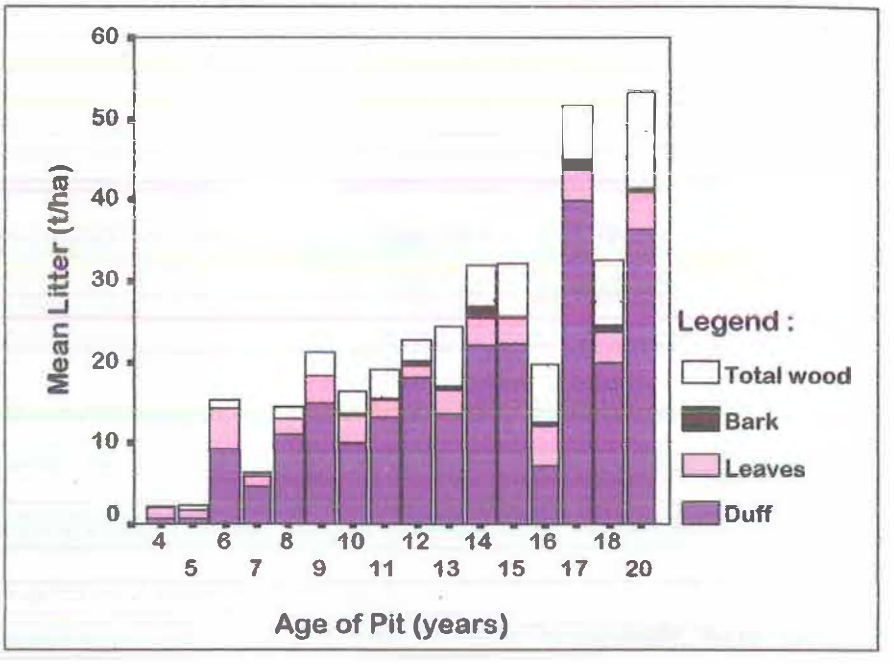
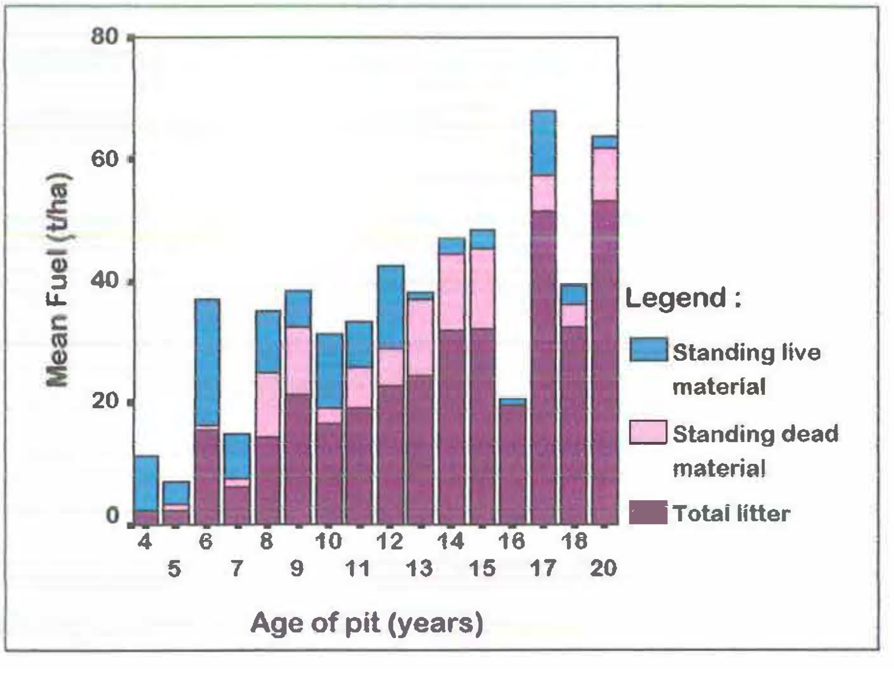


Figure 3.4 : Fuel quantity and composition of rehabilitated mine pits aged between 4 and 20 years old



four year age intervals ($r = -0.69$) and classification groups determined by the multivariate analysis ($r = 0.74$) (Table 3.3, Figure 3.5).

Although the fuel increased with age since rehabilitation (Figure 3.4 & 3.6), the fuel loads were highly variable. This is most obvious in the period between 16 and 20 years. When the rehabilitation sites were grouped into age classes (Figure 3.6) the relationship between average fuel and age was stronger than where individual ages were used. Several sites exhibited fuel loads that were atypical for the age class. They were 6, 16 and 18 year-old pits (Figure 3.4 & Table 3.1). The dendrogram produced by the multivariate analysis showed that the fuel loads in the rehabilitated sites were generally grouped into age classes (Figure 3.5). Some sites did not fit into the time sequence. Sites aged 6, 12 and 18 years for example, were not classified into their expected age groups.

The heterogeneous nature of the fuel loads was also indicated by the large range and standard error found within sites (Table 3.1). At a 15 year-old site for example, total fuel load ranged from 23.19t/ha to 120.17t/ha (Appendix 2A : Information Tables).

There were significant differences in the total fuel loads between the age classes (Table 3.2). Tukeys b post-hoc test indicated that class 4-7 years was not significantly different to class 8-11 years, but was different from 12-15 years and 16-20 years. Litter, a sub-group of total fuel, also showed significant differences with age. Standing fuel, the other sub-group of total fuel, was not significantly different between the age classes. As expected, One-way ANOVA of the classification groups indicated significant differences between the groups for the fuel loads of total average fuels, standing material and litter.

3.3.2 Fuel Composition

The composition of fuel changed over time in the rehabilitated pits (Figure 3.3, 3.4 & 3.6). This was evident for the individual sites, the age classes and the classification

groups. The proportions of standing and litter components of fuel also changed in dominance over time.

Litter composition in the rehabilitated pits

Litter load showed a significant positive correlation with age of the site for both the individual sites (r = 0.90), and with age classes (r = 0.84) (Table 3.3). Litter loads ranged from 2.29t/ha (20.4% of total fuel) for a 4 year-old pit to 52.67t/ha (83.5% of total fuel) at a 20 year-old pit (Appendix 2: Information tables). Leaves, round-wood[⊗], duff and bark, sub-groups of the litter component, also increased significantly with age since rehabilitation (Table 3.3, Figure 3.3). As expected, litter and all of its components were strongly correlated with the multivariate classification groupings (Table 3.3).

The composition of the litter sub-groups changed over time in the rehabilitated pits (Figure 3.3). Duff increased in its contribution to the weight of litter and total fuel over the time period represented. It ranged from 0.75t/ha (6.7% of total fuel) at 4 years to 36.39t/ha (57.0% of total fuel) at 20 years. Duff also increased its dominance in the litter load ranging from 32.8% of litter at 4 years to 77.4% of litter at 17 years. Round-wood increased from representing 8.3% of litter (1.3% of total fuel) at 4 years to 22.4% (18.7% of total fuel) at 20 years. Leaves, the litter component that had the lowest correlation with time (r = 0.60), exhibited a small weight increase with age since rehabilitation. It ranged from 1.01t/ha (14.0% of fuel) at 5 years to 4.98t/ha (23.9% of fuel) at 16 years with a mean of 2.97t/ha (Figure 3.3).

Standing aerated Fuel in the rehabilitated pits

The total standing component of fuel decreased as a proportion of the total fuel over time, ranging from 61% of total fuel between 4-7 years to 19% between 16-20 years (Figure 3.6). Standing fuel was correlated with total average fuel ($r = 0.51$, $p \leq 0.05$)

[⊗] Wood is made up of 3 sub-classes (0-15mm, 16-30mm and 31-45mm round-wood diameter classes). An average of 87% of total round-wood was in the 0-15mm class, 10% in the 16-30mm class and 3% in the 31-45mm class. As the 16-30mm and 31-45mm classes made up small proportions of the round-wood class it was decided that analysis would be carried out on total round-wood.

but was not significantly correlated with age of rehabilitation ($r = -0.11$, $p \geq 0.05$), age classes ($r = 0.13$, $p \geq 0.05$) or the classification groups ($r = -0.05$, $p \geq 0.05$) (Table 3.3). The relationship between standing fuel and age is not linear, and is better described as curvilinear with a peak at about 11 years of age (Figure 3.7a).

The standing fuel exhibited changes in the composition of live and dead material over time (Figure 3.6). The proportion of live material decreased from 56% (10t/ha) of the total fuel (91% of standing fuel) at 4-8 years to 9% at 16-20 years. It was significantly negatively correlated with individual sites over time ($r = -0.50$, $p \leq 0.05$) but did not have a significant correlation using age classes ($r = 0.47$, $p \geq 0.05$) or the classification groups ($r = -0.40$, $p \geq 0.05$). Standing material also proved to have an insignificant relationship with age classes using ANOVA ($p < 0.05$) (Table 3.2).

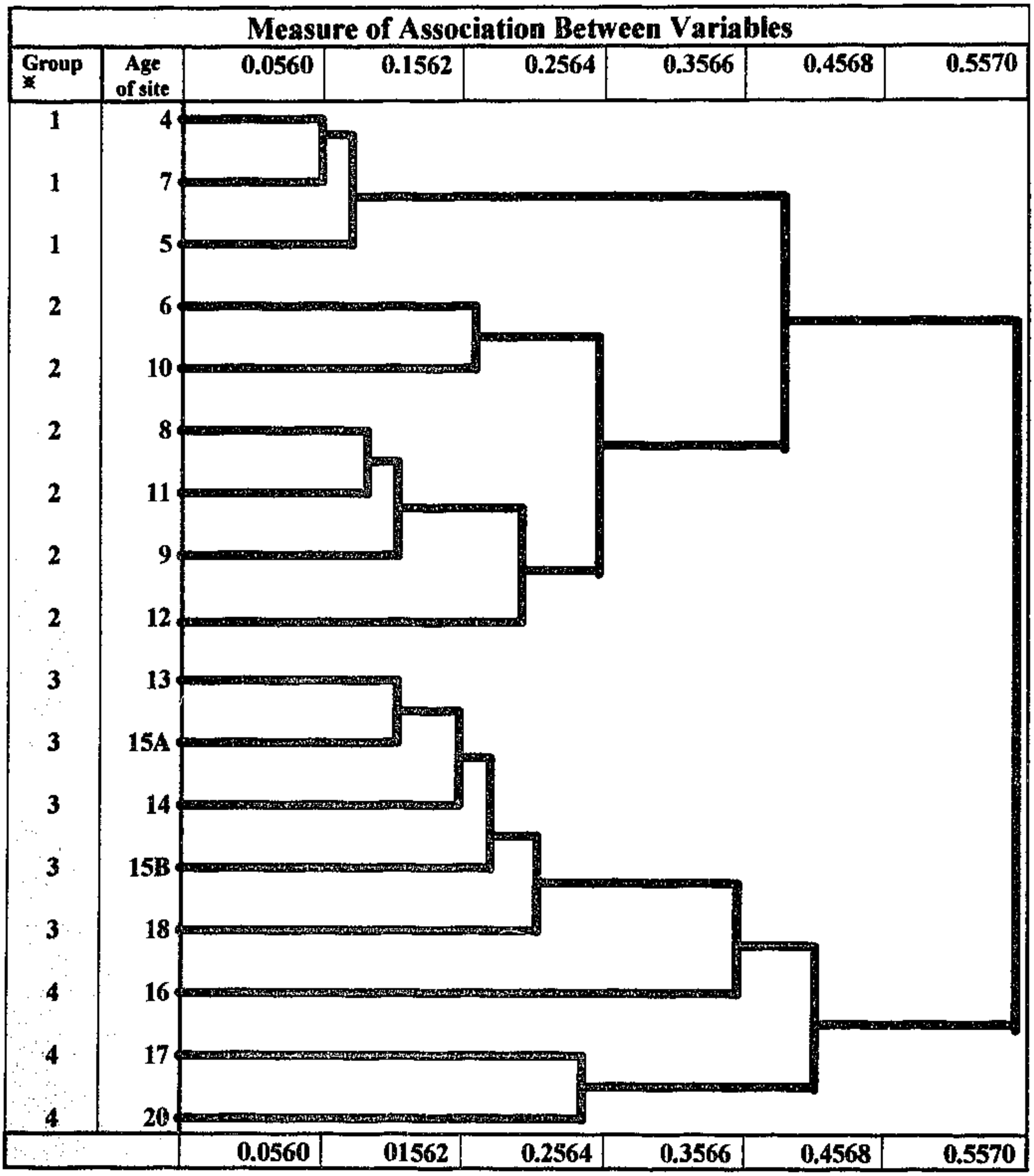
Standing dead fuel showed a curvilinear trend with a peak value at about 14 years of age (Figure 3.7b). As would be expected from a variable that had a non-linear relationship with time, standing dead fuel was not correlated with any of the classifications used in this study (Table 3.3). Standing dead fuel contributed a small proportion to the total fuel at 4-8 years (6%), as well as a small proportion of the standing fuel component (9%) but increased to 26% of total fuel in the 9-11 year group, then decreased again to 11% in the 16-20 year group (55% of total standing fuel).

3.3.3 Study of forest sites

Fuel loads

In the unmined forest average loads were 23.16t/ha and 30.43t/ha in forest aged 6 years and 43 years since last burn respectively. The fuel loads recorded in the jarrah forest sites were generally less variable than the fuel loads of the rehabilitation areas. The standard error of total fuel in the forest study sites were lower than all except one of the rehabilitated pits.

Figure 3.5 : Dendrogram produced using UPGMA in PATN analysis (The division of sites into general classification groups are identified)



Note :※ = Classification Group

Fuel composition

Litter made up a large proportion of the fuel loads in the jarrah forest sites. It made up approximately 95% of the average fuel load at the site aged 43 years since last burn year-old site and approximately 83% of total fuel for the site aged six years (Appendix 1A : Information tables). Litter loads ranged from 8.50 - 39.39t/ha, and 16.48 - 39.19t/ha in the sites age six and 43 years since last burn respectively.

The standing aerated fuel was dominated by live material in the jarrah forest sites (Appendix . 1A : Information tables). The 43 year-old site averaged only 1.62t/ha of standing fuel and 0.93t/ha of this was live standing fuel. More standing material was sampled in the pit aged 6 years since last burn where an average of 3.87t/ha was sampled. An average of 3.09t/ha of live material and 0.78t/ha of dead material was sampled

Figure 3.6 : Fuel loads and composition in rehabilitated mine sites in 4 age classes

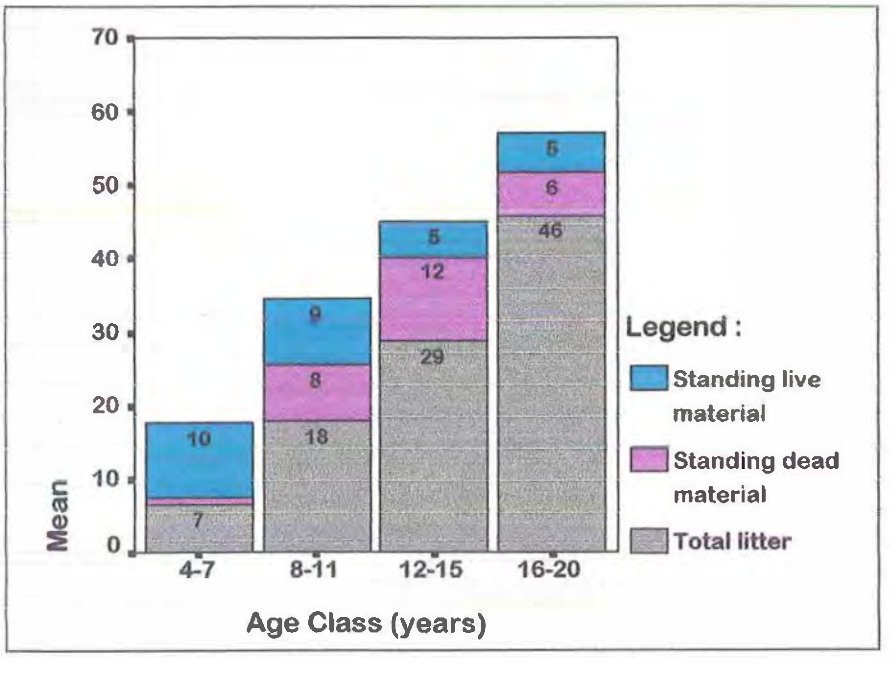
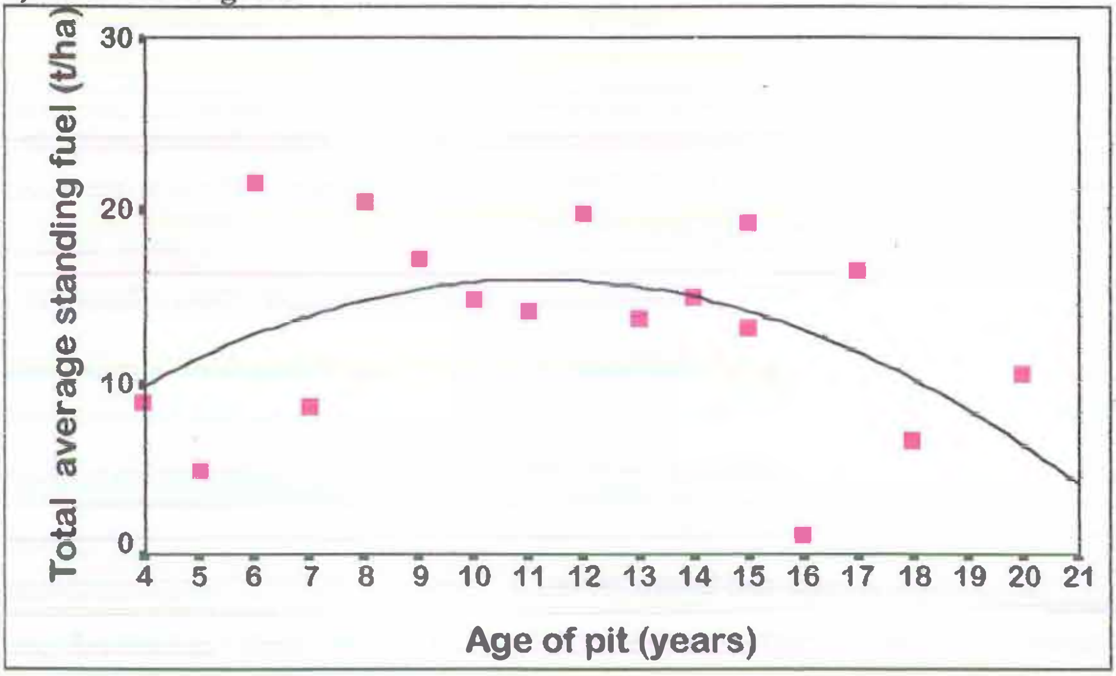
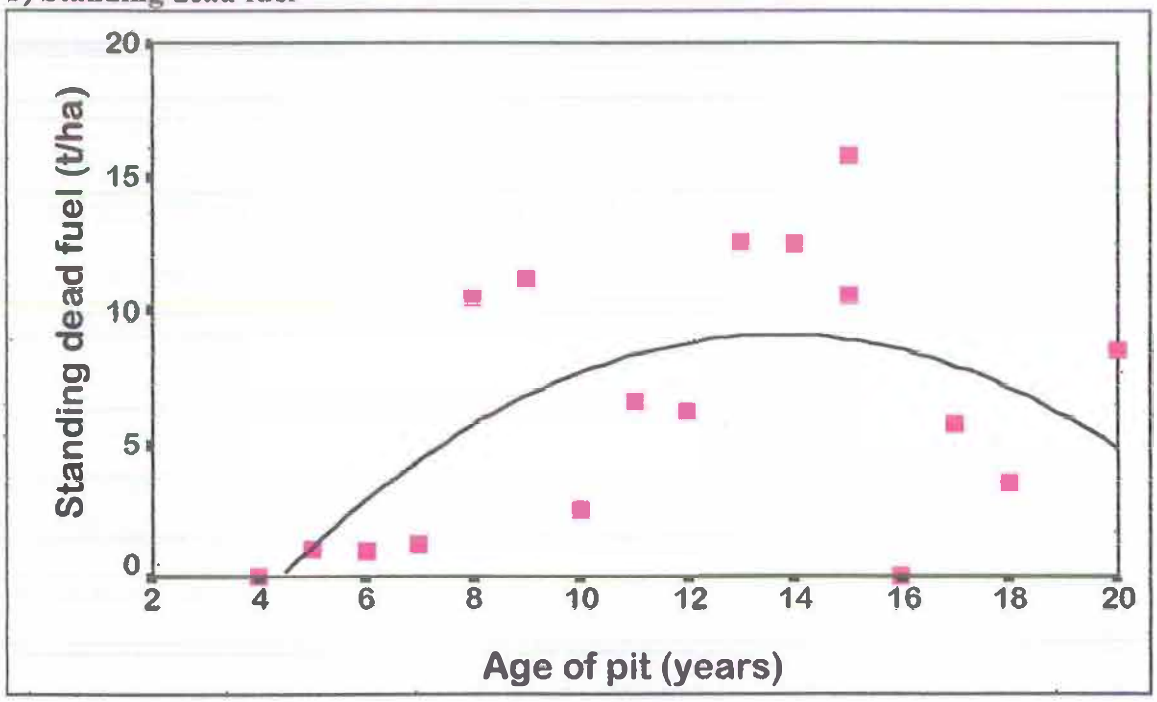


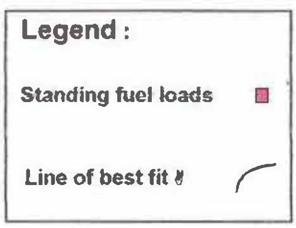
Figure 3.7 : Scattergrams indicating curvilinear relationships between age and standing fuel components

a) Total standing fuel



b) Standing dead fuel





* Note : The line of best fit was produced in these figures using Locally weighted regression scatterplot smoothing which is available in SPSS. It determines the line of best fit using an algorithm (Norusis, n.d.)

3.4 DISCUSSION

Fuel loads in rehabilitation areas increase over time. In the 20 year age period that has been studied it appears that an equilibrium fuel level had not been reached. Studies of native *eucalyptus* forest fuel (e.g. Fox *et al.*, 1979; Woods *et al.*, 1983; O'Connell, 1987; Burrows *et al.*, 1990; Burrows, 1994) have found that an equilibrium is reached between fuel loads and time in response to a balance of fuel accumulation and decomposition. Burrows (1994) estimated that native jarrah forest fuels reach an equilibrium at 15 years since burning. Although the level of increase appeared to diminish in the older rehabilitation areas, they have not established this equilibrium after 20 years. However, it can be argued that these ecosystems are new and developing. Other studies in eucalypt forests have been carried out in mature ecosystems, in which the time period to reach the equilibrium levels of fuel loads relates to time since last fire. As the rehabilitation areas are developing ecosystems, they may take longer to reach an equilibrium than Burrows (1994) and other scientists (e.g. Fox *et al.*, 1979; Woods *et al.*, 1983, Birk *et al.*, 1987, Johnson *et al.*, 1995) have estimated for mature ecosystems responding to fire. The high variability of fuel loads in the older sites have the potential to conceal equilibrium levels in the rehabilitated areas. It may therefore be beneficial to exclude the oldest sites and monitor sites that are currently aged over 15 years.

Fuel loads in Alcoa's rehabilitation areas are high. This is a consequence of the rehabilitation strategies applied to these areas which employs the use of mainly leguminous species in the regeneration of the understorey. These species are characterised by fast growth and short life spans and therefore produce large amounts of fuel (Koch *et al.*, 1993; Koch *et al.*, 1994) (refer to Chapter 2 for further explanation). Other studies of fuel characteristics in eucalypt forests indicate equilibrium fuel levels that are considerably lower than the older sites measured in the rehabilitated pits (which had an average fuel for 16-20 years of 46.0t/ha). For example, Van Loon (1977), Fox *et al.* (1979) and Birk *et al.* (1989) approximated

available fuel between 12-20t/ha in the Manning River blackbutt (*Eucalyptus pilularis*) forests and dry sclerophyll forests of the N.S.W. Blue Mountains. Studies undertaken in the south-west of Western Australia are particularly pertinent to this study as they occur in the same general region as Alcoa's bauxite mine operations. O'Connell (1987) for example, estimated 30t/ha of litter will occur in Karri (*Eucalyptus diversicolor*) forests when they are at equilibrium (average litter for 16-20 years in the rehabilitation areas sampled was 39.35t/ha). Burrows (1994) estimated that equilibrium fuel in the jarrah forests to occur at 16t/ha. Larger fuel was included in this study which may have resulted in higher fuel load estimations than other studies. However, the estimations of litter loads made in remnant jarrah forest during the pilot study yielded fuel estimations comparable to those of Burrows (1994) in the same forest type. It was therefore considered that comparisons with other studies would be relevant.

Increased fire intensity is associated with higher fuel loads (Sneeuwjagt, 1985). CALM recommends fuel quantities of < 8t/ha in the jarrah forest (Burrows, 1994). The fuel loads in the older rehabilitation pits have not yet reached equilibrium and are already nearly six times greater than the CALM recommendation. This places them far beyond fuel levels that are considered to be controllable in moderate weather conditions (Fox *et al.*, 1979; Burrows, 1994; Grant *et al.*, 1996a). Accordingly, the high fuel loads of the rehabilitation areas have important implications in the development of a fire management plan.

Studies by Fox *et al.* (1979) and Woods *et al.* (1983) suggested that an equilibrium between fuel accumulation and decomposition will occur when suitable decomposer communities are established. In this study, the litter components exhibited relationships with time that are consistent with the development of functioning decomposer communities. Leaves were characterised by a relatively constant weight over the time period, while wood quantities increased with time. Constant leaf levels were probably the result of the breakdown of leaves by decomposers. Wood on the other hand, was found by Fox *et al.* (1979) to take longer to break down. This longer decomposition period combined with the large amount of senescing material that is

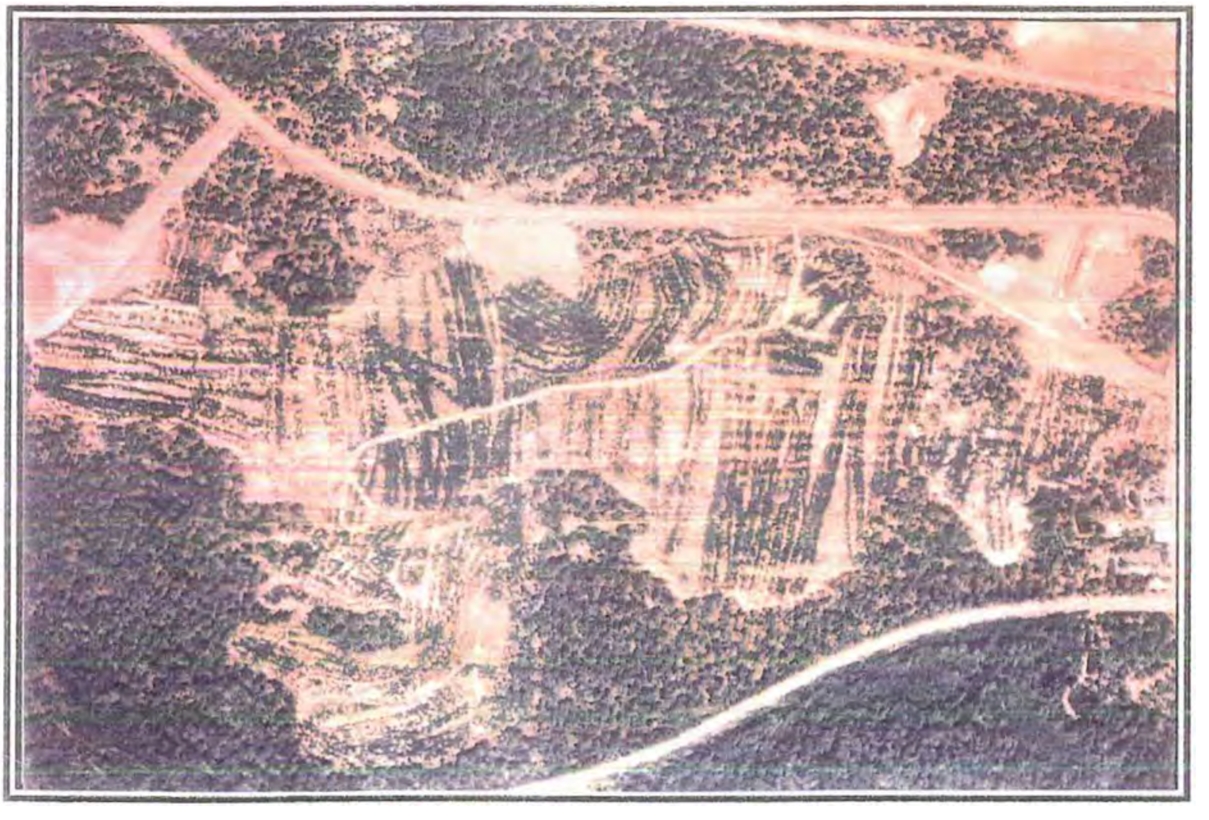
incorporated into the litter over time could cause wood levels to increase. An equilibrium may occur when decomposers are able to deal with the large wood inputs.

The increase in duff over time also has implications for the development of decomposer communities in Alcoa's rehabilitation areas. Duff increased in its proportion of litter and total fuel over time. In the older sites it became a dominant feature of the fuel. It appears that the duff is not becoming completely incorporated into the soils or is doing so at a slower rate than duff is being produced. This suggests that a component is missing or has been debilitated in the decomposition process. On the other hand, it could be a consequence of the large litter inputs creating too much material for the micro organisms to breakdown. Study in this area is necessary to determine whether an equilibrium will be reached over time or whether a missing link in the decomposition process is preventing equilibrium.

Rip lines in the rehabilitation areas influence vegetation patterns and consequently litter and standing aerated fuel because fuel tends to accumulate at the bottom of rip lines. Fertiliser and seeding methods also influence the vegetation and fuel patterns in the rehabilitated pits (Figure 3.8). Areas where aerial fertilising was used can develop banded vegetation patterns if the fertiliser is not applied evenly (Koch, 1993). Striping due to uneven seed application can also occur (Koch, 1993). These features of rehabilitated pits, as well as natural site variations such as topography, have contributed to the heterogeneous nature of fuel loads found within pits. This heterogeneity was exemplified by the large range of total fuel in each pit and high standard errors for average total fuel loads (Table 3.1). The jarrah forest sites assessed in the pilot study were found to have much less variability in fuel loads. This characteristic of the rehabilitated pits, as well as the large amounts of aerated fuel, can make fire management more difficult. A study by Grant *et al.* (1996a) of fire ecology in Alcoa's rehabilitated areas aged between 11 and 15 years found that the heterogeneous nature of total fuel loads within pits led to diverse fire behaviour in controlled burns. Studies by Burrows (1994) and Burrows *et al.* (1990) found that jarrah forest fuels are continuous and are contained mainly in the ground litter. These characteristics allow more flexibility and safety for a prescribed burn programme

Figure 3.8: Photographs showing the banding and striping patterning that may occur in rehabilitated pits due to uneven fertiliser and seeding processes in the initial rehabilitation phase

a) An aerial photograph of a pit rehabilitated in 1990. Both seeding banding and fertiliser striping are evident.



b) Pit rehabilitated in 1991 showing an unseeded band which is dominated by plants emerging from the topsoil

c) Pit rehabilitated in 1992 shows stripes caused by an uneven aerial fertiliser application

(Burrows, 1994) than the fuel loads of rehabilitation areas which are discontinuous and have a significant proportion of aerated fuel.

The total average standing material in the rehabilitated areas had a generally curvilinear relationship with time and was not linearly correlated with the yearly, four yearly age classes, or the classification groups. This curvilinear relationship between time and standing material is related to the understorey species composition which showed fast growth followed by senescence into the litter layer (which is discussed further in chapter 4 'Fuel structure'). This growth pattern causes the pits to have large amounts of standing live and dead vegetation until approximately 15 years.

Variability is an inherent characteristic of standing material in rehabilitated areas (Grant *et al.*, 1996a). Walker (1981) suggested that spatial variation in fuel quantities would create problems in estimates of available fuel. This is the case in the rehabilitation areas with regard to standing fuel. The extreme variability made analysis of the standing material difficult and may have confounded some of the results. The amount of live standing material for example, was seen to decrease over time, but no significant relationship was evident between the amount of live standing fuel and age class. Larger sampling quadrats and a larger sample size may improve the outcomes of standing fuel sampling by taking the variability of the fuel into account. A larger quadrat size would effectively decrease the variability between quadrats and in turn decrease the standard error of the mean.

Multivariate classification of the study sites indicated that the fuel characteristics of the study sites were generally related to age since rehabilitation. Importantly though, the classification also indicated that time was not the only factor influencing fuel characteristics as some sites did not group into the general time sequence that the multivariate classification indicated. This suggests that the different methods of rehabilitation implemented in Alcoa's mined areas have produced variations in fuel characteristics between pits of similar age. The 18 year-old site for example, was fertilised by aerial methods which may have contributed to its lower levels of fuel

compared to the 17 and 20 year-old pits which were hand fertilised. This point is also highlighted by the low fuel levels exhibited by the 16 year-old rehabilitation pit. Low fuel levels occurred here because phosphate fertilisation of the pits was not carried out in 1980 (Alcoa, 1976 - 1992). This resulted in little understorey development which was reflected in the low fuel loads.

The variability of fuel characteristics in pits of similar ages may influence the ability to make accurate generalised assessment of fuel loads in relation to time, as increases in fuel loads were not consistent over time. Continued monitoring of fuel loads will help to determine whether the heterogeneity of fuel loads as a consequence of different rehabilitation methods will diminish over a longer time span. As mentioned earlier, it may be of benefit to exclude the sites rehabilitated before 1981 due to their high variability.

CHAPTER FOUR

FUEL STRUCTURE

4.1 INTRODUCTION

Fire behaviour is heavily influenced by the structure of standing vegetation (Sneeuwjagt, 1971; Sneeuwjagt *et al.*, 1985; Luke *et al.*, 1986). The determination of fuel loads alone is therefore insufficient to estimate fuel characteristics for fire management. The structure and density of the understorey, for example, is a major determinant in the rate of spread of a fire, especially upwards into the crown (McCaw, 1986; Bond *et al.*, 1996) The importance of standing fuel is also suggested by Grant *et al.* (1996a) who reported that standing fuel may have the largest impact on fire spread in Alcoa's rehabilitated areas. The definition of the vertical (i.e. stratification of the vegetation) and horizontal (i.e. the spatial distribution of individuals) structure of vegetation (Kershaw, 1973) is therefore important because the way vegetation is arranged has a large impact on its performance as a fuel (Burrows, 1986).

The species composition in rehabilitated bauxite mine areas is dominated by leguminous species that are characterised by fast growth and a relatively short life span (Ward *et al.*, 1990; Koch *et al.*, 1993; Koch *et al.*, 1994; Bright, 1995; Grant *et al.*, 1996a). The changes in fuel composition associated with these species were indicated in Chapter 3. The study of fuel loads and their composition in that chapter indicated that the quantity of fuel in the understorey progressed over time from a dominance of live material to a dominance of dead material. Standing fuel was found to make-up a significant proportion of the fuel load in the study pits, particularly between 4 and 15 years since rehabilitation.

Distinguishing between live and dead standing fuel is considered to be of importance in the definition of vegetation structure for fire management purposes. This is because they have different fire attributes. Live fuels change their moisture content only marginally in response to atmospheric conditions (Tunstall, 1991) (Figure 5.2b, 5.3b, 5.4b). Dead fuels on the other hand, dry out passively to equilibrium with the atmosphere (Johnson *et al.*, 1995) and may consistently remain at a low moisture content (Burrows, 1990) in the dry season. This is

because when a plant is alive much of its biomass is water. As a plant senesces the cellular spaces that have been filled with moisture are no longer controlled by the plant and will therefore be affected by the amount of moisture that is in the atmosphere (Tunstall, 1991). It is, then, the dead aerated standing fuel rather than the live that initially carries fire in the standing layer of the fuel. A fire will not normally be sustained in this layer if there is not enough dead standing material, or in the event that the dead material is too moist (Bond *et al.*, 1996). The proportions of live and dead material in the vegetation structure is also of importance because the combustion of dead material may dry out live material to the point where it too will combust (Bond *et al.*, 1996).

The spatial (or horizontal) structure of fuel is of importance in the assessment of fuel loads because if the fuel is patchy a fire front may not be able to continue and the fire will burn itself out. The aim of this chapter is to determine the fuel structure of the rehabilitated pits and to see if this structure has changed over time. This assessment will be made by estimating the horizontal and vertical distribution of fuels in pits aged between 4 and 20 years.

4.2 METHODS

Horizontal and vertical fuel distribution were estimated by using a levy pole method. It is a point-intercept sampling method which is used to construct height/density profiles of the understorey layer (Mueller-Dombois *et al.*, 1974; McCaw, 1991). Originally the levy transects were designed for use in pastoral vegetation (Levy *et al.*, 1933). It was adapted by Sneeuwjagt (1971) for use in forests and has been used since then in a number of forest studies (Sneeuwjagt 1973; Sneeuwjagt *et al.*, 1985; Nichols *et al.*, 1986; Burrows 1990, Van Etten, 1995).

Point-intercept methods are considered to be the most accurate in estimating the structure of herbaceous and shrubby vegetation (Chambers *et al.*, 1983), and they work well in dense shrub ecosystems (Burrows, 1986). Several disadvantages exist with the use of the levy pole method. These disadvantages include difficulties with its use on windy days and an over estimation of vegetation density that may occur when counting the number of contacts for fine branches and leaves (Catchpole *et al.*, 1992). These disadvantages were taken into account in the methods in which the levy pole was used. On windy days, counting of contacts at the upper limits of the

levy pole were stalled as much as possible to periods between wind gusts. Fine branches and leaves were dealt with by counting only the first touch of branchlets or leaflets.

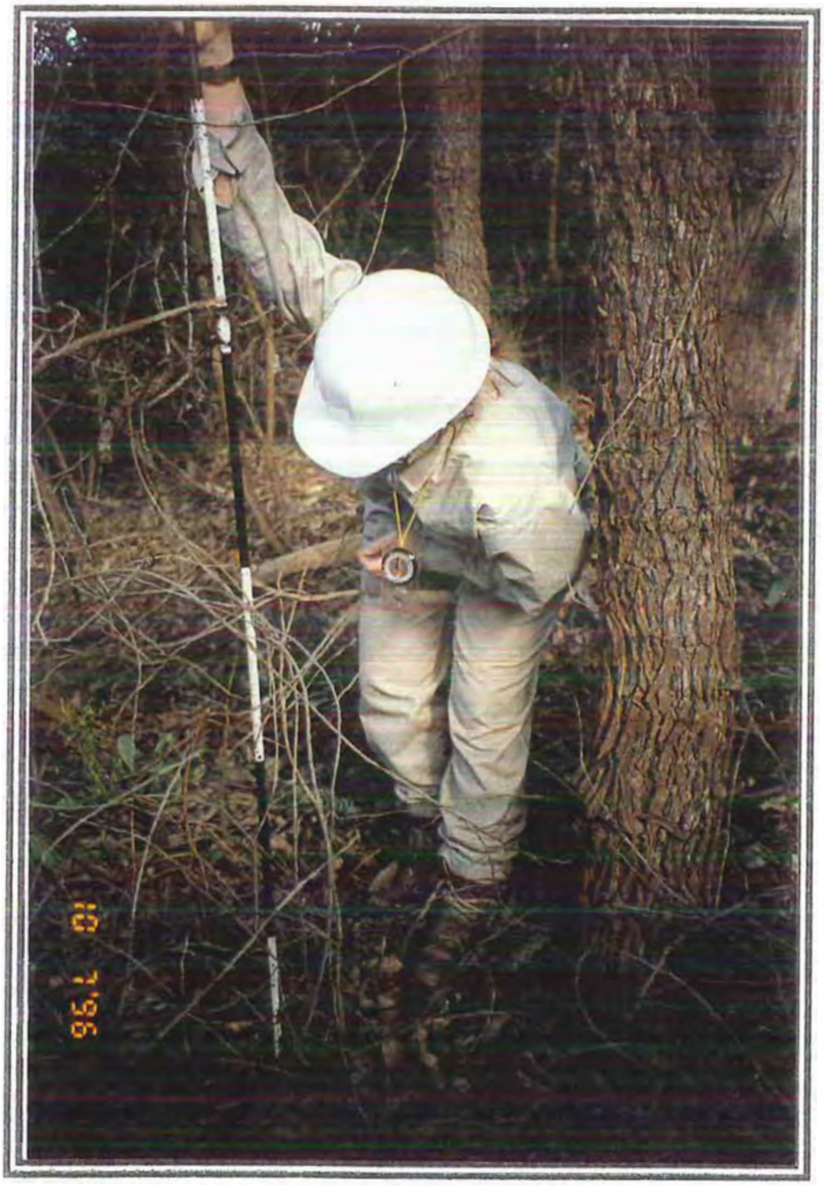
Two transects of 100m were made through each pit (Figure 3.1). At intervals of 2m, the levy pole (a rod that is marked at 30cm intervals) was placed vertically (Figure 4.1). The number of points where live and dead material touched the pole at each 30cm interval were counted and noted from the litter level up to a height of 3.9m. Where the contacts were made by fine branches and leaves every second contact was counted. Correlation between contacts and biomass was maximised by making the pole diameter as small as possible (~ 1cm) (Catchpole *et al.*, 1992). The species of the live material were noted to give an indication of the species composition of the standing fuel for each pit. The starting point for each transect was selected at random along the pit perimeter.

The vertical distribution of fuel was determined by calculating, for each height interval, the average number of touches of the 50 rod placings (Nichols *et al.*, 1986). These averages were used to produce height density profiles for each pit. The profiles indicated the height at which fuels were most dense and the composition of this fuel. Standard errors showed how variable the vertical distribution of fuel was.

The 2m levy pole intervals along the length of the transect measured the horizontal distribution of fuel. This distribution was measured by determining the maximum height of the understorey vegetation over the length of the transect. The average and standard error of the maximum touch points indicated the variability of the horizontal distribution of fuel in each pit.

The structure of fuels was estimated in two areas of jarrah forest within the mining lease. The methods used at these sites to determine fuel structure were the same as the methods used in the rehabilitated pits (as described above). The two sites were the same as those used for the study of fuel characteristics in the native jarrah forest (see Chapter 3). Comparisons were made between the forest sites and three rehabilitated pits of different ages. These comparisons indicated differences in the distribution of fuels in the two ecosystem types.

Figure 4.1 : The levy pole (3.9m in height and divided into 30cm intervals along its length)



4.3 RESULTS

4.3.1 Vertical Distribution

The vertical structure of fuel clearly changes over time (see Appendix 2 :Information tables for individual sites). The main changes that occurred are demonstrated by graphing them in four yearly intervals (Figure 4.2). Standing fuels were made up of mainly live material in the 4-7 year age class (Figure 4.2a). The highest density of live fuel occurred between 120-210cm in height. Some dead standing material was present in this age class, mainly below 90cm in height. Live standing material continued to dominate in the 8-11 year age group but dead standing material had increased (Figure 4.2b). Live material attained its highest density in the 120-150cm height range. Dead standing material dominated in fuel density up to 90cm particularly in the 0-30cm height range. The vertical fuel structure changed from dominance of live material to dominance of dead material from 12 years onwards (Figure 4.2c & 4.2d). In the 12-15 year class the density of standing dead fuel was very high between ground level and 60cm in height. Dead fuel continued to be the most important component of fuel up to about 120cm in height. The 16-20 year age class had the lowest density of standing fuel of all the classes. It was dominated by standing dead fuel from the ground level up to 60cm.

The vertical distribution of the standing fuel also changed over time in the classification groups defined by multivariate analysis (Figure 4.3). The distribution and density of the groups are very similar to the 4 yearly age intervals (Figure 4.2 & 4.3). As discussed in chapter 3, the quantity of standing fuel was not significantly correlated with any of the classifications used.

The vertical distribution of fuels in the jarrah forest differed from rehabilitated sites. The jarrah forest sites were dominated by live standing material. The forest sites aged 6 years since last burn was most dense between 0-90cm. The site that had been left unburnt for approximately 47 years had the highest density of live material close to the ground between 0 and 30cm. Both sites showed a significant proportion of dead material in the 0-30cm height interval, but dead material contributed very little to the overall density of the vegetation above 30cm in height. The vertical distribution of fuel was less variable in the jarrah forest sites than the rehabilitated pits. This was shown by the accumulative standard errors for the average density of fuels which were higher in the rehabilitated pits (Table 4.1).

Table 4.1 : Results indicating average touches and standard error for the jarrah forest sites and three representative rehabilitation sites

Levy interval (30cm intervals)	*Mean touches for Jarrah Forest aged 6yrs*	*Standard error for Jarrah Forest aged 6yrs*	*Mean touches for Jarrah Forest aged 43yrs*	*Standard error for Jarrah Forest aged 43yrs*	*Mean touches for rehabilitation site aged 5yrs*	*Standard error for rehabilitation site aged 5yrs*	*Mean touches for rehabilitation site aged 11yrs*	*Standard error for rehabilitation site aged 11yrs*	*Mean touches for rehabilitation site aged 20yrs*	*Standard error for rehabilitation site aged 20yrs*
0-30	2.12	*0.27*	2.26	*0.18*	0.66	*0.23*	2.20	*0.36*	1.38	*0.21*
30-60	1.34	*0.30*	0.73	*0.16*	1.24	*0.28*	1.50	*0.32*	0.68	*0.18*
60-90	1.16	*0.33*	0.54	*0.16*	1.56	*0.38*	0.96	*0.26*	0.30	*0.14*
90-120	0.46	*0.20*	0.04	*0.03*	1.72	*0.39*	0.74	*0.20*	0.20	*0.09*
120-150	0.14	*0.11*	0.17	*0.08*	1.40	*0.33*	0.80	*0.23*	0.08	*0.05*
150-180	0.02	*0.02*	0.00	*0.00*	1.66	*0.35*	0.46	*0.19*	0.28	*0.12*
180-210	0.04	*0.04*	0.00	*0.00*	1.06	*0.24*	0.44	*0.20*	0.44	*0.16*
210-240	0.00	*0.00*	0.00	*0.00*	1.38	*0.33*	0.28	*0.14*	0.34	*0.12*
240-270	0.00	*0.00*	0.00	*0.00*	0.76	*0.19*	0.52	*0.22*	0.36	*0.12*
270-300	0.00	*0.00*	0.00	*0.00*	0.92	*0.28*	0.24	*0.12*	0.26	*0.12*
300-330	0.00	*0.00*	0.00	*0.00*	0.96	*0.26*	0.16	*0.10*	0.16	*0.08*
330-360	0.02	*0.02*	0.00	*0.00*	0.94	*0.24*	0.18	*0.08*	0.32	*0.24*
360-390	0.04	*0.03*	0.11	*0.05*	0.70	*0.17*	0.20	*0.08*	0.14	*0.06*
Accumulative standard error	-	*1.32*	-	*0.66*	-	*3.67*	-	*2.50*	-	*1.69*

Figure 4.2 : Stacked bar graphs indicating average vegetation structure using information gathered by levy pole transects

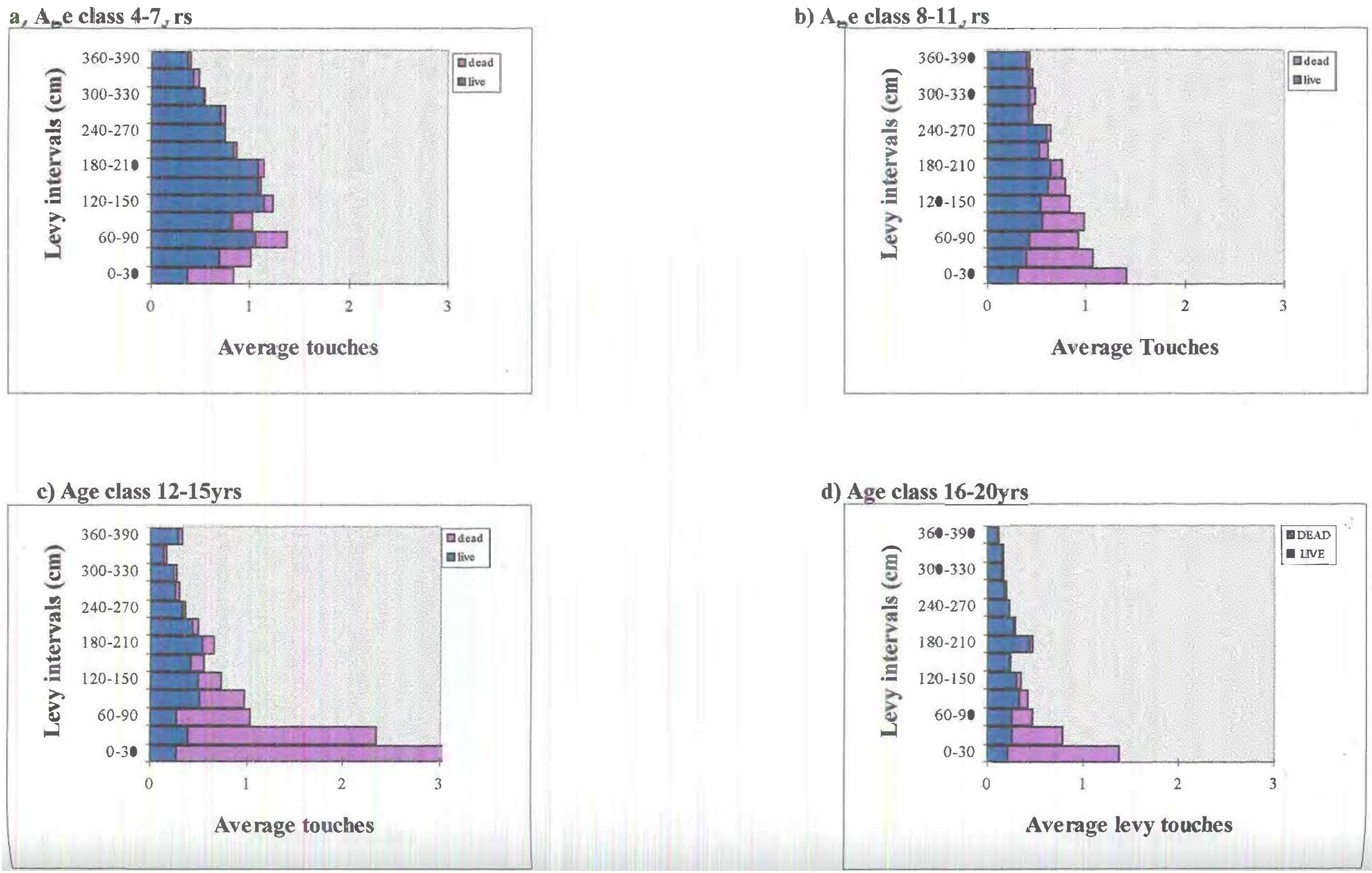


Figure 4.3 : Stacked bar graphs indicating average vegetation structure in the PATN classification groups using information gathered by levy method

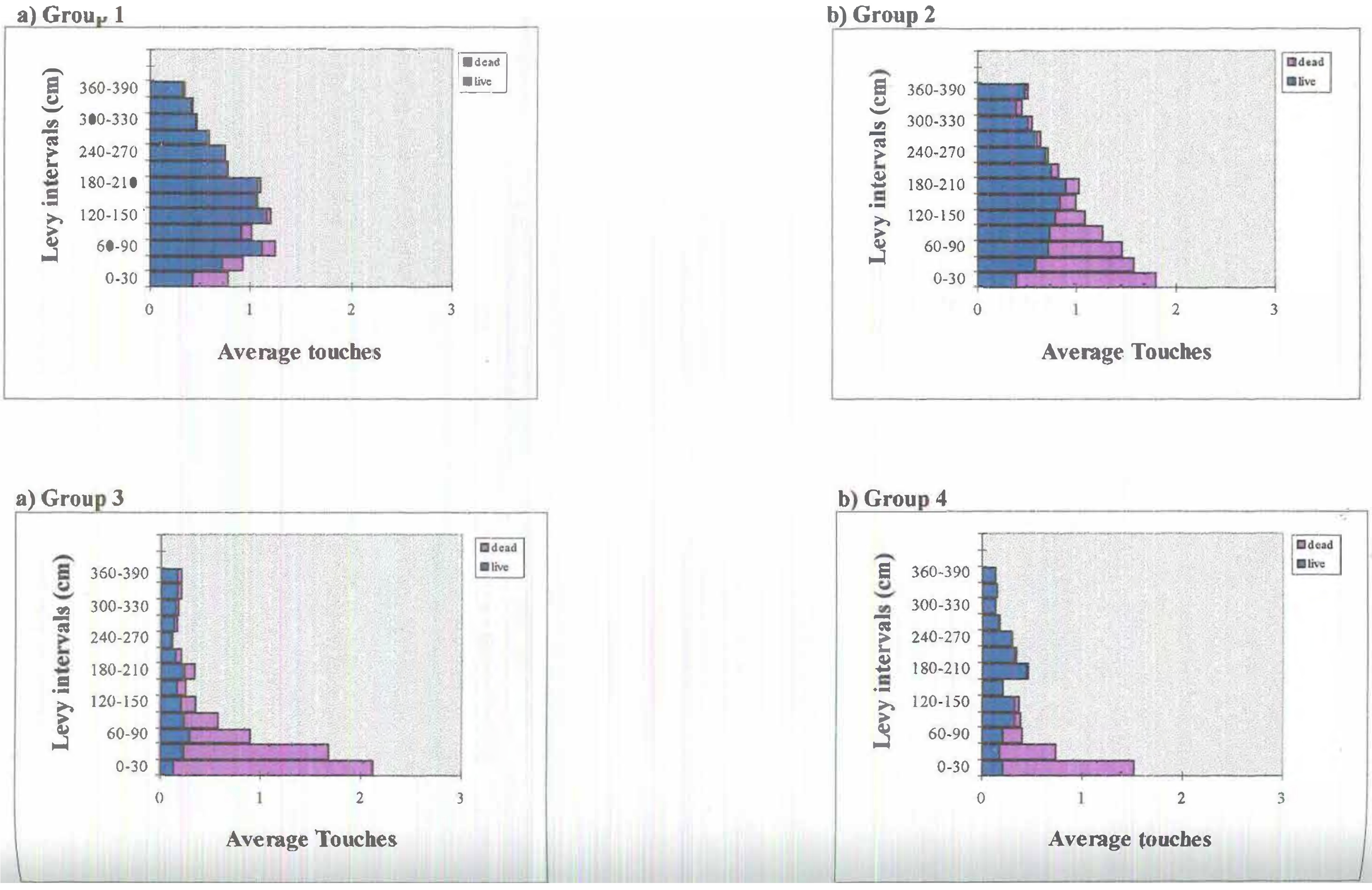


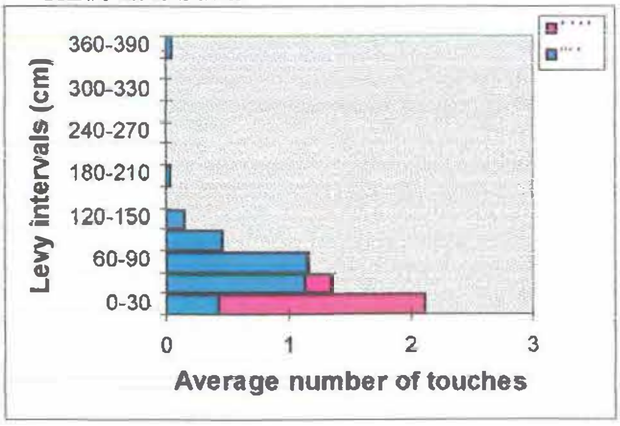
Table 4.2 : Results indicating the variability of the horizontal distribution of fuels in the jarrah forest sites compared with three representative rehabilitated pits.

Site and age ✍	*Mean height of maximum levy touch (cm)*	*Standard error*
Pit - 5 years	230	20.22
Pit - 11 years	260	17.48
Pit - 20 years	150	19.97
Jarrah forest - 6 years	60	8.99
Jarrah forest - 43 years	60	8.45

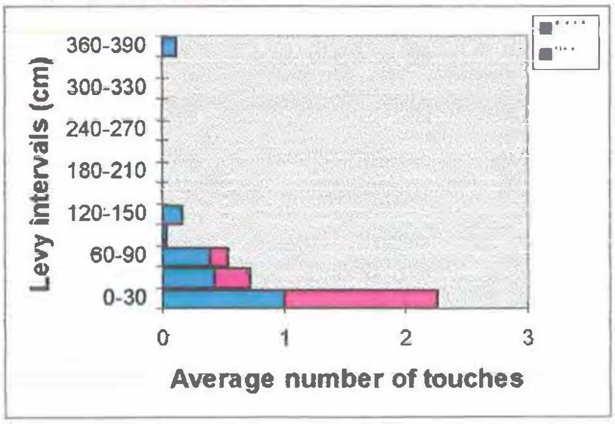
✍ The age of pits refers to it age since rehabilitation. For the jarrah forest sites age refers to time since last controlled burn.

Figure 4.4 : Vegetation structure of the native jarrah forest

a) Jarrah Forest aged six years since last burn



b) Jarrah Forest aged forty three years since last burn



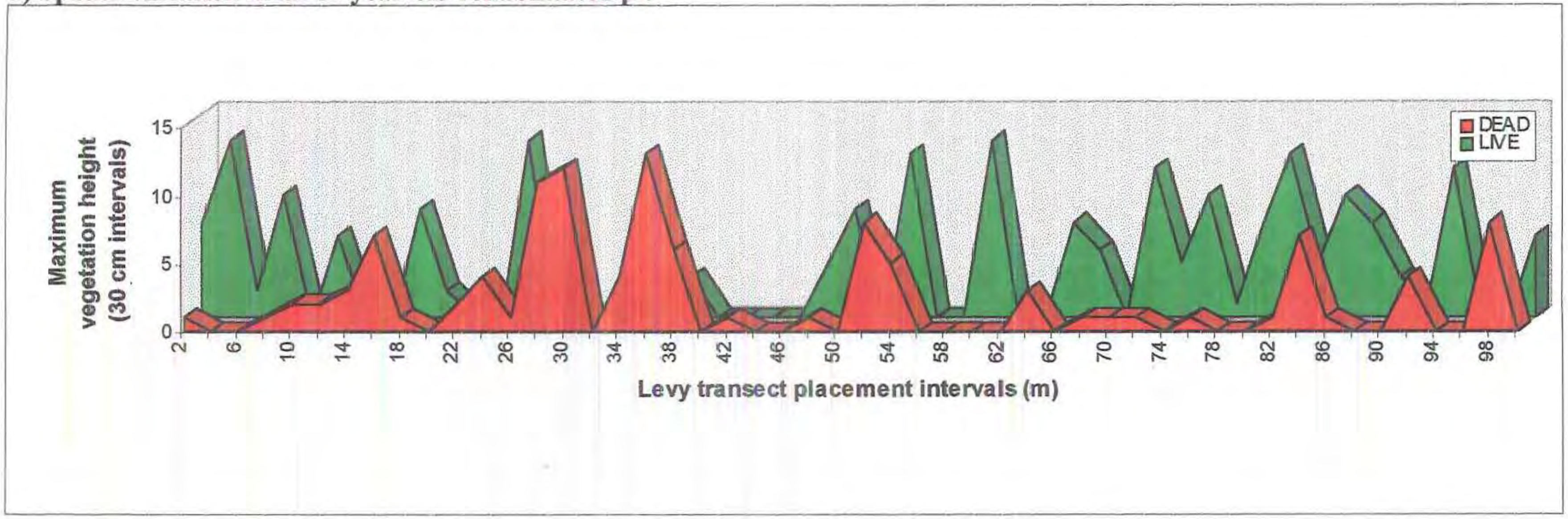
4.3.2 Horizontal Distribution

The horizontal or spatial distribution of fuel in the rehabilitated pits was highly variable. Within the representative pits the standard error for the average maximum height of understorey vegetation was large. It ranged from 17.48 to 20.22 (Table 4.2). In the forest sites the standard errors were much smaller (8.45 and 8.99). Figure 4.5 provides two examples of transects carried out in different aged pits. Both pits indicate that the maximum understorey vegetation height varies largely over the 100m distance. Patches of between 1-8m in horizontal length are evident (Figure 4.5). The native jarrah forest does not have the same degree of variation as the rehabilitated areas (Figure 4.6). They have a lower degree of standard error compared to the rehabilitated sites (Table 4.2). The transects (Figure 4.6a & 4.6b) are characterised by a generally homogenous spatial pattern.

The average maximum height of the understorey vegetation was 60cm in both jarrah forest sites (Table 4.2). This was considerably lower than the representative rehabilitation pits. They had an average maximum understorey height of 230cm, 260cm and 150cm in pits aged 5, 11 and 20 years since rehabilitation respectively.

Figure 4.5 Horizontal Distribution indicated be the maximum height of touches recorded in levy pole transects of two representative rehabilitated pits

a) Spatial variation in an 11 year-old rehabilitated pit



b) Spatial variation in a 5 year-old rehabilitated pit

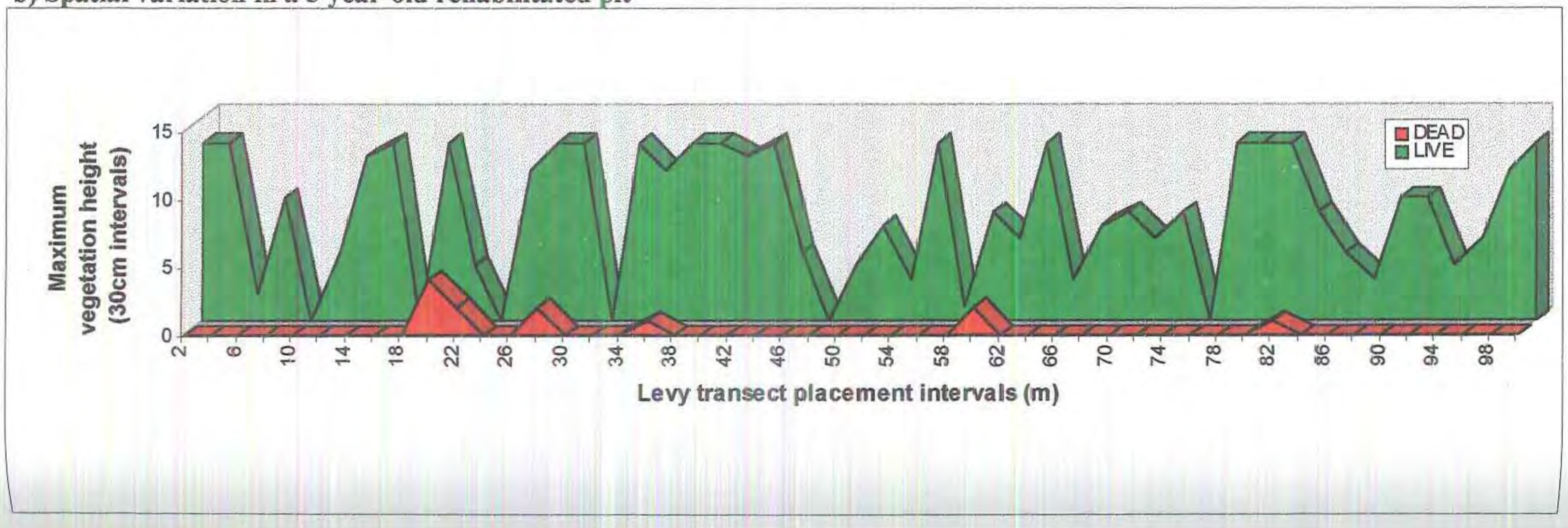
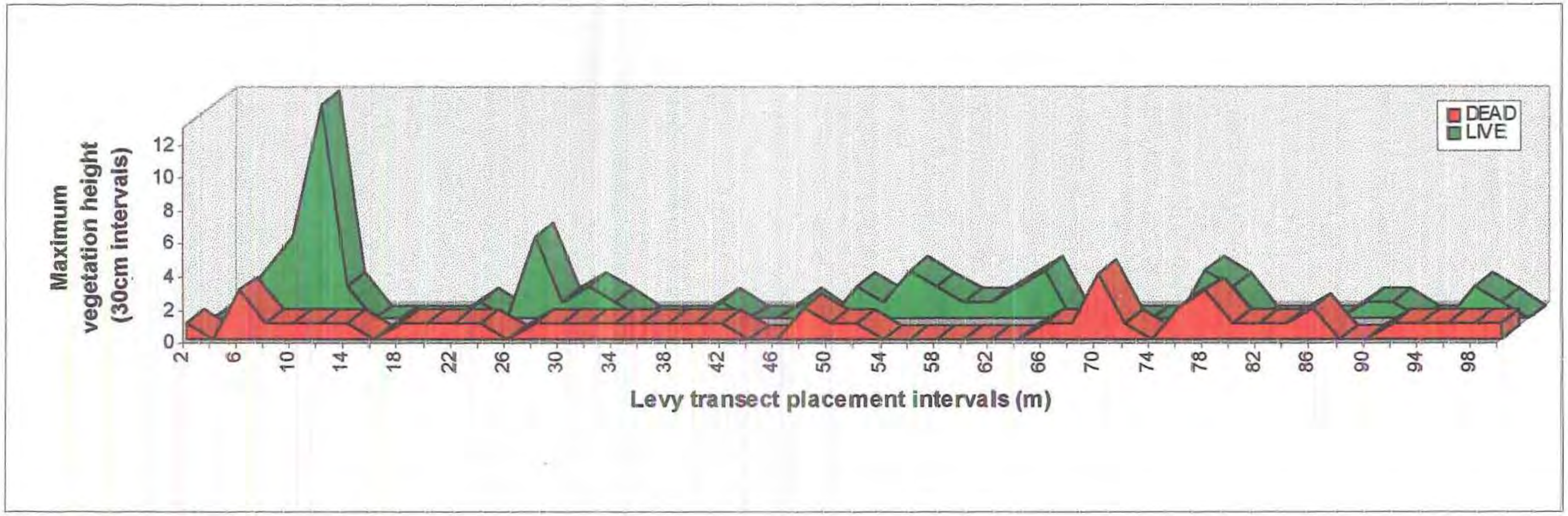
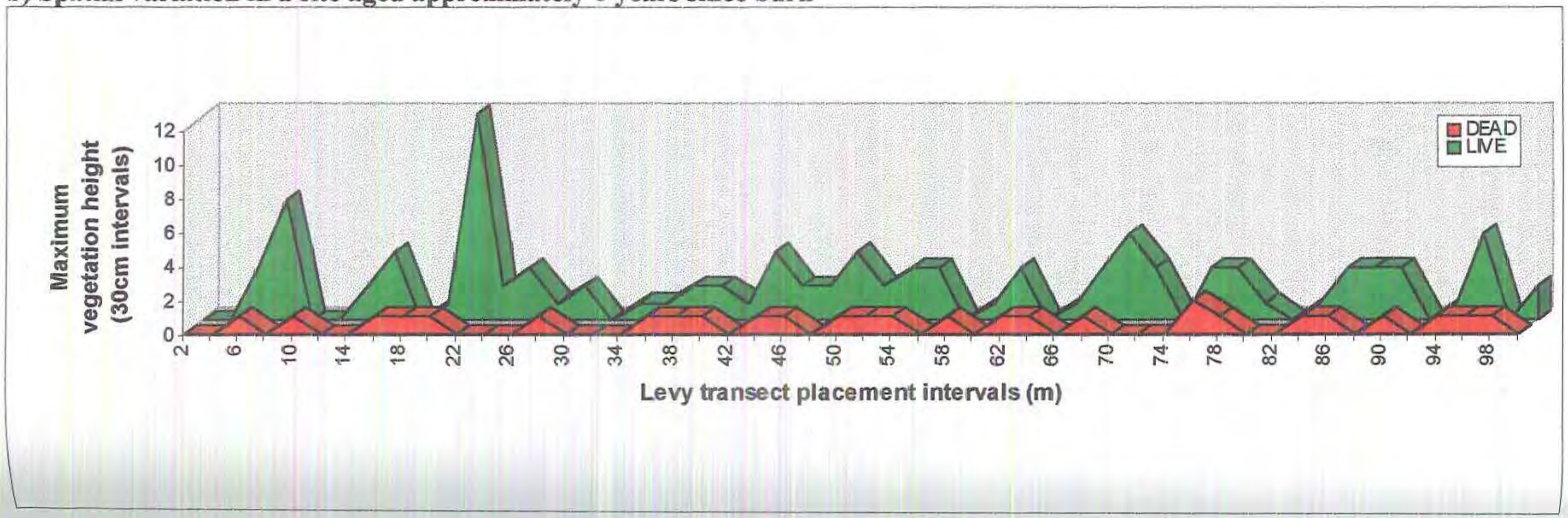


Figure 4.6 Horizontal Distribution of native jarrah forest sites indicated by the maximum height of touches recorded in levy pole transects

a) Spatial variation in a site aged approximately 47 years since burn



b) Spatial variation in a site aged approximately 6 years since burn



4.4 DISCUSSION

The results of this study indicate that the vertical distribution of fuel in the rehabilitated pits changes over time. The vertical structure of the fuel changed in respect to the proportion and density of live and dead material, the height of the most dense layers of fuel and also the total amount of material that contributes to the standing component of fuel. The classification groups defined by multivariate analysis were very similar to the 4 year age classes which supports that changes in fuel structure are time related. The horizontal distribution of vegetation was also characterised by heterogeneity throughout the 16 year time period studied. These aspects of the vegetation structure are important to a fire management plan. They have implications regarding the age of pit that is most appropriate to burn and the effects that the structure of the vegetation will have on a controlled burn.

Over time, changes in the rehabilitated understorey as it developed toward maturity were reflected by shifts in the distribution of the most dense layers of standing fuel and its proportion of live and dead material. The standing material studied in the rehabilitation areas was dominated by r-selected species in the understorey (Koch *et al.*, 1993; Koch *et al.*, 1994). They exhibited a typical life-cycle of rapid growth followed by senescence. This could be seen in the changing height at which vegetation was most dense and the changing dominance between live and dead fuel. The young rehabilitation was dominated by live growth. As the leguminous species began to senesce the proportion of dead material in the midstorey increased. *Acacia pulchella, A.lateriticola* and *A. drummondii* for example, are included in the seed mix in rehabilitated areas and have a life-span of between 5-8 years (Koch *et al.*, 1993). The rapid growth of these and other species is indicated by large proportions of live material in the young rehabilitation areas followed by senescence in the 8-11 year class, shown by the increase of dead material. This trend of senescence continued as longer lived species died off, including *A.myrtifolia* and *A.celastrifolia* (Koch *et al.*, 1993). The fall and incorporation of the dead material into the litter layer is the last step in senescence. This is indicated by the high density of dead vegetation close to the ground between 12-15 years and the lower proportions of fuel in this layer after 15 years as the fuel falls into the litter layer. The progression of the fuel structure from live to dead fuel domination is important as dead aerated fuel has been found by Burrows (1994) and Grant *et al.* (1996a) to have a large impact on controlled burns. This is

because standing dead fuel assists the movement of fire from the litter layer into the crown and is also responsible for the ignition of spot fires (Figure 4.7).

Standing aerated fuel was found in the study sites to be highly variable spatially. Grant *et al.* (1996a) also found that the standing layer of fuel made a patchy contribution to the amount of fuel that was available for burning. Within a pit, areas of dense understorey were adjacent to areas of little or no understorey growth resulting from a number of factors including rip lines, seeding and fertiliser patterning (discussed in Chapter 3). Burrows (1990) suggested that such a lack of continuity would make controlled burns difficult as they would be less predictable. Alternatively, Grant. *et al.* (1996a) suggests that this characteristic of rehabilitated pits has positive aspects because it may leave areas within a pit unburnt during controlled burns. These areas could act as a refuge for fauna and as sources of plant recruitment in the regeneration period of the pits after a controlled burn. The spatial variability inherent in rehabilitated areas needs to be incorporated into a burn program in terms of both its positive and negative aspects.

This current study and previous work (Nichols *et al.*, 1985; Grant *et al.*, 1996a) has shown that, up to about 15 years of age, the fuel of Alcoa's rehabilitated bauxite areas is different from the fuel structure of the northern jarrah forest. Grant *et al.* (1996a) studied pits aged between 11 and 15 years and found that they had a definite midstorey layer. This concurs with the findings of this study, where the midstorey was prominent up to 15 years. The midstorey is not a characteristic of the northern jarrah forest. Fire in these forests is carried by their continuous litter layer (Burrows *et al.*, 1990; Burrows, 1994). In contrast, Grant *et al.* (1996a) proposed that fire in the rehabilitated areas was carried by the trash of the midstorey. This may be due to the fact that the trash layer has a lower moisture content than the litter layer and lower temperatures are therefore required to consume this layer (Burrows *et al.*, 1990). The discontinuous nature of the litter layer in the rehabilitation areas may also contribute to this.

The vegetation structure of the older rehabilitation sites suggests that the rehabilitation areas will resemble the structure of the northern jarrah forest given more time. After 15 years senescence of the understorey was shown to have reached the point where most of the standing material had been incorporated into the litter layer. The midstorey layer is therefore less prominent and the overall vertical structure was similar to the jarrah forest. Although Grant *et al.* (1996a) found that the vegetation structure of younger rehabilitation areas did not fit the

Figure 4.7 : Photograph showing the wick effect caused by the middlestorey, transporting the flames into the overstorey.

standard fuel types recognised by CALM, this may change as the rehabilitation areas become more mature. The quantity of fuel in rehabilitated areas far exceeds those of the native jarrah forest and the species composition in rehabilitated areas is different. The rehabilitated areas must therefore still be considered as unique and fire management developed for the jarrah forest would not be appropriate.

Controlled burning may be easier to control in older rehabilitation areas where the understorey has collapsed into the litter layer. Further investigation of the fuel structure of rehabilitation areas over 15 years is necessary to explore this recommendation. The sample size in this study was small and findings may have been constrained by this. Further monitoring is also suggested because the rehabilitation techniques utilised in the older sites differs in some respects to the younger sites. Prior to 1981, the species used in the understorey seed mix changed significantly every year (Alcoa, 1976 -1992). The general rehabilitation methods employed by Alcoa also changed a great deal in the period prior to 1981 (Chapter 2). Since then the understorey seed mix composition and rehabilitation methods have been relatively standardised. Therefore, continued monitoring of the rehabilitation areas should be carried out in pits rehabilitated after 1981 as they should give a more reliable picture of the development of the fuel structure.

CHAPTER FIVE

FUEL CONSUMPTION

5.1 INTRODUCTION

Plant communities differ in their ability (or susceptibility) to burn depending on certain properties. These properties are associated with the ecosystem's fuel levels, moisture content, vegetation structure and decomposition levels (Bond *et al.*, 1996). The combinations of these properties that exist in the community at any given time, combined with natural conditions such as weather, determine the amount of fuel that is available to burn at that time. Controlled burns are carried out for a number of reasons, including fuel reduction, maximising biodiversity, habitat manipulation and species management (Burrows, 1994; Bond *et al.*, 1996; Grant *et al.*, 1996b). The purpose of a burn will usually influence the characteristics wanted in that burn in terms of its intensity, rate of spread and other factors that effect the way that the ecosystem responds after the burn. Some Australian plant species, for example, require high intensity burns to produce enough heat to stimulate the germination of their seed. A fire manager, therefore, needs to have accurate estimates of the fuel characteristics, moisture content, terrain and weather characteristics in order to meet the objectives of the burn.

Estimations of fuel loads, their composition and structure have been discussed in the previous chapters. For fire management it is important to be able to estimate how much of these fuels will burn in a fire. In order to develop a robust model, the maximum amount of fuel likely to combust needs to be recorded. Hence, for the estimation of the fuel available to burn it is important to have a range of fuel diameter size categories that encompass a range of possible fuel consumption outcomes. Categories that have incorrect fuel diameter classes could cause an under or over estimation of the available fuel in a pit. The objective of this chapter is to determine the fuel that is likely to combust in a controlled burn in rehabilitated bauxite mine areas by assessing fuel consumption in two controlled burns. It will indicate available fuel, and how this fuel is influenced by factors such as weather, moisture content and fuel

composition. Comparisons will also be made with fuel that is usually available in the native jarrah forest that surrounds the bauxite mine areas.

5.2 METHODS

The combustibility of fuels are influenced by a number of factors. Fuel characteristics were assessed in terms of the direct consumption of fuels. This was measured in two controlled burns. Analysis of moisture content was also made for the sites studied as moisture has been found to have a large influence on the combustibility of fuels (McArthur, 1967; Hatton *et al.*, 1991; Ryan *et al.*, 1991; Turnstall, 1991; Burrows, 1994; Bond *et al.*, 1996).

5.2.1 Fuel consumption

Available fuel was determined directly by measuring fuels before and after two controlled burns at the Huntly mine. Controlled burns had already been planned as part of studies being undertaken by Carl Grant, a PhD student from The University of Western Australia. It was appropriate to take advantage of these burns by using them as study sites, particularly as no suitable burns were planned at the Jarrahdale mine. The first burn was used as part of a pilot study for this research. It was carried out in spring 1995 in half of a 15 year-old rehabilitation area planted with a mixed overstorey dominated by *Eucalyptus resinifera, E. calophylla, E.wandoo* and seeded *E. marginata.* In autumn 1996, a second burn was carried out in the other half of the pit.

Pre-burn fuel assessments were made using the same methods in chapter 3, that is 10 1m x 0.5m quadrats in each burn area. In the spring burn area these methods were also used except the size categories of round-wood were <6 mm and >6 mm. These size categories were suggested by Burrows *et al.* (1990).

After the burns the remaining fuel was collected by replicating the pre-burn sampling. The quadrat sampling points were located immediately adjacent to the pre-burn sample plots. The litter was not sorted into the different components due to difficulty in determining the original nature of the remaining fuel.

The average fuel loads prior to the burn were compared to those determined after the burn. This gave an estimate of the amount of fuel that had been consumed in the burn. The proportion of fuel consumed in each burn was compared using a t-test for independent samples. This is a test designed to determine whether there is a significant difference between the means of two independent groups (Blackmore, 1994; Kinnear *et al.*, 1994). The H_0 was that there was no difference between the amount of fuel consumed in spring and autumn ($p \leq 0.05$). Levene Test of the homogeneity of variance was included in this analysis. An assumption of a valid t-test is homogeneity of variance (Kinnear *et al.*, 1994). Where the F value of the *Levene* test is not significant, the variances were assumed to be homogeneous and the equal values t-test outcomes used. Where a significant value was recorded by the *Levene* test, the unequal t-test results were used (Kinnear *et al.*, 1994). A second t-test was carried out on the samples excluding the quadrats that had not been burnt.

Two levy pole transects were also carried out prior to the autumn burn but not in the spring burn area. The methods used for the levy pole transects are described in Chapter 4. These transects were used to estimate the fuel structure of the pit prior to the burn.

A third form of fuel sampling was carried out after both of the burns. It involved the measurement of the diameter of round-wood stems of material not consumed by the burns. These measurements inferred the size of the wood consumed in the fires. A measurement of a stem diameter of 50mm, for example, indicated that all of the stem under 50mm was consumed in the fire. Methods of the measurement of the stems differed between the spring burn area and the autumn burn area. In spring, stem diameters were measured using callipers. The measurement was done in a random fashion walking through the pit.

In the autumn burn ten quadrats of 2.0m x 2.0m were set out prior to the burn. They were placed in the vicinity of the fuel quadrats to facilitate relocation after the burn. The position of each quadrat was chosen visually to be representative of the fuel structure of the pit. After the burn, measurements of the stem diameters of litter and standing fuel were taken using callipers.

5.2.2 Moisture content

Fire behaviour is influenced by the moisture content of the fuel. Decreasing moisture is related to an increasing combustion rate (Luke *et al.*, 1986; Burrows, 1994; Bond *et al.*, 1996). The moisture content (percent of oven dry weight or %ODW) therefore gave an indication of the relative combustibility of the components of the fuel. The formula for moisture content is as follows :

$$\text{Moisture Content (oven dry weight)} = \frac{WW - DW}{DW} \times 100\,\%$$

Where: WW = Wet Weight, and DW = Dry Weight

As the fuel sampling for this study occurred continuously between February and July, measurement of changes in moisture content over this period was possible. The moisture content of litter and standing fuel was plotted against the average rainfall, relative humidity and temperature for each month. The weather data was supplied by the Bureau of Meteorology from the Serpentine and Jarrahdale weather stations (1996).

5.3 RESULTS

5.3.1 Fuel consumption

A higher percentage (86.63%) of fuel was consumed in the spring burn than the autumn burn (62.56%) (Table 5.1). Testing to see if a difference could be identified between the mean amount of fuel consumed in each pit found no significant difference ($t = 0.89$, $df = 19$, $p = 0.387$). A second test, where the unburnt quadrats were excluded, did find a significant difference between the amount of fuel consumed in the two burns ($t = -4.35$, $df = 17$, $p = 0.002$) (Table 5.1).

The consumption of wood recorded through the measurement of stem diameters indicated that a larger proportion of stems were consumed in spring (28.26mm) than in autumn (15.95mm) (Appendix 1 : Pilot study). Average recorded fire intensity was also higher in the spring burn (1820Kw/m) than those recorded for the autumn burn (1104Kw/m) (Table 5.1).

Table 5.1 : Average fuel characteristics pre- and post-burn

	SPRING BURN			AUTUMN BURN		
Measurements	**Average Litter (t/ha)**	**Average Standing Fuel (t/ha)**	**Total Average Fuel (t/ha)**	**Average Litter (t/ha)**	**Average Standing Fuel (t/ha)**	**Total Average Fuel (t/ha)**
Pre-burn	8.27	18.32	**27.60** (7.21)	33.06	19.26	**52.32** (9.56)
Post-burn	1.61	2.09	**3.69** (1.85)	18.56	1.40	**19.96** (4.36)
Fuel consumed	6.66	16.23	**23.91**	14.51	17.86	**32.36**
Fuel consumed %	80.53	88.59	**86.63**	43.88	92.73	**62.57**
Fuel consumed **(unburnt quadrats excluded)**	90.81	99.67	**97.06**	-	-	-
Fire Intensity (Kw m^{-1})	-	-	**1820 ∇**	-	-	**1104 ∇**
Litter Moisture % (0 - 5 cm)	8.7 ∇	-	-	11.7 ∇	-	-
Litter Moisture % (whole profile)	22.5 ∇	-	-	28.9 ∇	-	-

** Note : ( ) = Standard error, ∇ = cited in Grant *et al.*. (1996a).

The spring burn fire intensity was close to the average fire intensity (1932Kw/m) measured by Grant *et al* (1996a) in controlled burns carried out between May 1994 and November 1995 (Table 5.1). The spring burn was therefore assumed to have been representative of average fuel consumption rates in rehabilitated areas. The average round-wood diameter measurement of 28.26mm indicated that material smaller than this was typically consumed in the fire. This diameter was used as a guide in the development of the round-wood size classes used in this study (classes are described in Chapter 3).

The quantity of standing fuel was similar in the spring and autumn burn pits. The consumption of this standing fuel was very high at both sites with 88.59% consumed in spring and 92.73% in autumn (Table 5.1). The standing material in the autumn burn pit was dominated by dead aerated material (Figure 5.1).

The fuel remaining after the controlled burns was found mainly in the litter layer. The data suggests that a much higher percentage of the litter was consumed in the spring controlled burn than in autumn (Table 5.1). Litter moisture was higher in the autumn burn pit.

5.3.2 Moisture content

Comparisons between fuel moisture in rehabilitated areas and the seasonal influences of rainfall, temperature and relative humidity indicated clearly that moisture content responded to all of these weather conditions (Figure 5.2, 5.3 & 5.4). As total rainfall and relative humidity increased the moisture content of the fuel also increased. Alternatively, average daily temperature had a strong negative relationship with moisture content. As temperatures decreased the moisture content increased. The strength of these relationships is indicated by the high correlation co-efficients between rainfall, humidity, temperature and the fuel variables tested (litter and standing material). All of the variables had absolute r-values larger than 0.92 ($p \leq 0.01$) (Table 5.2). The relationship between rainfall and the fuel variables was particularly pronounced. Live standing material exhibited the lowest increase in moisture content, rising from approximately 59.23(%ODW) in February to 89.71% in June (Figure 5.2b). Dead standing material increased from 8.41% in February to 58.22% in July (Figure

5.2b). Litter showed the largest increase in moisture content % from 8.19 % in February to 107.78 % in July (Figure 5.2a).

Figure 5.1 : A Height density profile of standing fuel prior to the autumn burn determined via levy pole transects

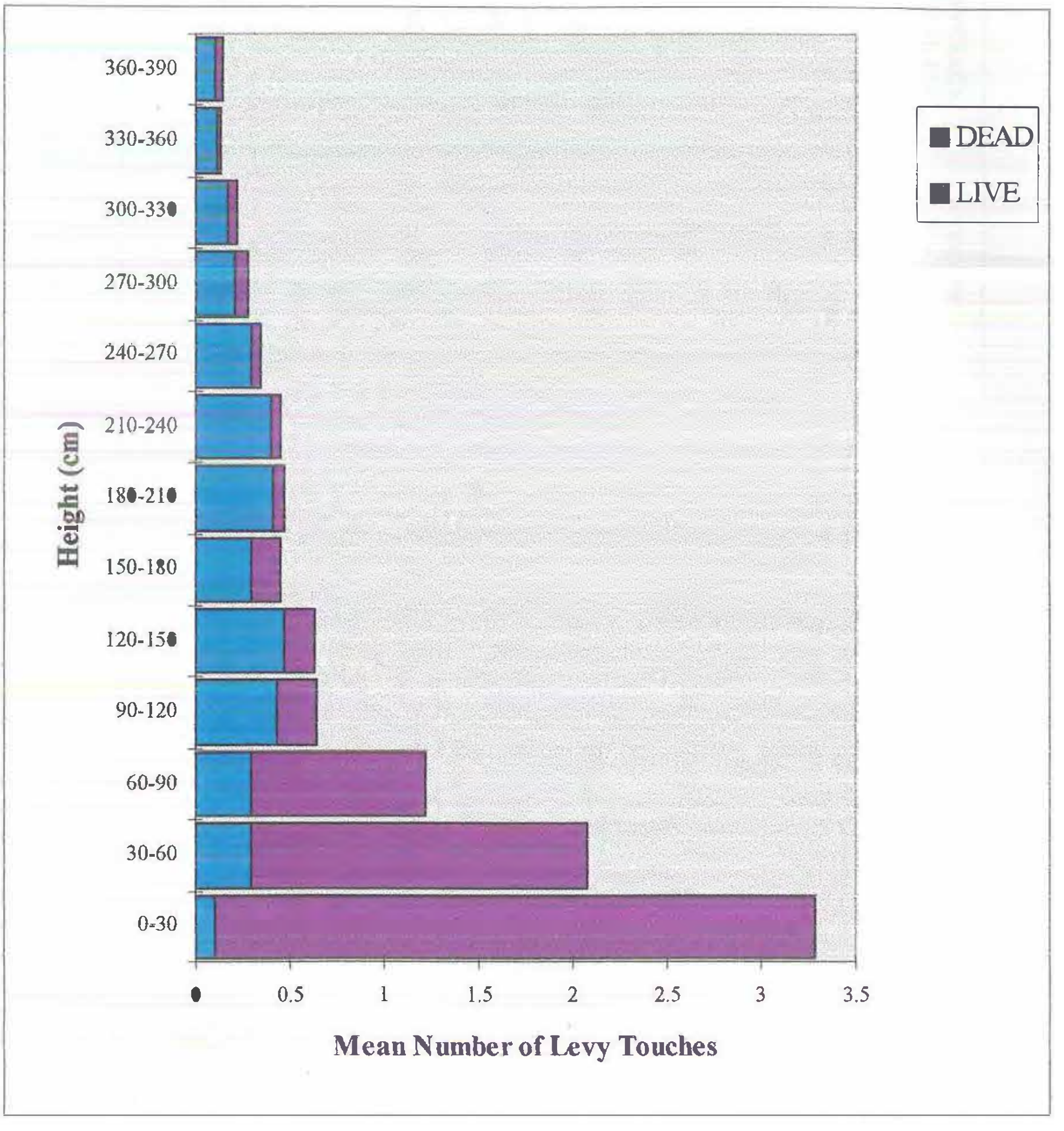


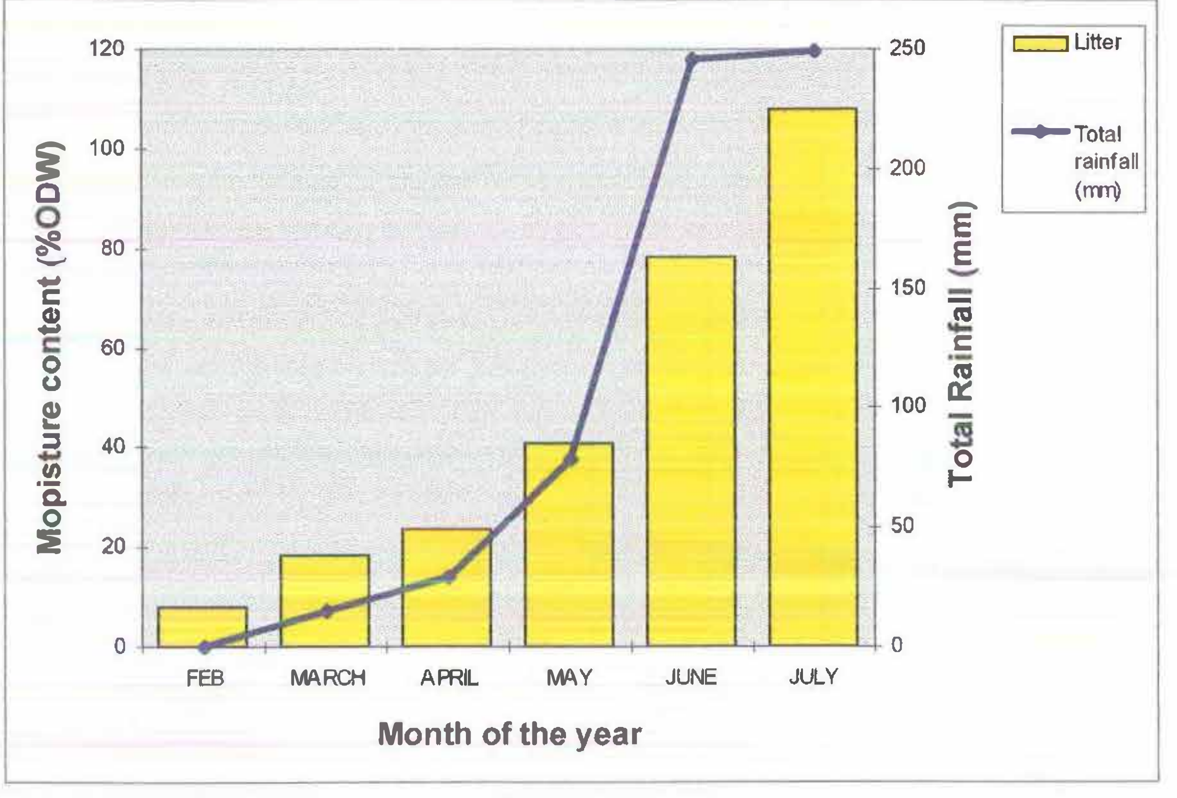
Table 5.2 : Correlation matrix for major fuel components and climatic conditions

	DEAD STANDING FUEL	AVERAGE TOTAL FUEL	AVERAGE MONTHLY RELATIVE HUMIDITY	AVERAGE LITTER	STANDING LIVE FUEL	AVERAGE MONTHLY RAINFALL	AVERAGE STANDING FUEL	AVERAGE MONTHLY MAXIMUM TEMPERATURE
DEAD STANDING FUEL	1.0000 ✓							
AVERAGE TOTAL FUEL	0.9913 ✓	1.0000 ✓						
RELATIVE HUMIDITY	0.9254 ✓	0.9598 ✓	1.0000					
AVERAGE LITTER	0.9849 ✓	0.9690 ✓	0.9193 ✓	1.0000				
STANDING LIVE FUEL	0.9779 ✓	0.9925 ✓	0.9551 ✓	0.9403 ✓	1.0000			
AVERAGE MONTHLY RAINFALL	0.9907 ✓	0.9837 ✓	0.9215 ✓	0.9707 ✓	0.9832 ✓	1.0000		
AVERAGE STANDING FUEL	0.9495 ✓	0.9768 ✓	0.9431 ✓	0.8998 ✓	0.9781 ✓	0.9338 ✓	1.0000	
AVERAGE MAX UMUM MONTHLY TEMPERATURE	-0.9053 ✓	-0.9395 ✓	-0.9929 ✓	-0.9166 ✓	-0.9283 ✓	-0.9037 ✓	-0.9069 ✓	1.0000

Note:✓=$p \leq 0.05$

Figure 5.2 : Graphs indicating the association between the moisture content (% oven dry weight) of fuel components and rainfall

a) A comparison between the moisture content (%ODW)of litter and rainfall



b) A comparison between the moisture content (%ODW) of the standing components of fuel and rainfall

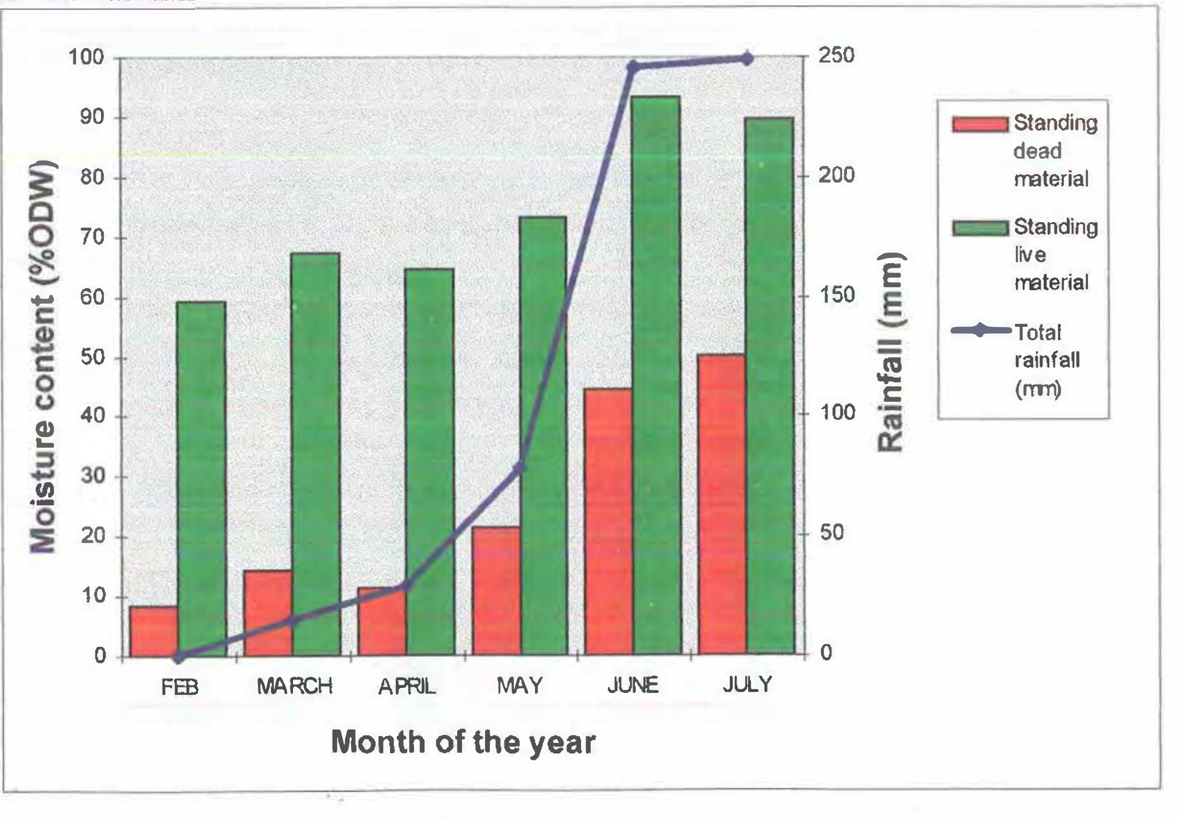
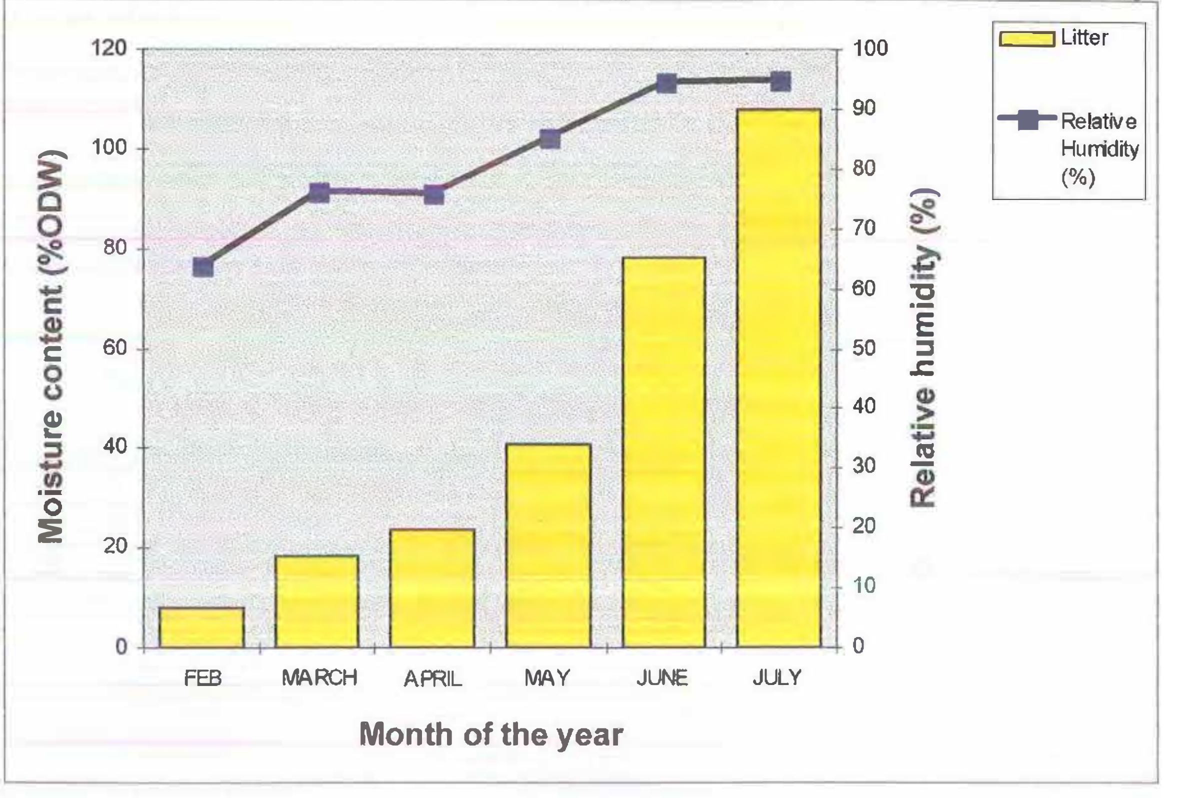


Figure 5.3 : Association between the moisture content (% oven dry weight) of fuel components and average monthly relative humidity.

a) A comparison between the moisture content (%ODW)of litter and relative humidity



b) A comparison between the moisture content (%ODW) of the standing components of fuel and relative humidity

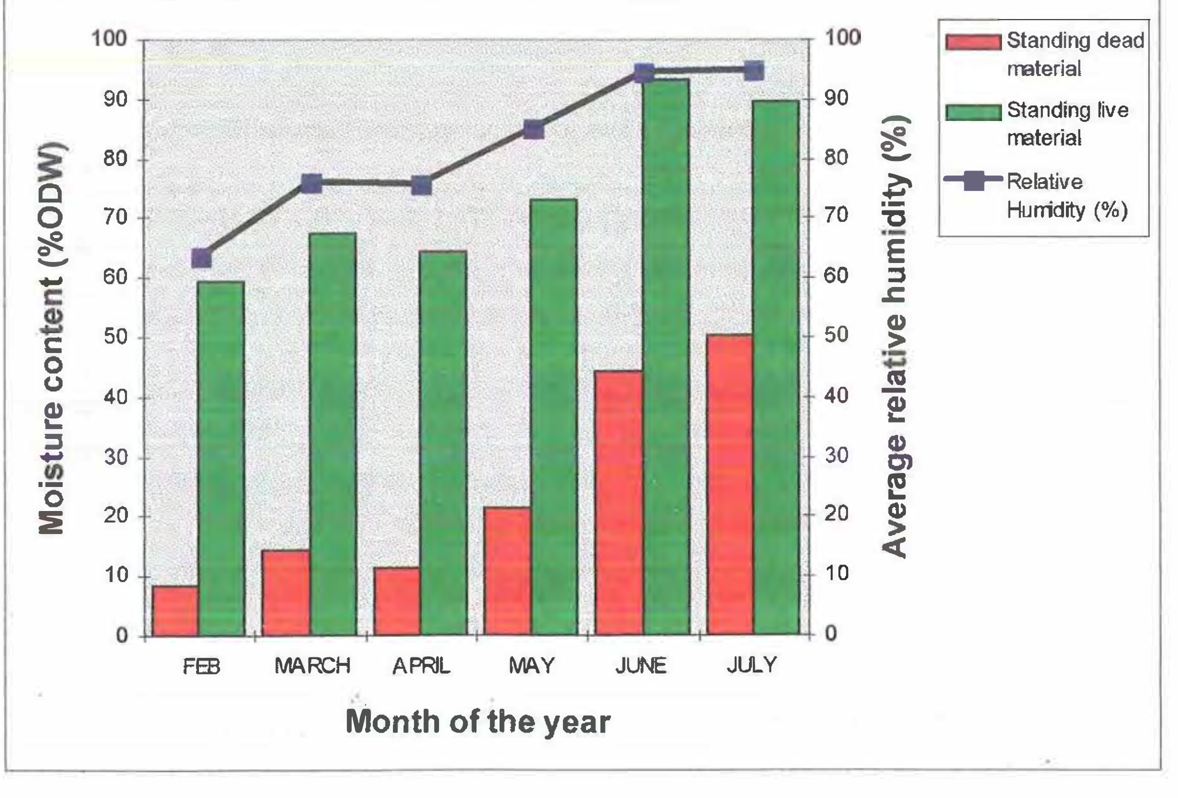
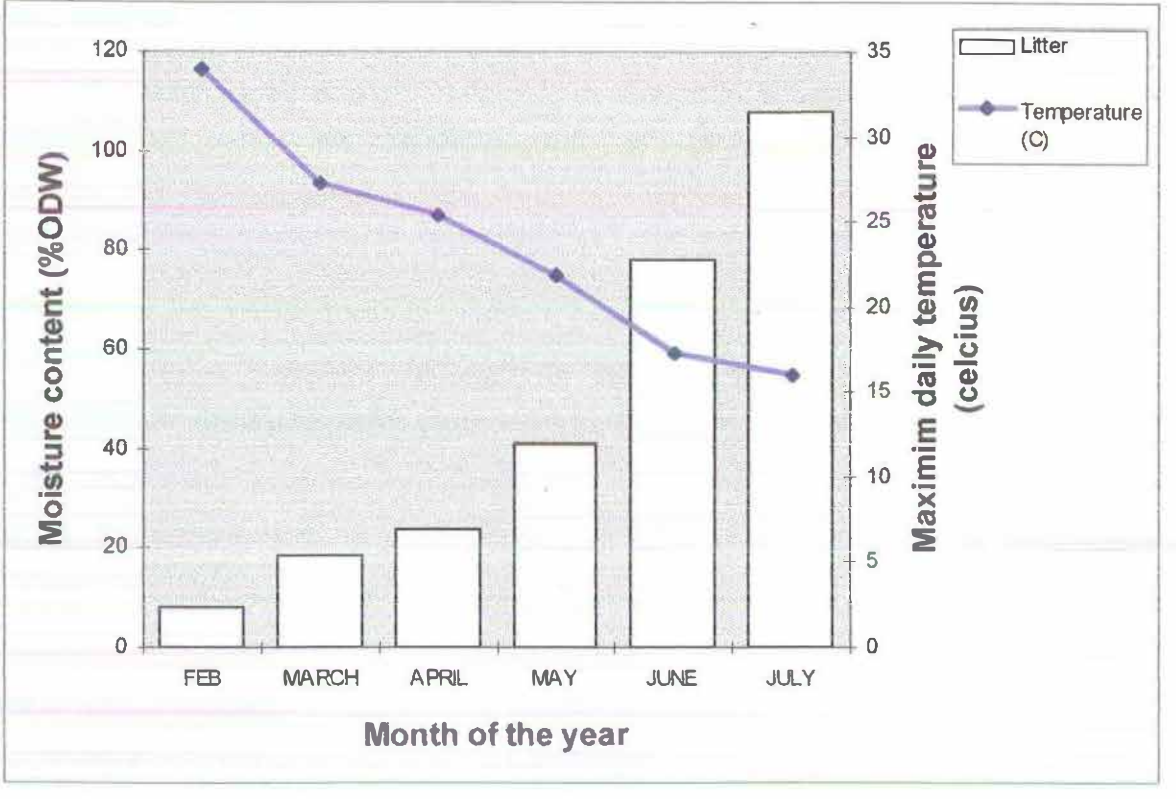
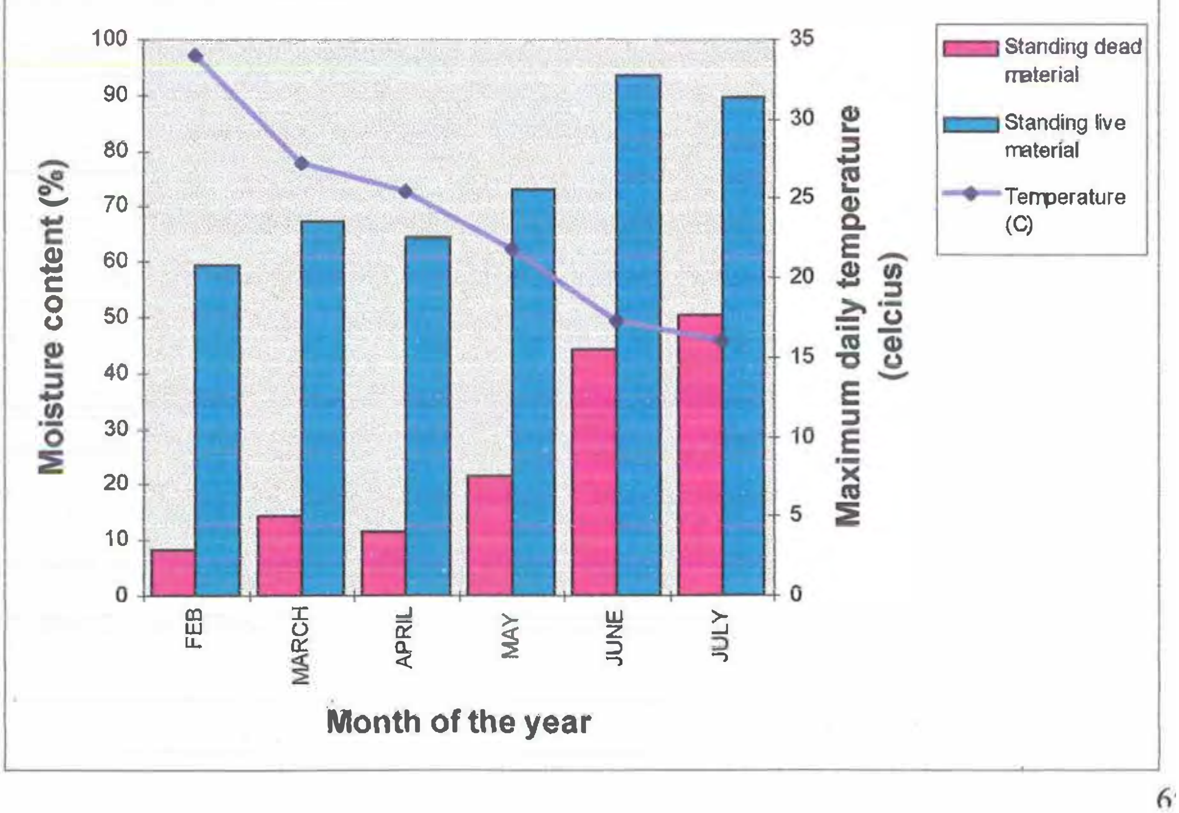


Figure 5.4a : Association between the moisture content (%oven dry weight) of fuel components and average maximum temperature (°C).

a) A comparison between the moisture content (%ODW) of litter and average maximum temperature



b) A comparison between the moisture content (%ODW) of the standing components of fuel a average maximum temperature (°C).



5.4 DISCUSSION

A study of fuel consumption in the two burns in the rehabilitation areas showed that a spring burn of moderate to high intensity consumed significantly more fuel than an autumn burn of lower intensity. This is unusual as autumn burns are characteristically more intense than those carried out in spring. This is due to the generally lower fuel moisture conditions that generally occur in Autumn. The drying effect of high temperatures, minimal rainfall, low humidity and other seasonal factors over the summer period cause this (Cheney, 1981; Burrows, 1994; Johnson *et al.*, 1995; Grant *et al.*, 1996). Moisture content is a major influence on fire behaviour as it inhibits the ignition of fuels (Burrows, 1994). The litter moisture content in the autumn burn area was higher than the spring burn area. It is suggested that the higher moisture content contributed to the lower fuel consumption and fire intensity in the autumn site. High moisture levels were particularly evident in the low lying areas of the pit. The success of the overstorey species in this area are evidence of the moist nature of this site. The trees were also of a very good size for their age, indicating that they have been assisted in their growth by sustained moisture levels (Grant pers comm, 1996). Temperature is also related to moisture content. The lateness of the burn in the fire season is also likely to have impacted on the moisture levels as temperatures were lower. Lower temperatures would cause less evaporation of moisture from the fuels. The fire was held in late April (30^{th}) when highest daytime temperatures averaged 25.4 °C, 29.4mm of rain had been recorded for the month (Bureau of Meteorology, 1996) and the first dews had been experienced in the area (personal observation). These are all factors that are associated with lower intensity burns.

The sloping aspect of the pit, a physical attribute of the area, is also likely to have contributed to the lower fuel consumption measured in the autumn burn. Fire spread is faster running up a slope than it is on flat ground. This is because the flames have closer contact with the fuel bed as the slope increases which causes the fuel ahead of the flames to dry out to the point of combustion faster (Cheney, 1981; Luke *et al.*, 1986). Johnson *et al.* (1995) found that running fires have lower fuel consumption because the fire is moving so fast that it only consumes the most flammable layers of fuel as it passes. In some areas of the pit ground litter was only partly consumed in the controlled burn and these were mostly at the bottom or on the sloped area which the fire ran up. This suggests that the fire skipped over this fuel as it moved, with increasing speed, up the slope. It also suggests that the litter fuel ignition was inhibited by its higher moisture content causing some litter to be left relatively untouched.

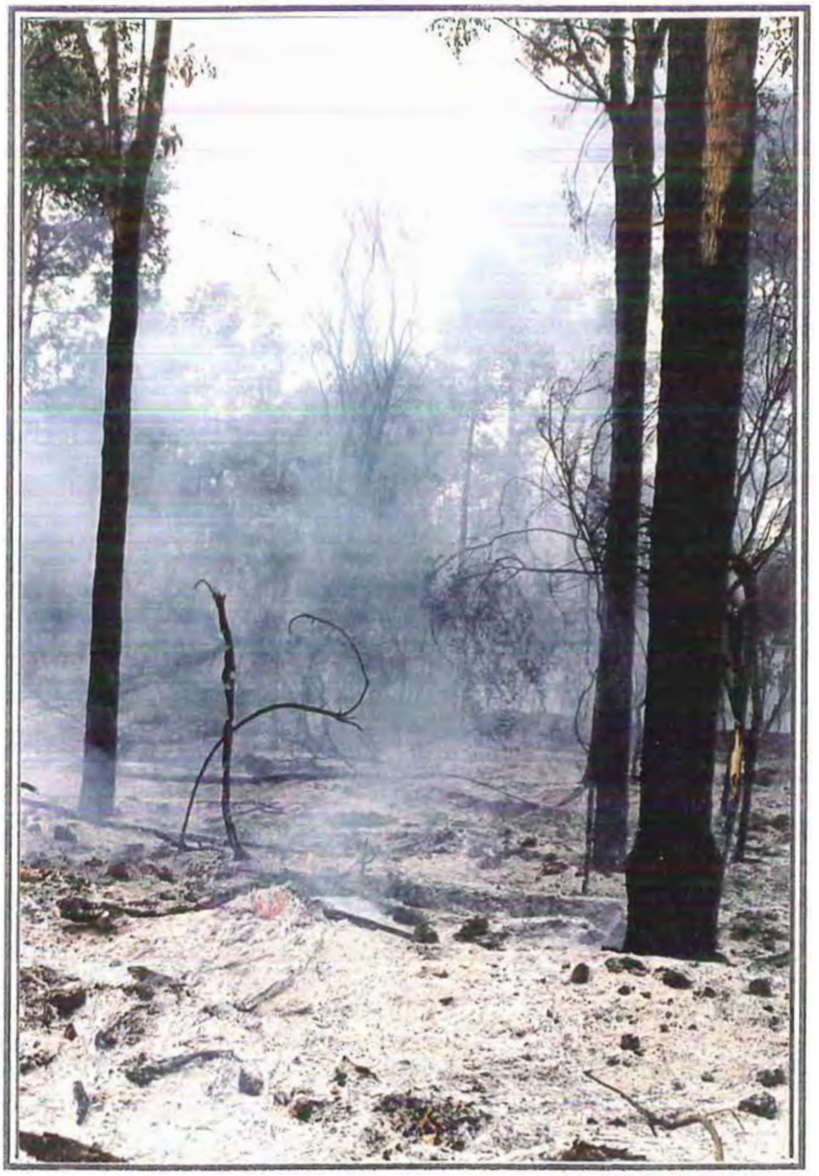
Importantly, these findings imply that the fire was not carried in the litter because the litter would probably have extinguished the flames due to the moisture content.

Grant *et al.*(1996a) suggested that a fire will be carried by the standing vegetation in the rehabilitated areas aged between 11 and 15 years as standing material make up a large proportion of the fuels, and has a highly combustible nature. The findings of this study support this proposal. The standing fuel loads in the rehabilitated areas assessed that were aged between 12-15 years (discussed in chapter 4) were dominated by dead aerated vegetation and this has been proven to have a large impact on the expectations of fuel behaviour and its associated fuel consumption. Walker (1981) for instance, suggests that the combustion of aerated fuels increases fire intensities. Bond *et al.* (1996) likened the effectiveness of aerated vegetation in fuel combustion to fuel in an internal combustion engine. According to this likeness the optimum fuel to air ratio causes the engine to run at its best with the highest combustion rate. In the rehabilitation area this likeness appears to be fitting. The standing vegetation was for the most part completely consumed in the burns. This is illustrated by Figure 5.5a and 5.5b which provide views of the standing vegetation before and after the spring burn. The high consumption rate of standing vegetation suggests that, although the moisture conditions of the litter layer may inhibit combustion in the litter zone, it is not of overall importance to the movement of the fire front in rehabilitated areas as fire is carried by the standing vegetation. This is in direct contrast to the jarrah forest where fire is carried in its litter layer (Burrows *et al.*, 1990; Burrows 1994).

The findings from the two controlled burns studied in this research have a number of implications for fire management in the rehabilitated areas. It is possible that moisture content in the litter layer may be used as a tool to create fires that do not completely combust the litter layer. This may be considered desirable for the germination of certain plants and for the maintenance of soil fauna. Further studies of the impact of moisture content in controlled burns in rehabilitated areas are being conducted (Grant, pers comm, 1996). The atypical nature of the autumn burn with regard to other burns that have been carried out in rehabilitation areas at Alcoa's mine sites also affirms that the rehabilitation areas need to be managed carefully for burning. The unique qualities of the rehabilitation areas combined with the high fuel levels means that careful assessment is required for a controlled burn programme.

The suggestion that fire is carried in the standing fuel is very important to a controlled burn programme. Other predictive models that are used in the forest in the south-west of western Australia use moisture content in the litter layer as a major indicator of fire behaviour (McArthur, 1977; Sneeuwjagt *et al.*, 1985; Burrows, 1994). If the burns in the rehabilitated areas are not carried in the litter layer, the importance of such measurements may be of questionable value for the prediction of fire behaviour in these areas. This is certainly the case in the 11-15 year-old sites studied where a large proportion of fuel is made up of dead standing aerated material. It can be suggested that sites older than 15 years will carry fire in the litter layer as most of the standing fuel has senesced by this stage (discussed in Chapter 4). Litter moisture content may be a more useful measurement at these sites. Further study will be necessary in older pits to determine if this proposition is correct.

Figure : 5.5 : Photographs taken before and after the autumn burn in a 15 year-old pit at the Huntly mine. Indicates the high consumption rate of standing fuel



ABOVE : Standing material before the burn

LEFT : Standing material after the burn

CHAPTER SIX

DEVELOPMENT OF PREDICTIVE MODELS

6.1 INTRODUCTION

Fire is a natural part of most Australian ecosystems and is integral to their dynamics in terms of growth, maintenance, recruitment and succession. In addition, long term exclusion of fire in sclerophyll forests is difficult and expensive and often results in catastrophic fires occurring due to the accumulation of large fuel loads (Gill, 1981; Shea *et al.*, 1981; Burrows, 1985; McCaw *et al.*, 1989; Pyne, 1991). Fire has therefore been incorporated into many land management schemes, to be used as a tool for the management of these ecosystems (Bond *et al.*, 1996). A reliable fire behaviour model is crucial for prescribed burning (Burrows, 1994; Johnson *et al.*, 1995). It also allows managers to predict, plan and develop suppression techniques for wildfire situations (Burrows, 1994).

Fire managers and researchers recognise that fuel characteristics have a profound influence on fire behaviour (Shea *et al.*, 1981; Burrows, 1985; Johnson *et al.*, 1995, Bond *et al.*, 1996). Therefore, attempts have been made to incorporate the key characteristics of fuel into models of fire behaviour. In Australia, fire behaviour models have been developed for specific vegetation types. In previous chapters the unique quality of the fuel characteristics in the rehabilitation areas have been described. It is therefore important, following Australian modelling methods, to develop predictive models that account for fuel characteristics specific to the area.

A wide variety of techniques exist for the classification and measurement of fuel characteristics (McCaw, 1991). The selection of a technique appropriate for the task depends on both the time and the resources available, and the required level of accuracy necessary for the study (Trevitt, 1991). Quadrat sampling (also called intensive sampling) is considered to be the most accurate method of determining fuel characteristics (Mueller- Dombois *et al.*, 1974), but it is time consuming and destructive to the vegetation. A method of fuel estimation without intensive sampling would therefore be of benefit for researchers in a

situation with time constraints and/or resource constraints. This would allow for faster and less destructive fuel prediction by the assessment of one or more other characteristics of a site, called surrogates, that have a reliable relationship with fuel loads. These are commonly referred to as non-intensive sampling methods. The objective of this chapter is therefore to outline the development and usefulness of models to predict fuel characteristics in the rehabilitation areas. This includes the suitability of using models that have been developed for the northern jarrah forest. The relevance of the predictive fuel models for the development of a controlled burn programme in the rehabilitated areas will also be discussed.

6.2 METHODS

A number of parameters were measured in order to determine one or more dependable predictors of total average fuel loads, and for litter and standing fuel which are the major fuel components of total fuel. For this, data was gathered at each of the 17 sites studied in this research. These measurements were taken during assessment of the pits using quadrat sampling. They were also incorporated into the levy pole transects. A predictive model developed by Burrows (1994) was also assessed to determine its applicability to the rehabilitated areas.

6.2.1 Predictive measurements

a) Quadrat measurements

Measurements were made at each of the 10 quadrats used to assess fuel (See 3.2 Methods for the determination of quadrat positioning). The measurements were taken as follows:

i) Tree canopy cover

Canopy cover was estimated using a spherical densiometer. The face of the densiometer was split into a grid of 24 squares. The instrument was held level at elbow height, so that the users head was outside of the grid area. It was assumed that 4 evenly spaced dots existed in each square of the grid thus giving a total of 96 dots. The dots were counted where the canopy completely covered the quarter square of each grid. The total dot count multiplied by 1.04 provided a percentage estimation of overstorey canopy cover. Four readings were taken

per quadrat, facing east, south, west and north. The average of these readings was determined to represent the canopy cover for each quadrat. An average for the site was also calculated.

ii) The overstorey basal area

The overstorey basal area is a measurement of the area of tree stem relative to the area of ground surface (Mueller-Dombois *et al.*, 1974). The method used in this study was an angle-gauge measurement, a method of basal area sampling first developed by Bitterlich in 1948 (Mueller-Dombois *et al.*, 1974) and has since been modified into a number of forms. This form involved using a wedge prism where measurements were made 4 times in the immediate vicinity of the quadrat. The sampling points were positioned 10 paces in a north, south, east and westerly direction from the centre of the quadrat. The overstorey trees were sampled in a circle by pivoting on a central sampling point. The prism creates an image that distorts the trunkline so that a section of the trunk is displaced to one side. When the section of the trunk is displaced outside the trunkline the tree is discounted. Trees where the displaced section of the tree is within the overall trunkline are counted (Mueller-Dombois *et al.*, 1974). The number of trees counted are considered proportional to the basal area of the stand. The 4 counts at each quadrat were averaged. The quadrat averages were then used to make a site average which was multiplied by a basal area factor of 2 in order to give the estimation of the basal area of the pit in $m^2\ ha^{-1}$.

iii) Litter depth

A litter depth gauge was used to measure the litter depth at the four corners of each quadrat. The corners were used so that variation in the litter due to the rip-lines would be taken into account. The 4 measurements were averaged for each quadrat which was then used to calculate the overall average of each pit.

iv) Bulk density

Litter depth indicates bulk density, a measure of compaction and aeration of the litter (Burrows, 1994). The bulk density of litter in each pit was calculated by applying the formula:

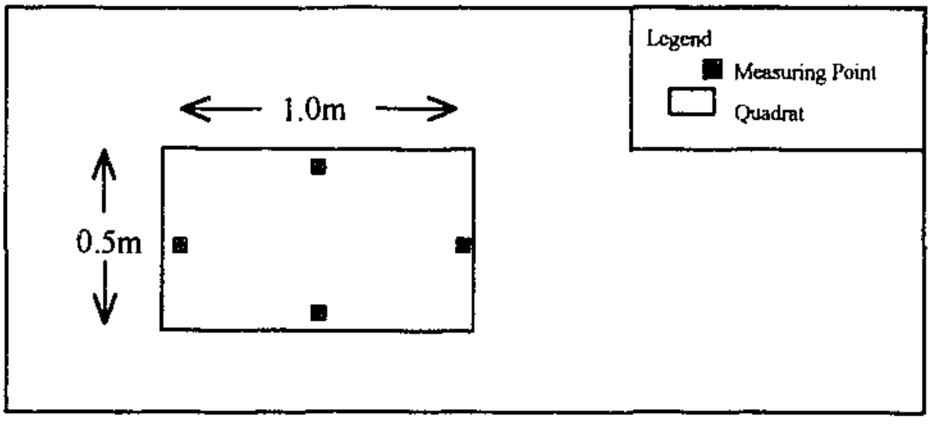
$$\text{Bulk density (kg/m}^3) = \frac{\text{Litter depth (m)}}{\text{Litter load (kg/m}^2)}.$$

Litter depth = the depth of the litter from the surface to the soil , Litter load = the average quantity of litter in the pit

v) Standing fuel height

The height of both trash and total standing fuel was measured to see if a relationship existed between their height and standing fuel loads and/or total average fuel loads. Both measurements were taken at four points within the quadrat using the levy pole. Measuring points were in the middle of each side of the quadrat as shown in Figure 6.1

Figure 6.1 : Measuring points for the height of understorey vegetation



vi) Levy pole touches

Levy pole readings were taken to see if the number of touches of live and dead vegetation correlated with the amount of standing aerated live dead and total fuel. Levy pole readings were taken at four points in each quadrat. The number of times that live and dead material touched the pole were counted at each measuring point which were the same points as those used for standing fuel height (Figure 6.1) (Levy poles and their use are described in 4.2 Methods).

b) Transect measurements

Two levy pole transects were undertaken at the each of the 17 sites (see Chapter 4). Along these transects a number of measurements were taken to see if they could be used to predict fuel characteristics. These measurements were as follows :

i) Absolute Density

a) To estimate the absolute density (i.e. number of individuals per unit area) of the overstorey vegetation in each pit, the Point-Centred Quarter method (or PCQ) was used. This method was chosen as it is considered to be simple in its application, required less time in the field and is more reliable than other methods (Mueller-Dombois *et al.*, 1974). It is also well accepted as shown by its use in many vegetation studies (e.g. Newsome, 1968; Dix, 1968 cited in Mueller-Dombois *et al.*, 1974,). Sampling points were situated at 20m intervals along the transects. They were placed at this distance to prevent the same tree being sampled twice. At each sampling point the area was divided into 4 quadrants (Figure 6.2). In each quadrant the nearest tree over 3 metres in height was located and the distance from the tree to the sampling point was measured (Figure 6.2). The distances were averaged to obtain an average for the pit. When squared this number equals the mean area occupied by each tree.

$$\text{ii) Density of trees per hectare} = \frac{10{,}000}{(\text{average distance})^2}$$

ii) Basal area[+]

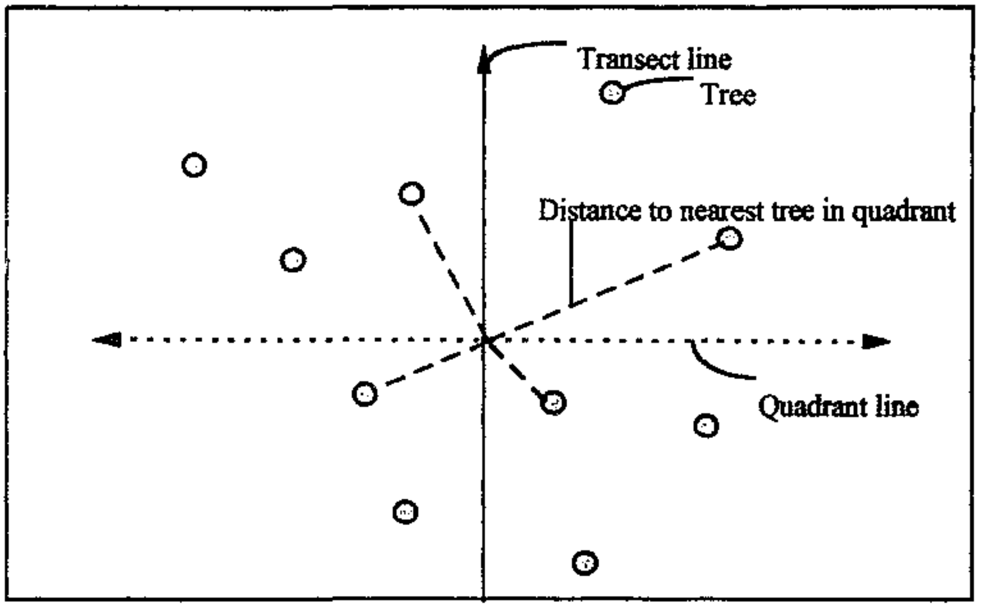
The basal area was measured at each PCQ sampling point. Each of the 4 trees chosen for the PCQ measurements were used to take basal area measurements. Diameter at breast height (Dbh) (~1.3m from the ground) was measured using a basal area measuring tape. All readings along the 2 transects in each pit were averaged, and then used to obtain the average tree basal area and the basal area for each pit. The following formulas were used:

$$\text{ii) Tree basal area} = \text{pi} \times \frac{(\text{Dbh})}{2}$$

$$\text{iii) Basal area for a pit} = \text{average tree basal area} \times \text{tree density}$$

[+] The basal was determined twice (ii and iv) because accuracy of the wedge prism method may be questionable in closed forest situations (Van Etten, pers comm, 1996).

Figure 6.2 : 'Point centred quarter method' to determine density and basal area in a pit.



Modified from Meuller-Dombois *et al.* (1974)

c) Burrows predictive model for litter

The equation developed by Burrows (1994) to determine the quantity of litter fuel in a jarrah forest was also applied to see if it could predict fuel loads in the rehabilitation areas. The equation is as follows :

$$wT = 0.406 * fD$$

Where : wT = total litter fuel quantity (t/ha), and fD = depth of litter bed (mm)

d) Seed mix

Information on the amount of seed used in the initial rehabilitation processes was collected (Alcoa, 1976-1992). This information was used to see if a relationship existed between the amount of seed used in the under- and over- storey (t/ha) with the fuel loads of the pits.

2.2.2 Data Analysis

Pearsons correlation analysis was performed on the data to determine the strength of association between the predictive variables, total fuel loads and the major fuel components. The variables with correlation coefficients, indicators of the level of association that were significant (≥95% confidence) were applied to regression analysis. Regression methods use the strength of association between one or more variables (the independent variables) to develop a model to predict one other variable (the dependent variable) (Kinnear *et al.*, 1994). In this study the dependent variables were total fuel, litter and standing material. The independent variables assessed were canopy cover, overstorey basal area (two methods), litter depth, bulk density, age, standing fuel height, levy pole touches, absolute density, and Burrow's predictor. Stepwise multiple linear regression was used, whereby variables were added to the equation sequentially. The multiple correlation coefficient (R) is a measure of the strength of the relationship between the dependent and independent variables (Kinnear *et al.*, 1994). At each step the variable which added the largest increase to the R value was included in the equation (Norusis, n. d.) and variables that did not contribute reliably to the strength of the regression were excluded (Kinnear *et al.*, 1994). The regression information was used to construct multiple linear regression equations that were appropriate for the estimation of fuel loads.

6.3 RESULTS

Correlation analysis found that a number of significant relationships existed between the total average fuel loads in the rehabilitation areas and predictive techniques (Table 6.1). Intensive sampling methods provided the best indicative model of average fuel loads. Duff weights, a component of litter, when combined with age since rehabilitation produced the best indicator of total fuel loads. The combination of these variables produced a Multiple R value of 0.99 (S.E. = 1.73). The equation developed through stepwise linear regression analysis was :

$$\text{Total fuel load (t/ha)} = 3.71(\text{Duff}) - 3.85(\text{Age}) + 24.29$$

Age = Age since rehabilitation (years), Duff = the partly decomposed layer of the litter (t/ha)

Table 6.1 : Correlation matrix of major fuel components and surrogate measurements

	AGE OF PIT	BASAL AREA	BASAL AREA 2*	BULK DENSITY	BURROWS LITTER PREDICTOR	% CROWN COVER	DENSITY	DEAD LEVY TOUCHES	AVERAGE FUEL	AVERAGE LITTER	AVERAGE STANDING FUEL
AGE OF PIT	1.000										
BASAL AREA	0.8124 ✓	1.000									
BASAL AREA 2*	0.7752 ✓	0.9214✓	1.000								
BULK DENSITY	-0.5712 ✓	-0.3848 ✖	-0.4965 ✓	1.000							
BURROWS LITTER PREDICTOR	0.5469 ✓	0.5227 ✖	0.3328 ✖	0.1976 ✖	1.000						
% CROWN COVER	0.4652 ✓	0.5725 ✓	0.3628 ✖	0.0887 ✖	0.7558 ✓	1.000					
DENSITY	-0.469 ✖	0.3096 ✖	0.4847 ✖	0.0002 ✖	-0.1121 ✖	0.0900 ✖	1.000				
DEAD LEVY TOUCHES	0.5600 ✖	0.4403 ✖	0.3633 ✖	-0.1273 ✖	0.4989 ✖	0.1663 ✖	-0.6102 ✓	1.000			
AVERAGE FUEL	0.7432 ✓	0.6936 ✓	0.2553 ✓	-0.3463 ✖	0.7980 ✓	0.7229 ✓	0.0268 ✖	0.5065 ✖	1.000		
AVERAGE LITTER	0.8950 ✓	0.8044 ✓	0.7040 ✓	-0 4820 ✓	0.7097 ✓	0.6348 ✓	0.0595 ✖	0.4646 ✖	0.9395 ✓	1.000	
AVERAGE STANDING FUEL	-0.1110 ✖	-0.0743 ✖	-0.2600 ✖	0.2142✖	0.5103✓	0.4826✓	-0.2288 ✖	0..3870 ✖	0.5138 ✓	0.1887 ✖	1.000

Note:✓=$p \leq 0.05$,✖=$p \geq 0.05$

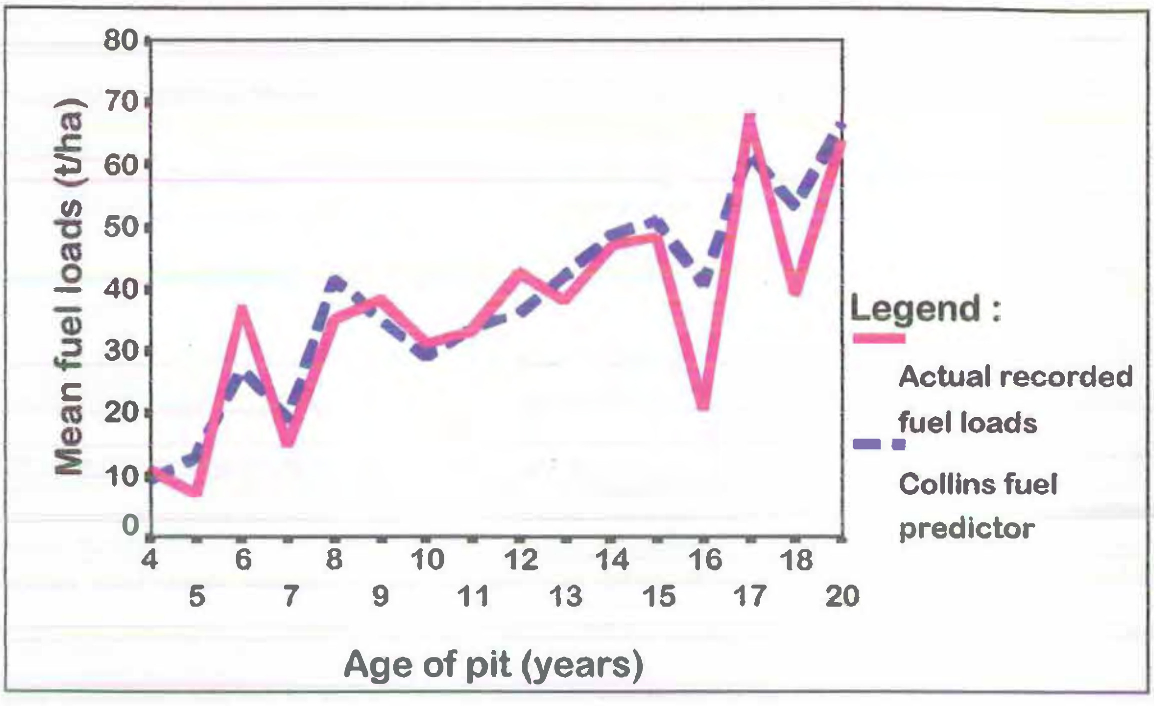
Table 6.1 (continued) : Correlation matrix of major fuel components and surrogate measurements

	FUEL	HEIGHT OF UNDERSTOREY	LITTER DEPTH	LITTER	LIVE LEVY TOUCHES	OVERSTOREY SEED MIX	STANDING FUEL	TOTAL LEVY TOUCHES	TRASH HEIGHT	UNDERSTOREY SEED MIX
FUEL	1.000									
HEIGHT OF UNDERSTOREY	-0.2847 ✖	1.000								
LITTER DEPTH	0.7980 ✓	-0.1802 ✖	1.000							
LITTER	0.9395 ✓	-0.5196 ✖	0.7097 ✓	1.000						
LIVE LEVY TOUCHES	0.1640 ✖	0.7237 ✓	-0.0029 ✖	-0.0331 ✖	1.000					
OVERSTOREY SEED MIX	-0.7325 ✓	-0.1188 ✖	-0.3778 ✖	-0.7110 ✓	0.0392 ✖	1.000				
STANDING VEGETATION	0.5138 ✓	0.6206 ✓	0.5103 ✓	0.1887 ✖	0.6185 ✖	-0.5503 ✖	1.000			
TOTAL LEVY TOUCHES	0.3881 ✖	0.6364 ✖	0.2199 ✖	0.1693 ✖	0.9008 ✓	-0.1324 ✖	0.7983 ✓	1.000		
TRASH HEIGHT	0.4525 ✖	-0.0709 ✖	0.4780 ✖	0.3601 ✖	-0.4756 ✖	-0.2141 ✖	0.3951 ✖	-0.1023 ✖	1.000	
UNDERSTOREY SEED MIX	0.3530 ✖	-0.3362 ✖	0.2574 ✖	0.3910 ✖	0.2741 ✖	0.2567 ✖	-0.0617 ✖	0.0228 ✖	-0.0016 ✖	1.000

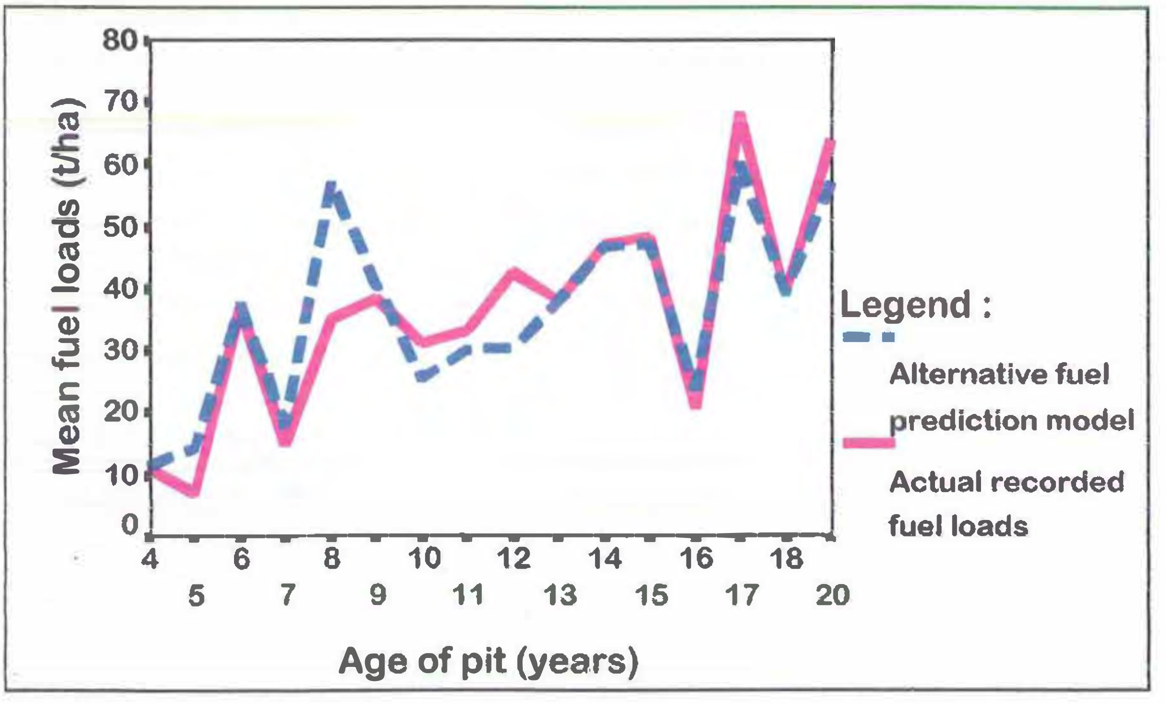
Note: ✓ = $p \leq 0.05$, ✖ = $p \geq 0.05$

Figure 6.3 : The application of regression models developed to predict fuel characteristics

a) Model developed to predict average fuel loads



b)The application of litter depth as an alternative predictive model for fuel loads



A number of variables collected through non-intensive sampling were correlated with total average fuel. They were measurements of age, basal area (both applications), Burrows litter predictor, crown cover, litter depth and height of standing vegetation (Table 6.1). The application of these variables into stepwise regression analysis determined that litter depth and age combined to produce the strongest predictive model for average fuel load using non-intensive sampling methods (R = 0.96, S.E. = 5.68). The equation using these variables is as follows :

$$\text{Average fuel load (t/ha)} = 2.09\ (\text{Age}) + 0.56\ (\text{Litter depth}) - 0.60$$

Age = the number of years since rehabilitation, Litter depth = the depth of the litter (mm)

The equation was applied to the data and plotted to see how closely it matched the actual findings. Figure 6.3a shows that the equation, named the Collins fuel predictor, predicted the actual fuel loads accurately except for the more atypical* fuel recordings. The Collins predictor had a more linear increase, as could be expected from a linear regression model, and therefore tended to either under or over estimate these atypical values. At 6 years for example, the Collins indicator underestimated fuel loads by approximately 10 t/ha and gave an overestimation of approximately 20 t/ha at 16 years.

Litter depth by itself was also a strong predictor of total average fuel loads (R = 0.90, S.E. = 7.67) using the equation :

$$\text{Average fuel load (t/ha)} = 1.07\ (\text{Litter depth}) + 8.38$$

Litter depth = the depth of the litter (mm)

However, more variation from the actual readings did occur (Figure 6.3b). This model predicted the variability of the fuel loads more closely, but under or overestimated fuel loads in the less variable ages. For example, it overestimated fuel loads by approximately 17 t/ha for a pit aged 8 years since rehabilitation.

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* Fuel loads have been defined as atypical in this context when they differ from pits of a similar age (+- one year) by > 10 t/ha

Predictive models were also developed for litter and standing material, the major categories of total average fuel. Age since rehabilitation was highly correlated with litter ($r = 0.90$). Basal area (both applications), bulk density, Burrows litter predictor, crown cover, litter depth and overstorey seed mix were also correlated with litter to a lesser degree ($p < 0.05$) (Table 6.1). The application of all of these variables into stepwise regression analysis showed that age had a sufficiently strong relationship with litter that the other variables were excluded from the predictive model (Multiple R = 0.96, S.E. = 4.73). The equation to predict litter loads is :

$$\text{Average litter load (t/ha)} = 3.23\,(\text{age}) - 12.57$$

Age = the number of years since rehabilitation

The application of this model to the data approximated the actual litter loads well Graph 6.3c. The predictive relationship followed a linear pattern which effectively moderated the variability that existed in the actual recorded litter loads. The more atypical actual litter readings were therefore not accounted for by the model. The largest discrepancy between the actual and predicted litter loads was 19t/ha at a 16 year-old site. The predictive model for total litter loads developed by Burrows (1994) was also plotted (Figure 6.3c). This model was highly correlated with the actual litter loads ($r = 0.80$) but it substantially underestimated the fuel in the rehabilitated areas that had litter loads larger than about 16t/ha. For example, it underestimated average litter fuels at 11 years by 14t/ha and at 17 years by 32t/ha.

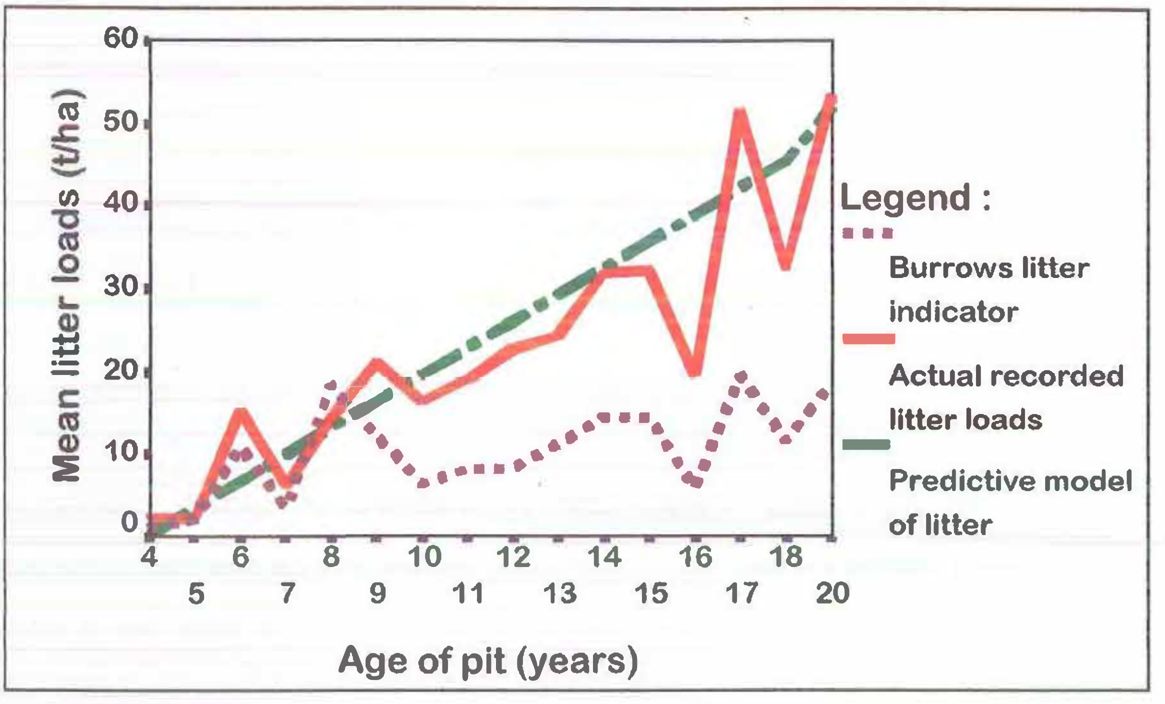
The standing vegetation was heterogeneous in the rehabilitation areas. It was only correlated with 3 of the variables measured to predict it. These variables were crown cover, number vegetation touches on a levy pole and the height of standing vegetation (see Appendix 2 for correlation coefficients). Application of stepwise regression determined that the height of the understorey vegetation had the strongest predictive ability (Multiple R = 0.62, S.E. = 5.28) for standing fuel using the equation :

$$\text{Average standing vegetation (t/ha)} = 0.06\,(\text{Height}) + 5.70$$

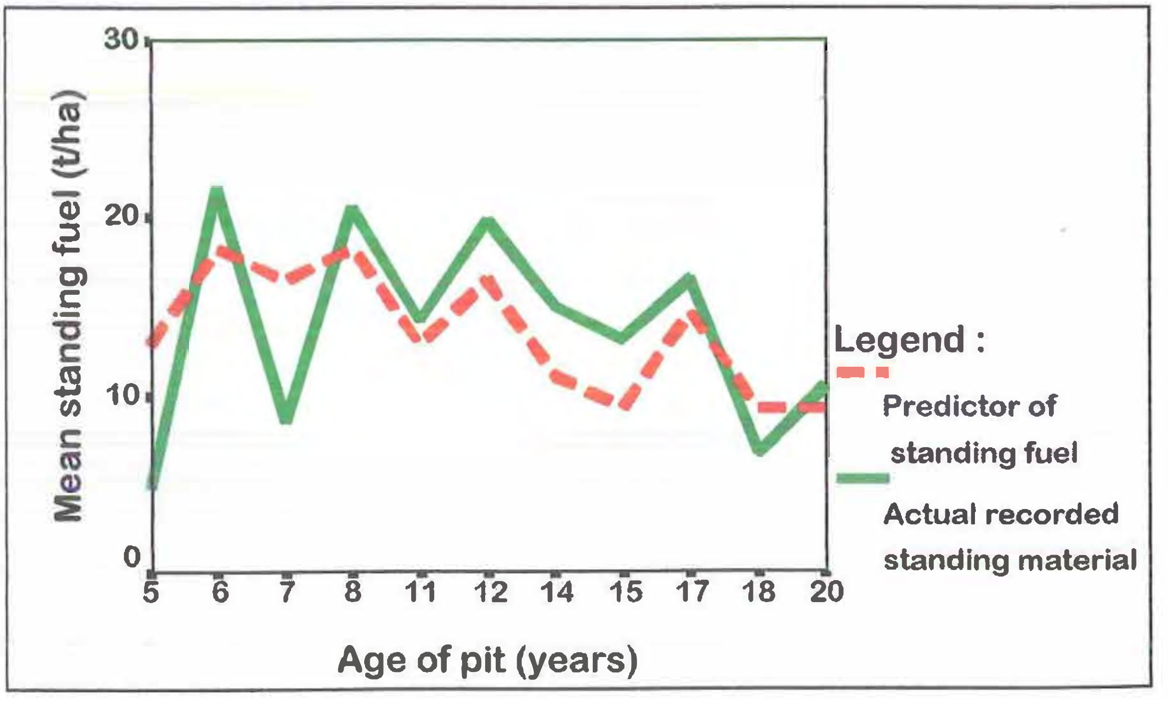
Height = The height of standing understorey vegetation (cm) measured at 30 cm intervals.

Figure 6.3 (continued) : The application of regression models developed to predict fuel characteristics

6.3 c) The application of a model for the prediction of litter loads



d) The application of a model for the prediction of Standing fuel loads



Although this predictor was not as highly correlated with the actual fuel recorded as the other predictors, Figure 6.3d indicates that it did predict the trends of actual standing fuel loads with a large degree of accuracy. This model underestimated the total fuel loads. Between 8 and 17 years since rehabilitation, for example, the predictor underestimated fuel loads by an average of 2.5t/ha yearly.

6.4 DISCUSSION

The models developed for the prediction of the fuel characteristics of a pit were highly successful. Models to predict total fuel were particularly successful. They relied on the measurement of litter characteristics (i.e. litter depth). Litter depth had a very strong relationship with both age and the total fuel loads which made it a reliable predictor. For this reason it has been applied in a number of fuel prediction models (Sneeuwjagt, 1973; Sneeuwjagt *et al.*, 1985; Burrows, 1994). In this study, the use of predictors that pertain only to litter was interesting because the standing components of fuel also made a significant contribution to the total fuel loads, particularly up to approximately 15 years (refer to Chapter 3 and Chapter 4). Generally, it could therefore be expected that measurements associated with standing fuel would be included in the prediction of total fuel loads. However, in this study, standing fuel was not highly correlated with total fuel, and did not have a significant relationship with age.

The predictive ability of the models developed for fuel characteristics reflected the relationships that existed between these fuel characteristics and the independent variables used to predict them. Where the relationships were strong the predictive ability of the model would also be strong. Litter weight for example, had very strong relationships with age since rehabilitation and litter depth. A model developed to predict litter using these variables could therefore be expected, with a reasonable degree of certainty, to be accurate. Standing fuel, on the other hand, did not relate well to measurements that were made to predict it. Consequently, the predictive ability of the model developed for standing material may be somewhat limited. Strong relationships between dependent and independent variables need to be found for accurate and useful fuel prediction.

Models based on measurements acquired through intensive sampling techniques (i.e. quadrat sampling) proved to be highly accurate in their ability to predict the actual recorded fuel levels. However, predictive models using these intensive sampling methods may have limited appeal. This is because these intensive methods, although they do not require the collection of all fuel characteristics, still involve extended time periods for the collection, sorting and drying of samples. Trevitt (1991) suggested that a primary objective of modelling is to obtain the simplest means of describing the characteristic to be modelled. The benefit of the accuracy of measurements made using intensive sampling may therefore be outweighed by other considerations (Mueller-Dombois *et al.*, 1974). This may be particularly true in situations such as this study where non-intensive sampling methods also had very strong relationships with fuel loads which made them accurate alternative predictors.

In the previous chapters the characteristics of the fuel in rehabilitated areas have been defined and discussed. Recognition that these characteristics make rehabilitated areas unique is important to the development of accurate models for fire behaviour. The application of existing methods for fire prediction that are used in the surrounding forest may cause inaccuracy as these models have been developed for forests with differing fuel characteristics. This is highlighted by the inaccuracy of the predictive ability of the model developed by Burrows (1994) for litter in the northern jarrah forest. The model had a high correlation with the recorded litter levels and it was accurate in the prediction of fuels up to a weight of approximately 18 t/ha but as the weight increased over this point the model became more inaccurate. Burrows (1994) suggested that equilibrium fuel levels are reached at approximately 16t/ha. The inaccuracy of the model beyond 18t/ha is probably due to the fact that this model was not developed for an ecosystem with fuel levels up to 4 times larger than those equilibrium levels. Models that have been developed specifically for the rehabilitated areas such as those developed here, do not have constraints caused by the high fuel loads because they were developed taking these characteristics into account.

Overall, the models developed in this study proved to have a good predictive capacity when applied to the actual fuel loads that were recorded through intensive sampling. This is an estimation of their ability to model the fuels from which they have been developed. They must be applied in the field to determine their true accuracy in predicting fuels overall. There

are a number of reasons for this. Importantly, the different rehabilitation strategies that have been used on the pits may have had an impact on the relationships between variables and total fuel. Estimations using the predictive models may therefore show some deviation from actual fuel characteristics. In addition, the sampling set was small, therefore relationships determined in this analysis, while indicative of relationships that can be expected in rehabilitation areas, must be assessed further for refinement and quantification. More experimentation will allow a comparison of other intensive sampling results with model predictions obtained using the predictive measurement tools developed in this study. Methods to test the usefulness of these predictive models should be similar to those applied in this study. High correlations were generally found between the predictive measurements and the fuel components the methods applied in this study can be considered adequate. Methods to estimate standing vegetation would need to be modified in future sampling to accommodate for its inherent variability. The use of quadrats of 2.0 x 2.0m might reduce the variability of standing fuel measurements. This may in turn result in higher correlations between predictors and standing vegetation.

The prediction of fire behaviour is a complex issue. The accurate modelling of fuel characteristics is an important step in the development of an overall model for this type of prediction. Incorporation of predictive models into a fire management plan will take time and experimentation in order to determine how the prediction of fuel loads and fuel components interact with other predictive tools such as flame height and length. The complete picture is the sum of each of the tools so some predictors may need to be modified to fit together in the overall management plan.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

1. The rehabilitated areas examined in this study are different to the northern jarrah forest ecosystem that they have replaced. The methods utilised in the rehabilitation processes have resulted in unique ecosystems (Koch *et al.*, 1994; Grant *et al.*, 1996a). This study has shown that differences exist in the fuel characteristics, the dynamics of the fuel as it changes over time, and the behaviour of fire in the rehabilitated areas compared to the surrounding forest. Therefore, these areas should be treated as unique in the development of fire management plans. This finding suggests that other ecosystems developed after mining, with the intention of replacing the original ecosystem, need to be assessed individually before developing fire management plans. This assessment should identify similarities and differences between the rehabilitated ecosystem and the ecosystem that has been replaced. Assessments such as these will identify the extent to which generalisations can be made about each of the ecosystems.

2. Alcoa's rehabilitation process involves the utilisation of an understorey that is dominated by leguminous species. These species are characterised by vigorous growth and a relatively short lifespan (Koch *et al.*, 1993; Koch *et al.*, 1994; Bright, 1995). The utilisation of these species have a number of positive influences on the environment. They are effective, for example, in soil stabilisation, erosion control, development of organic matter, and nitrogen input into the ecosystem (Koch, 1987; Ward *et al.*, 1990). However, a consequence of their utilisation has been the accumulation of very high fuel loads in these areas (Grant *et al.*, 1996a, Ward *et al.*, 1990). In this study, the fuel loads were found to be up to 6 times higher than the maximum fuel levels suggested by CALM for the surrounding jarrah forest (Burrows, 1994).

3. The large proportion of leguminous species has also impacted on the structure of fuels in the rehabilitated areas. The rehabilitated areas have a pronounced middlestorey, particularly up to an age of 15 years, which is not a feature of the jarrah forest vegetation

(Dell *et al.*, 1989; Koch *et al.*, 1993; Koch *et al.*, 1994; Bright, 1995; Grant *et al.*, 1996a). In future, it may more beneficial for Alcoa to seed the rehabilitation areas with a larger proportion of small shrub and herb species in order to reduce high fuel loads in this middlestorey.

4. Total fuel increased with age since rehabilitation. Litter quantities generally increased with age while standing fuel decreased. With age, the composition and structure of standing fuel also underwent significant changes. Standing fuel changed in its proportion of live and dead material, the height at which the material was most dense and also the total amount of standing fuel. These changes were related to the lifecycle of the leguminous species of the understorey as it progressed from fast growing live material to dead fuel that collapsed into the litter layer (Koch *et al.*, 1993; Grant *et al.*, 1996a).

5. The fuels in the rehabilitated areas were much more variable than in the surrounding jarrah forest. This variability exists in the range of fuel loads found within a pit, between pits of similar ages and also in terms of the changes that occurred in the distribution of fuel over time. Variability within pits can be explained by the accumulation of fuels in the bottom of rip lines (Grant *et al.*, 1996a), seeding and fertiliser methods which may have caused a striping pattern in some pits (Koch, 1993), as well as natural variations caused by factors like topography and soil structure. Variability between pits of similar age can be explained by looking at the rehabilitation methods that Alcoa utilised (Alcoa, 1976 - 1992). During the time period studied, a number of different methods of rehabilitation were employed (Alcoa, 1976 - 1992; Tacey, 1979; Grant *et al.*, 1996a; Elliot *et al.*, 1996). This had a marked influence on the fuel characteristics of some of the rehabilitated sites. This was particularly obvious in older rehabilitation areas where rehabilitation processes changed from year to year (Alcoa, 1976 - 1992). A great deal of experimentation, implementation and improvement of methods occurred during this period (Alcoa, 1976 - 1992; Elliot *et al.*, 1996). Consequently, the fuel loads of these sites are generally very different from each other. It may be worthwhile to exclude older rehabilitation areas, currently aged over 15 years, from future monitoring programmes. This is because the large variation inherent in them could cause difficulties in distinguishing overall trends in the ecosystem dynamics.

6. The unique characteristics of the rehabilitation areas will have a number of impacts on fire behaviour. The high fuel loads, for example, will impact significantly on the rate of spread of a fire and its intensity. Luke *et al.* (1986) suggested that the rate of spread increases in proportion to the amount of available fuel and Sneeuwjagt (1985) found that higher fuel loads are associated with increased fire intensity. The importance of fuel loads is exemplified by the model developed by Bryman (1959 cited in Cheney, 1981) which used fuel loads as a determinant of fire intensity. Therefore, where other influencing factors (like wind and moisture content) are the same, a fire in rehabilitated areas could be expected to be much more intense and have a higher rate of spread than a fire in the native jarrah forest. The distribution of fuel in the rehabilitated areas will also impact on fire behaviour. It has been suggested by Grant *et al.* (1996a) that the variable nature of fuel in the pits causes variable fire behaviour. In addition to this, the large amount of standing fuel in pits aged less than 15 years is likely to lead to fires of high intensity and crown scorching because standing dead fuels carry flames into the crown and are more combustible due to their aerated nature (Luke *et al.*, 1986; Burrows *et al.*, 1990; Grant *et al.*, 1996a; Bond *et al.*, 1996).

7. This study found that the fuel loads of the rehabilitated areas were strongly influenced by climatic conditions. Increasing rainfall and humidity between February and July, coupled with decreasing temperatures were strongly associated with increasing moisture content in the fuel. As moisture content effects the propensity of fuels to ignite (Burrows, 1994; Tunstall, 1991; Bond *et al.*, 1996), it is suggested that burns in the wetter seasons would normally be of lower intensity. The moisture content of the litter was generally higher than the standing dead fuel. This suggests that litter is less likely to combust than standing fuels in the rehabilitated pits.

8. Fire tends to be carried in the standing fuel of the rehabilitated areas Grant *et al.* (1996a). This supported by the fact that nearly all standing fuel is consumed in controlled burns in the rehabilitated areas while some fuel remained in the litter layer (Grant *et al.*, 1996a). The variable nature of the litter may also contribute to fire being carried by the standing vegetation as the patchy fuel may inhibit fire spread (Burrows *et al.*, 1990; Grant *et al.*, 1996a). This has significant implications for a fire management programme, particularly as fire is carried in the continuous litter layer in the northern jarrah forest (Burrows *et al.*,

1990; Burrows, 1994). The fire behaviour predictive models utilised in the jarrah forest and many other ecosystems in Australia use measurements of the moisture content of the litter and soils to indicate fire behaviour (McArthur, 1977; Sneeuwjagt *et al.*, 1985; Cheney, 1991; Burrows, 1994). Where fire is not carried in the litter such predictions will be of limited value. Predictive models that utilise moisture content in soils and litter should therefore not be used in the rehabilitated areas aged in the period where standing vegetation is a prominent part of the ecosystem. Models developed specifically for the rehabilitation areas need to take this into account.

9. Equilibrium fuel levels are reached in an ecosystem when fuel accumulation equals fuel decomposition (Fox *et al.*,. 1979; Woods *et al.*, 1983; Simmons *et al.*, 1986) which is carried out by communities that include beetles, cockroaches, slatters (Chambell *et al.*, 1981); fungi, algae and bryophytes (Warcup, 1981). The findings of this study suggest that such an equilibrium has not yet been reached in the rehabilitation areas that are aged up to 20 years old. The rehabilitation areas are new and developing ecosystems. It is therefore not surprising that they have not yet reached this equilibrium in a similar time span to the jarrah forest where time is used in relation to the response of a mature ecosystem to a controlled burn (Peet *et al.*, 1971; Burrows, 1994). Monitoring of the rehabilitation areas to determine when an equilibrium is reached and what the associated fuel characteristics will be, is important in the development of accurate predictive models. This knowledge will provide a basis for the long term expectations of fuel characteristics in the rehabilitated areas.

Litter had a very strong linear relationship with rehabilitation age. The near linear increase of duff (partly decomposed organic matter) over the time period suggests that it is not becoming completely incorporated into the soil. An equilibrium will not be reached until the complete decomposition of the litter has become a part of the dynamics of the ecosystem (Fox *et al.*, 1979; Woods *et al.*, 1983). The increasing duff levels may be the consequence of an inhibited decomposer community. This inhibition may be caused by a number of factors. The temperature and moisture content may limit decomposition of this material (Cambell *et al.*, 1981). Although not measured in this study, high Carbon : Nitrogen ratios could also limit decomposition rate (Sawada, 1996). Decomposer communities may be unable to deal with the large amounts of fuel being incorporated into

the litter layer. The communities may, on the other hand, be lacking organisms that are essential for the final incorporation of the organic material into the soil. Further study is needed to determine the characteristics of litter decomposition in the rehabilitated areas.

10. The findings of this study enable a number of recommendations to be made with regard to the age of pit that would be most suitable to burn. These are outlined as follows :

    a) Pits that are aged under 9 years are dominated by young live growth in the understorey. Burning of these pits may cause the loss of important organic material before it can become a part of the nutrient cycling system. The overstorey may also be too young to withstand fire damage at this age due to a lack of bark thickness and insufficient height to place susceptible leaf material out of reach of the flames (McCaw, 1986; Bell *et al.*, 1989).

    b) Pits that are aged between 9 - 15 years are characterised by high fuel loads and a large amount of standing aerated fuel. The combination of these characteristics could cause intense fires with a rapid rate of spread. The understorey vegetation also carries flames into the crown. Control of fires in these areas may be difficult and would therefore need careful management. It will be important to burn in these pits during periods of lower fire danger i.e. suitable fire weather with low wind, high relative humidity etc., and use sufficient managers to control potential problems of fire escaping into the surrounding areas.

    c) After 15 years much of the dead understorey fuel in the rehabilitated pits has been incorporated into the litter layer. Although the fuel loads are still high in these areas, the reduced midstorey layer may make burns easier to manage than the pits aged between 9-15 years.

    These recommendations should be incorporated into studies of fire behaviour in the rehabilitated areas, particularly in the older pits where the senesced standing fuel has become incorporated into the litter layer.

11. A more complete assessment of the fuel characteristics in the rehabilitation areas is necessary. This study was constrained by the length of an honours project. This project concentrated on trends in fuel characteristics in pits aged over a sixteen year age period since rehabilitation. A longer time period would allow a more detailed assessment of accession and decomposition processes. Replication on a large scale, using the methods of

this study, is impractical in the rehabilitated areas due to the time necessary to sample each pit (2 workers x 40 hours for collection and sorting).

Models for the rapid assessment of fuel characteristics were developed in this study and they could be of use in further fuel studies. These models use surrogate measurements to predict fuel characteristics. They allow the assessment of fuel which can then be extrapolated for management decisions or research purposes without lengthy time delays. These models had very strong predictive relationships with the fuel characteristics on which they were modelled. It will be important to test these models in the field before applying them as a basic tool in other studies. The sampling methods that were used in this study for the litter will be sufficient for testing the models. This is indicated by the strong relationship that existed between the components of litter collected and the surrogate measurements that were taken. Larger quadrat sizes for the sampling of standing material could be of benefit. 2m x 2m quadrats should be large enough to remove the variability in the standing fuel component. The strength of the predictors could be determined by sampling three pits of differing ages. Sampling should entail the collection of fuel samples, litter depth and understorey vegetation height. A comparison between the actual fuel loads recorded and the predicted loads determined by the surrogate measurements would determine if these predictors can be used in further studies.

12. Although many other factors need to be considered in relation to the controlled burning of rehabilitated mined areas, the findings of this study have important implications. They will be of use in the development of a fire management programme for Alcoa's rehabilitated areas. These findings suggest that more study is necessary both in Alcoa's rehabilitated areas and in rehabilitated ecosystems in general. As the amount of land mined and rehabilitated on the Australian continent grows such studies will be of increasing importance. They will allow managers of the land to develop and improve their management capacities and capabilities.

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Appendix 1 : Sampling information for controlled burns

A : Quadrat sampling data

B : Study of unconsumed wood diameter readings

Appendix 1A - Table 1: Pre burn fuel loads for area that was subjected to a controlled burn in spring 1995 (All Samples 0.5m² Unless Specified)

Quadrat	Sample	Total Net Weight (g)	Total Dry Weight (g)	Wet Weight Sample (g)	Dry Weight Sample (g)	H_2O %	Dry Weight t/ha	Total fuel t/ha
1	Litter	816.7	662.2	754.2	599.7	20.48	12.0	36.6
	< 6mm	907.7	235.8	845.2	741.6	12.25	14.8	
	> 6mm	731.7	552.8	669.2	490.3	26.73	9.8	
2	Litter	1147.4	954.3	1084.5	891.8	17.77	17.8	37.2
	< 6mm	502.5	462.5	440.0	400.0	9.09	8.0	
	> 6mm	698.9	632.0	636.4	569.5	10.51	11.4	
3	Litter	267.2	239.2	204.7	176.7	19.97	3.5	12.3
	< 6mm	291.8	270.6	229.3	208.1	9.24	4.2	
	> 6mm	310.8	292.0	248.3	229.5	7.57	4.6	
4	Litter	476.0	342.2	413.5	279.6	32.38	5.60	11.4
	< 6mm	118.7	111.1	56.2	48.6	13.52	1.0	
	> 6mm	335.1	305.2	272.6	242.7	10.97	4.8	
5	Litter	478.9	443.0	416.4	380.5	8.62	7.6	14.9
	< 6mm	256.2	237.1	193.7	174.6	9.86	3.5	
	> 6mm	269.7	251.4	207.2	188.9	8.83	3.8	
6	Litter	289.6	273.0	227.1	210.5	7.31	4.2	4.2
	🖫 6mm	-	-	-	-	-	-	
	✇ 6mm	-	-	-	-	-	-	
7	Litter	866.3	716.0	803.8	653.5	18.70	13.1	59.1
	< 6mm	623.5	297.6	561.0	502.8	10.37	10.1	
	> 6mm	2115.3	561.6	2052.8	1794.0	12.61	35.9	
	Litter	227.8	115.3	165.3	144.5	12.58	2.9	
8	< 6mm	389.8	164.2	327.3	290.2	11.33	5.8	17.4
	> 6mm	538.4	486.2	475.9	423.7	10.97	8.5	
	Live < 4mm	73.7	70.0	11.2	7.5	33.04	0.15	
	Litter	311.2	158.0	248.7	222.4	10.58	4.5	
9	< 6mm	183.7	100.0	121.2	102.1	15.73	2.0	11.3
	> 6mm	295.7	263.6	233.2	201.1	13.76	4.0	
	live < 4mm	114.2	101.4	51.7	38.9	24.76	0.8	
	Litter	1031.6	639.4	969.1	576.9	40.47	11.5	
10	< 6mm	526.3*	479.0	463.8	416.5	10.20	16.7	
	> 6mm	1062.5*	459.2	1000.0	896.7	10.33	35.9	71.6
	live < 4mm	308.5	221.1	246.0	158.6	35.53	3.2	
	live > 4mm	369.5	276.5	307.0	214.3	30.19	4.3	

Note : * = quadrat of 25m² used to sample material

Total fuel mean (t/ha) = 27.6
Total fuel S. dev (t/ha) = 22.8
standard coefficient = 7.2
range for total fuel = 71.6 - 4.2 = 67.4

Appendix 1A -Table 2 : Post burn fuel loads (t/ha) for a pit subjected to a controlled burn in spring 1995

Quadrat	Litter	Trash	Total Fuel
1	2.80	0.00	2.80
2	0.24	0.00	0.24
3	0.39	0.18	0.57
4	5.60	5.80	11.40 (unburnt)
5	0.55	0.15	0.70
6	0.17	0.00	0.17
7	0.90	0.00	0.90
8	2.90	14.50	17.40 (unburnt)
9	0.86	0.24	1.10
10	1.66	0.00	1.66
Mean	**1.61**	**2.09**	**3.69**
S.Error	**0.54**	**1.49**	**1.86**

Appendix 1A - Table 3 : Post burn fuel loads (t/ha) for a controlled burn carried out in Autumn 1996

Quadrat	Total Standing material	Litter	Total Fuel
1	0.00	34.36	34.36
2	0.00	18.65	18.65
3	0.00	12.52	12.52
4	0.06	6.35	6.41
5	6.20	10.17	16.37
6	0.00	10.27	10.27
7	0.90	34.20	35.10
8	3.95	3.45	7.39
9	0.00	46.47	46.47
10	2.88	9.17	12.06
Mean	**1.40**	**18.56**	**19.96**
S.Error	**0.70**	**4.61**	**4.36**

Appendix 1B - Unconsumed wood diameter readings from a spring burn at the Huntly Mine Site 1995

Readings were taken in a random manner using a ruler to measure the unconsumed plant matter after the Spring burn carried out in late November 1995. Readings were taken randomly along two notch lines, North and South. The readings have been split into sub-groups along the route to help determine differences in fire intensities across the site. A sub-group represents an average from an area where a number of readings were taken from either one plant unit or a number of plant units.

Table 1 : Diameter of unconsumed wood
(unit of measurement - mm)

Sub-group	Northern Notch Line	Southern Notch Line
1	7.50	13.00
2	25.50	29.9
3	29.60	18.00
4	29.57	17.40
5	17.00	41.00
6	18.50	13.20
7	13.30	23.80
8	27.57	27.20
9	44.38	58.17
10	42.00	25.00
11	59.00	21.80
12	28.00	30.75
Mean	***29.49***	***27.02***
S.dev	***14.10***	***6.00***

Overall mean of stem diameter = 28.26 mm

Appendix 1B - Unconsumed wood diameter readings from an burn at the Huntly Mine Site 1996

Table 1 : Diameter of unconsumed wood
(unit of measurement - mm)

Quadrat	Average diameter of standing materail
1	15.50
2	18.50
3	24.69
4	28.14
5	9.90
6	22.90
7	18.42
8	10.85
9	16.50
10	8.17
mean	***15.95***
S.error	***0.96***

Appendix 2 : Information tables

A : Site tables from quadrat sampling

B : Jarrah forest quadrat sampling

C : Site height density profiles

Appendix 2A - Table 1 Pit rehabilitated in 1976 (20 years-old)

Quadrat	Standing live fuel	Standing dead fuel	Total standing fuel	Leaves	Bark	Duff	Round-wood	Total litter	Total Fuel
1	0.43	2.44	2.88	9.15	0.67	40.00	14.96	64.78	67.66
2	1.22	0.29	1.51	4.36	0.00	29.93	7.87	42.16	43.67
3	0.01	27.38	27.39	5.39	1.99	35.89	7.46	50.74	78.13
4	0.00	7.28	7.28	3.96	0.07	32.06	15.81	51.91	59.19
5	0.13	7.43	7.56	2.28	0.00	22.15	6.22	30.65	38.21
6	6.03	19.13	25.16	1.25	0.00	31.10	9.60	41.94	67.11
7	0.66	2.11	2.77	3.84	1.05	47.97	14.25	67.12	69.89
8	0.33	7.41	7.73	4.69	0.45	35.77	8.83	49.74	57.47
9	8.98	9.32	18.31	5.30	0.00	49.44	22.96	77.70	96.01
10	1.91	2.58	4.49	6.05	0.12	39.62	11.30	57.09	61.58

Appendix 2A - Table 2 Pit rehabilitated in 1979 (18 year-old)

Quadrat	Standing live fuel	Standing dead fuel	Total standing fuel	Leaves	Bark	Duff	Round-wood	Total litter	Total Fuel
1	5.80	0.00	5.80	3.44	4.86	33.38	16.43	58.12	63.92
2	7.26	2.49	9.76	2.43	0.35	8.94	10.31	22.04	31.79
3	2.01	0.00	2.01	6.65	1.54	21.77	9.60	39.56	41.57
4	9.53	0.00	9.53	5.90	0.00	17.70	10.5	34.1	43.63
5	0.65	0.51	1.16	4.82	0.37	13.70	2.16	21.06	22.21
6	0.15	10.42	10.57	1.34	0.00	26.59	3.01	30.94	41.50
7	0.00	0.00	0.00	4.34	0.00	18.23	6.00	28.57	28.57
8	6.68	0.00	6.68	1.70	0.52	20.02	3.59	25.83	32.51
9	0.00	21.67	21.67	2.57	0.33	9.43	4.52	16.84	38.51
10	0.19	0.00	0.19	4.48	0.34	31.43	12.91	49.16	49.36

Appendix 2A - Table 3 Pit rehabilitated in 1979 (17 years-old)

Quadrat	Standing live fuel	Standing dead fuel	Total standing fuel	Leaves	Bark	Duff	Round-wood	Total litter	Total Fuel
1	5.29	14.41	19.70	2.11	0.00	33.04	12.48	47.64	67.34
2	3.04	0.00	3.04	8.28	0.44	78.61	13.15	100.47	103.51
3	58.24	6.02	64.26	6.55	0.00	61.04	3.90	71.49	135.75
4	0.25	5.13	5.37	4.00	0.51	44.11	4.13	52.74	58.12
5	14.28	10.12	24.4	2.80	0.13	16.53	1.86	21.31	45.71
6	6.79	0.35	7.13	4.62	1.01	21.22	7.03	33.88	41.01
7	9.31	8.58	17.88	1.54	0.00	48.08	8.60	58.22	76.10
8	4.63	6.17	10.8	4.56	0.07	27.60	6.77	39.00	49.80
9	4.76	2.49	7.25	3.01	0.00	45.32	4.59	52.92	60.17
10	1.17	4.76	5.94	0.89	8.59	24.45	4.93	38.86	44.80

Appendix 2A - Table 4 Pit rehabilitated in 1980 (16 years-old)

Quadrat	Standing live fuel	Standing dead fuel	Total standing fuel	Leaves	Bark	Duff	Round-wood	Total litter	Total Fuel
1	0.00	0.21	0.21	6.64	0.76	1.95	2.59	11.95	12.15
2	0.00	0.00	0.00	14.09	0.42	7.97	7.14	29.62	29.62
3	0.90	0.00	0.90	0.96	0.07	1.48	2.07	4.58	5.48
4	0.15	0.00	0.15	3.13	0.56	0.58	1.37	5.63	5.78
5	0.00	0.00	0.00	0.71	0.00	0.70	18.27	19.68	19.69
6	0.00	0.00	0.00	4.19	0.15	3.44	6.88	14.66	14.66
7	6.72	0.00	6.72	5.52	0.17	8.81	8.9	23.40	30.12
8	2.96	0.00	2.96	7.23	0.39	25.36	11.00	43.98	46.94
9	0.12	0.00	0.12	4.39	3.43	18.62	11.27	37.71	37.83
10	0.11	0.00	0.11	2.91	0.14	2.99	0.34	6.37	6.48

Appendix 2A - Table 5 Pit rehabilitated in 1981 (15 years old)

Quadrat	Standing live fuel	Standing dead fuel	Total standing fuel	Leaves	Bark	Duff	Round-wood	Total litter	Total Fuel
1	6.65	1.29	7.94	5.00	0.15	31.49	1.53	38.17	46.11
2	6.06	14.11	20.17	4.62	0.34	17.01	4.43	26.40	46.57
3	1.85	0.87	2.72	3.95	0.16	14.95	1.41	20.47	23.19
4	4.69	47.10	51.79	1.70	0.00	32.57	3.58	37.86	89.65
5	6.72	0.00	6.72	3.67	0.12	20.60	9.70	34.09	40.80
6	0.03	24.40	24.43	4.08	0.70	21.09	4.79	30.66	55.09
7	2.28	45.55	47.83	3.03	0.09	54.58	14.64	72.34	120.17
8	1.17	13.12	14.28	3.24	0.32	14.93	3.54	22.03	36.31
9	2.31	10.88	13.19	3.66	0.81	15.80	6.41	26.68	39.87
10	3.12	0.36	3.48	2.82	0.00	17.55	1.61	21.98	25.45

Appendix 2A - Table 6 Pit rehabilitated in 1981* (15 years-old)

Quadrat	Standing live fuel	Standing dead fuel	Total standing fuel	Leaves	Bark	Duff	Round-wood	Total litter	Total Fuel
1	1.33	45.84	47.17	2.52	0.53	18.73	11.20	32.97	80.14
2	0.01	20.77	20.78	1.07	0.00	28.26	12.13	41.47	62.25
3	0.01	7.33	7.34	4.19	0.09	13.80	27.11	45.19	52.53
4	13.40	1.79	15.19	3.26	0.00	37.36	5.29	45.91	61.10
5	1.64	0.00	1.64	0.53	0.00	3.16	0.60	4.29	5.93
6	0.08	1.35	1.42	2.97	0.00	37.83	2.55	43.34	44.77
7	0.06	5.37	5.43	2.24	0.00	7.72	5.20	15.15	20.58
8	0.02	7.76	7.78	3.16	0.25	13.32	4.22	20.96	28.74
9	9.25	0.00	9.25	3.38	0.05	17.44	4.57	25.45	34.70
10	0.00	15.76	15.76	3.99	0.52	30.55	5.25	40.31	56.06

Note* Pit sampled at the Huntly mine for study of controlled burn

Appendix 2A - Table 7 Pit rehabilitated in 1982 (14 years old)

Quadrat	Standing live fuel	Standing dead fuel	Total standing fuel	Leaves	Bark	Duff	Round-wood	Total litter	Total Fuel
1	0.44	1.03	1.46	3.66	0.00	8.18	6.97	18.81	20.27
2	0.94	13.87	14.80	7.76	0.31	28.32	7.70	44.10	58.91
3	0.33	0.00	0.33	2.64	0.00	11.50	2.00	16.14	16.48
4	1.74	14.89	16.63	4.96	6.57	20.54	5.09	37.17	53.80
5	0.00	10.65	10.65	2.24	1.11	32.31	5.80	41.47	52.12
6	0.30	34.96	35.27	1.63	0.29	24.52	6.48	32.91	68.18
7	1.90	18.62	20.52	5.60	5.48	27.27	9.92	48.26	68.78
8	18.89	12.50	31.39	0.31	0.00	16.95	4.39	21.65	53.04
9	0.27	10.56	10.83	2.90	0.15	23.79	1.23	28.07	38.90
10	0.00	8.22	8.22	2.14	0.15	27.43	2.43	32.15	40.36

Appendix 2A - Table 8 Pit rehabilitated in 1983 (13 years-old)

Quadrat	Standing live fuel	Standing dead fuel	Total standing fuel	Leaves	Bark	Duff	Round-wood	Total litter	Total Fuel
1	0.09	0.31	0.39	3.06	0.23	1.84	0.56	5.69	6.08
2	0.00	28.97	28.97	2.46	0.41	15.63	6.61	25.11	54.08
3	2.57	0.27	2.84	0.94	0.00	8.73	2.76	12.43	15.27
4	0.00	6.09	6.09	1.84	3.49	10.11	7.52	22.96	29.05
5	0.00	39.64	39.64	3.45	0.08	6.52	6.13	16.18	55.82
6	2.55	9.86	12.41	2.34	0.08	22.02	7.83	32.27	44.68
7	2.30	0.00	2.30	4.70	0.00	3.48	4.60	12.78	15.08
8	0.52	18.84	19.36	2.63	0.27	13.92	9.84	26.66	46.02
9	3.06	4.49	7.55	1.38	0.17	19.55	16.41	37.51	45.06
10	0.33	17.16	17.49	5.88	0.39	35.48	10.90	52.65	70.13

Appendix 2A - Table 9 Pit rehabilitated in 1984 (12 years-old)

Quadrat	Standing live fuel	Standing dead fuel	Total standing fuel	Leaves	Bark	Duff	Round-wood	Total litter	Total Fuel
1	2.04	3.97	6.00	1.85	0.21	10.43	1.51	14.01	20.01
2	20.74	0.00	20.74	2.01	0.00	38.63	1.21	41.85	62.59
3	19.90	9.92	29.81	2.50	0.20	21.11	3.01	26.82	56.63
4	9.74	7.56	17.30	1.66	0.11	19.32	1.12	22.22	39.52
5	8.67	14.08	22.74	1.36	0.00	15.14	2.78	19.28	42.03
6	10.15	3.67	13.82	2.13	0.00	12.47	2.78	17.38	31.20
7	0.27	2.81	3.08	0.96	6.87	19.16	6.68	33.67	36.75
8	24.14	0.00	24.14	0.72	0.00	12.81	2.42	15.94	40.08
9	16.39	4.67	21.06	1.32	0.20	22.85	1.41	25.77	46.83
10	24.85	15.36	40.21	0.37	0.00	8.84	2.14	11.34	51.56

Appendix 2A - Table 10 Pit rehabilitated in 1985 (11 years-old)

Quadrat	Standing live fuel	Standing dead fuel	Total standing fuel	Leaves	Bark	Duff	Round-wood	Total litter	Total Fuel
1	4.04	12.26	16.30	1.81	0.36	17.11	2.87	22.15	38.45
2	0.00	17.92	17.92	1.36	0.82	12.23	6.17	20.58	38.50
3	21.78	0.00	21.78	1.48	0.03	17.88	7.60	26.98	48.76
4	7.86	18.37	26.23	1.68	0.00	18.07	6.04	25.78	52.01
5	9.86	2.53	12.39	1.78	0.16	14.48	0.92	17.33	29.72
6	2.69	3.83	6.52	1.82	0.00	8.73	1.00	11.54	18.06
7	0.77	0.00	0.77	1.60	0.00	15.65	6.16	23.40	24.17
8	0.00	3.74	3.74	4.05	0.57	15.69	3.87	24.18	27.91
9	7.26	1.59	8.86	2.43	0.00	9.30	0.55	12.28	21.13
10	21.97	5.76	27.73	2.05	0.09	4.99	0.40	7.54	35.26

Appendix 2A - Table 11 Pit rehabilitated in 1986 (10 years-old)

Quadrat	Standing live fuel	Standing dead fuel	Total standing fuel	Leaves	Bark	Duff	Round-wood	Total litter	Total Fuel
1	4.91	10.09	15.00	4.64	0.00	7.18	2.90	14.72	29.71
2	2.83	0.00	2.83	2.02	0.10	7.14	2.42	11.68	14.51
3	1.73	9.48	11.21	5.74	0.81	9.17	2.34	18.06	29.28
4	0.68	0.19	0.87	0.54	0.00	0.45	0.51	1.49	2.37
5	13.67	0.00	13.67	3.25	0.56	8.75	3.59	16.14	29.81
6	39.30	0.00	39.30	7.32	0.04	18.72	4.03	30.12	69.41
7	0.93	0.00	0.93	2.57	0.15	9.47	2.26	14.45	15.38
8	45.35	3.80	49.15	2.63	0.00	14.30	1.71	18.63	67.78
9	10.74	2.03	12.77	3.50	0.97	14.27	4.41	23.15	35.92
10	2.62	0.00	2.62	1.76	0.24	11.41	3.30	16.71	19.33

Appendix 2A - Table 12 Pit rehabilitated in 1987 (9 years-old)

Quadrat	Standing live fuel	Standing dead fuel	Total standing fuel	Leaves	Bark	Duff	Round-wood	Total litter	Total Fuel
1	10.03	6.65	16.68	5.11	0.00	13.69	4.09	22.89	39.57
2	5.76	8.16	13.93	7.42	0.00	14.58	0.77	22.76	36.69
3	4.60	70.33	74.93	2.64	0.00	15.38	6.51	24.54	99.46
4	16.24	2.11	18.35	3.06	0.00	20.2	0.94	24.19	42.54
5	11.10	0.00	11.10	1.60	0.00	18.29	2.49	22.39	33.49
6	0.22	4.39	4.610	3.74	0.00	6.98	4.50	15.22	19.83
7	7.67	0.41	8.08	3.53	0.00	17.12	0.57	21.22	29.29
8	3.46	5.62	9.08	2.34	0.19	25.09	1.26	28.88	37.96
9	0.49	14.46	14.95	2.82	0.00	18.44	7.69	28.95	43.90
10	0.00	0.00	0.00	1.01	0.00	0.00	0.49	1.50	1.50

Appendix 2A - Table 13 Pit rehabilitated in 1988 (8 years-old)

Quadrat	Standing live fuel	Standing dead fuel	Total standing fuel	Leaves	Bark	Duff	Round-wood	Total litter	Total Fuel
1	0.00	13.05	13.05	1.55	0.00	11.81	1.48	14.85	27.90
2	2.69	2.06	4.75	0.83	0.00	2.53	0.19	3.55	8.29
3	5.41	4.13	9.54	4.19	0.00	11.50	3.58	19.27	28.82
4	20.09	11.96	32.05	2.76	0.00	17.95	1.50	22.20	54.25
5	14.32	14.01	28.33	1.53	0.00	12.05	1.55	15.13	43.46
6	8.37	16.48	24.85	1.13	0.00	12.25	0.50	13.88	38.73
7	32.59	13.08	45.67	1.37	0.00	14.05	1.47	16.89	62.55
8	3.19	21.93	25.12	2.69	0.00	13.56	1.70	17.95	43.08
9	8.03	2.12	10.15	1.25	0.00	8.30	1.02	10.57	20.72
10	6.77	5.42	12.19	1.65	0.00	8.06	1.45	11.16	23.35

Appendix 2A - Table 14 Pit rehabilitated in 1989 (7 years-old)

Quadrat	Standing live fuel	Standing dead fuel	Total standing fuel	Leaves	Bark	Duff	Round-wood	Total litter	Total Fuel
1	0.5o	0.00	0.5o	0.18	0.00	0.52	0.24	0.94	1.44
2	0.85	0.00	0.85	1.26	0.00	4.97	0.63	6.86	7.71
3	12.51	0.49	13.00	1.19	0.00	14.81	1.50	17.51	30.51
4	1.85	0.00	1.85	1.01	0.00	2.44	0.04	3.49	5.34
5	0.00	0.00	0.00	2.06	0.00	3.87	0.22	6.16	6.16
6	6.74	0.00	6.74	1.67	0.00	2.31	0.75	4.73	11.46
7	13.89	0.00	13.89	2.11	0.00	2.54	0.17	4.82	18.72
8	1.37	0.00	1.37	0.09	0.00	0.52	0.18	0.79	2.16
9	22.95	0.22	23.17	0.62	0.00	5.77	0.04	6.43	29.59
10	12.57	11.81	24.37	2.36	0.00	9.37	0.54	12.27	36.64

Appendix 2A - Table 15 Pit rehabilitated in 1990 (6 years-old)

Quadrat	Standing live fuel	Standing dead fuel	Total standing fuel	Leaves	Bark	Duff	Round-wood	Total litter	Total Fuel
1	10.61	0.14	10.75	0.57	0.00	4.65	2.65	7.86	18.62
2	5.75	0.00	5.75	2.19	0.00	8.02	0.60	10.81	16.56
3	58.41	0.74	59.15	6.66	0.00	14.17	1.19	22.01	81.16
4	8.62	0.55	9.17	2.05	0.00	12.78	1.01	15.85	25.01
5	20.82	0.56	21.38	7.64	0.00	2.15	0.42	10.21	31.59
6	29.66	0.00	29.66	4.26	0.00	0.78	0.80	5.84	35.50
7	20.04	5.24	25.28	6.92	0.00	21.89	2.47	31.29	56.57
8	2.36	0.04	2.40	3.26	0.00	5.76	1.13	10.15	12.55
9	33.42	0.00	33.42	5.57	0.00	8.35	0.00	14.47	47.89
10	17.01	2.82	19.83	10.17	0.00	14.92	0.98	26.07	45.90

Appendix 2A - Table 16 Pit rehabilitated in 1991 (5 years-old)

Quadrat	Standing live fuel	Standing dead fuel	Total standing fuel	Leaves	Bark	Duff	Round-wood	Total litter	Total Fuel
1	0.02	0.00	0.02	0.10	0.00	0.23	0.29	0.62	0.63
2	1.63	0.85	2.48	0.39	0.00	2.67	0.06	3.12	5.60
3	14.11	0.00	14.11	2.02	0.00	2.17	0.14	4.33	18.44
4	13.44	1.38	14.81	0.34	0.00	0.19	0.11	0.65	15.46
5	2.17	8.22	10.39	4.03	0.00	0.87	3.43	8.33	18.72
6	1.35	0.00	1.35	0.63	0.00	0.61	0.07	1.31	2.66
7	0.41	0.05	0.46	2.24	0.00	1.08	0.43	3.76	4.21
8	3.86	0.46	4.31	0.19	0.00	0.40	0.09	0.67	4.99
9	0.11	0.00	0.11	0.05	0.00	0.05	0.08	0.19	0.30
10	0.69	0.00	0.69	0.15	0.00	0.00	0.04	0.19	0.88

Appendix 2A - Table 17 Pit rehabilitated in 1992 (4 years-old)

Quadrat	Standing live fuel	Standing dead fuel	Total standing fuel	Leaves	Bark	Duff	Round-wood	Total litter	Total Fuel
1	28.71	0.00	28.71	4.30	0.00	0.86	0.21	5.37	34.08
2	5.86	0.00	5.86	0.95	0.00	0.00	0.13	1.08	6.94
3	8.00	0.00	8.00	4.49	0.00	4.14	0.17	8.80	16.80
4	6.95	0.00	6.95	1.83	0.00	0.00	0.55	2.38	9.33
5	12.27	0.00	12.27	0.38	0.00	0.00	0.04	0.42	12.69
6	7.40	0.00	7.40	0.43	0.00	0.00	0.04	0.47	7.88
7	0.44	0.03	0.47	0.30	0.00	0.00	0.07	0.37	0.84
8	0.21	0.00	0.21	0.19	0.00	0.00	0.02	0.21	0.42
9	2.46	0.05	2.51	0.44	0.00	2.47	0.17	3.08	5.59
10	16.72	0.00	16.72	0.23	0.00	0.00	0.51	0.74	17.46

Appendix 2B - Table 1 : Fuel loads collected by quadrat sampling for remnant jarrah forest (t/ha)

a) Aged 6 years since last controlled burn

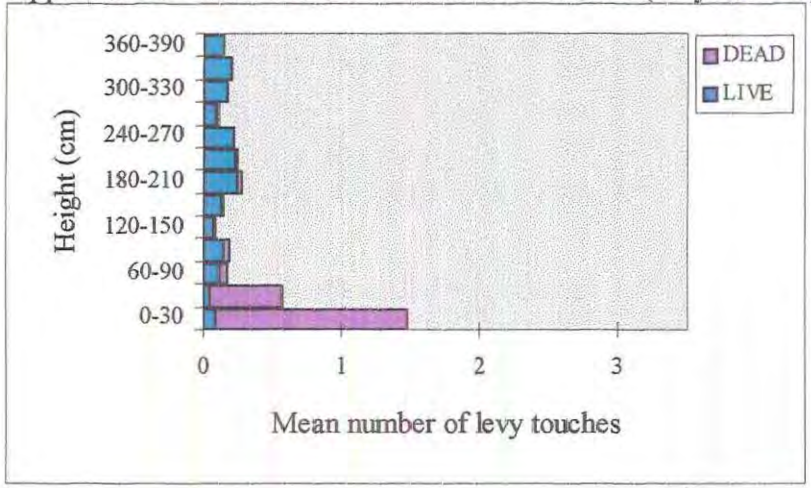
Quadrat	Standing live material	Standing dead material	Total average standing material	Total average litter	Total average fuel
1	0.62	0.00	0.62	23.61	24.23
2	0.75	0.00	0.75	15.82	16.56
3	1.47	0.13	1.60	26.47	28.07
4	0.90	0.00	0.90	14.18	15.08
5	1.73	1.50	3.22	24.54	27.76
6	7.03	3.12	10.15	8.50	18.66
7	0.64	0.00	0.64	8.510	9.15
8	10.97	3.01	13.98	12.86	26.85
9	2.58	0.08	2.66	39.02	41.68
10	4.22	0.00	4.22	19.39	23.60
mean	3.09	0.78	3.87	19.29	23.16
s.error	1.09	0.41	1.45	2.98	2.85

b) Aged 43 years since last controlled burn

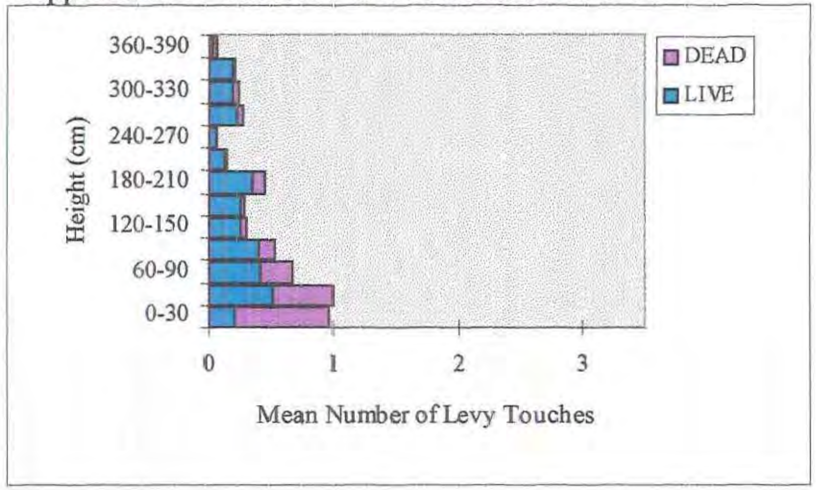
Quadrat	Standing live material	Standing dead material	Total average standing material	Total average litter	Total average fuel
1	0.86	0.00	0.86	39.19	40.05
2	0.61	0.54	1.15	16.48	17.63
3	0.38	1.26	1.64	25.78	27.41
4	0.20	0.00	0.20	26.38	26.58
5	0.53	2.30	2.83	25.23	28.06
6	0.78	0.00	0.78	33.68	34.46
7	0.02	0.00	0.02	36.81	36.83
8	1.97	1.89	3.85	29.32	33.17
9	1.12	0.81	1.93	34.07	36.00
10	2.83	0.12	2.95	21.20	24.15
mean	0.93	0.69	1.62	28.81	30.43
s.error	0.27	0.27	0.40	2.26	2.16

Appendix 2C : Height density profiles for the study sites developed from levy information

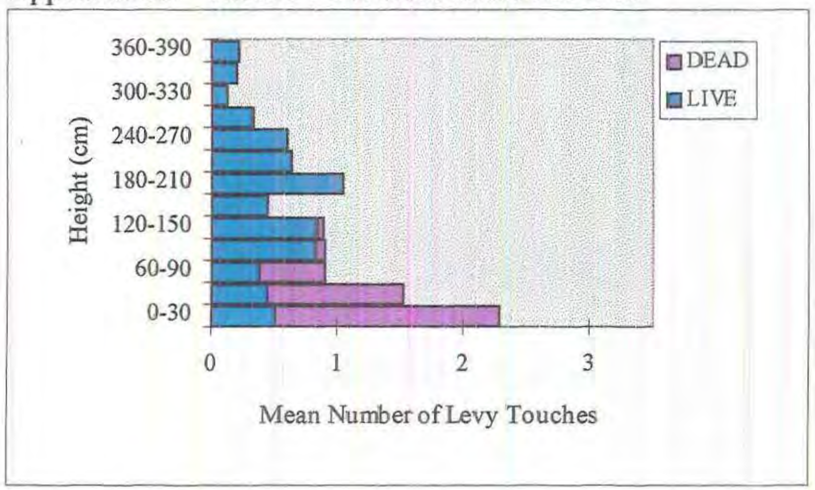
Appendix 2C - Table 1: Pit rehabilitated in 1976 (20 years old)



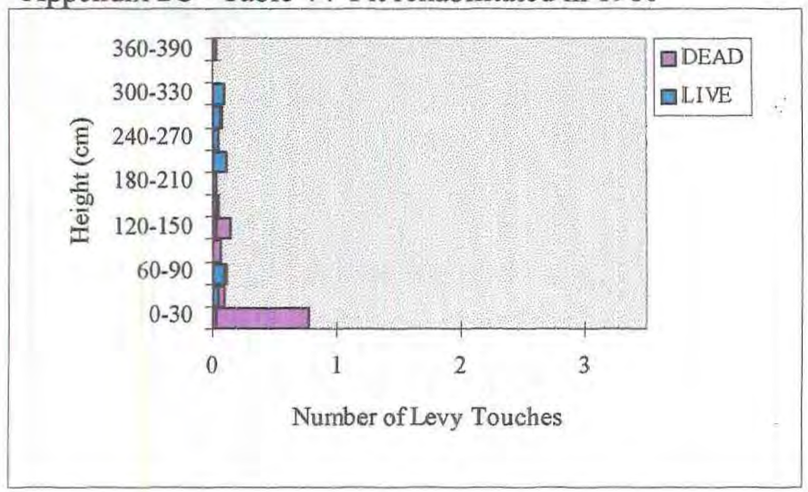
Appendix 2C - Table 2 : Pit rehabilitated in 1978



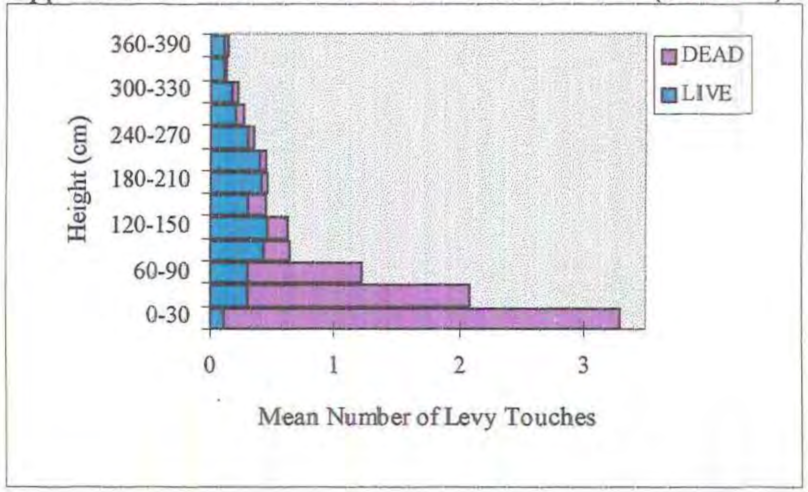
Appendix 2C - Table 3 : Pit rehabilitated in 1979



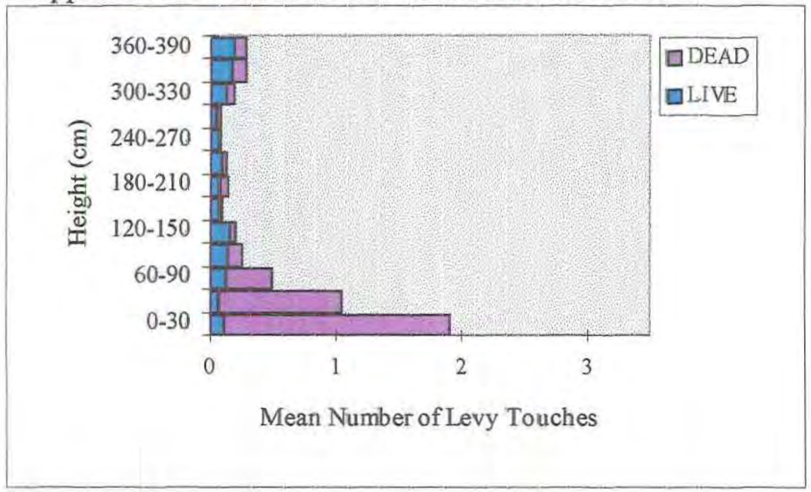
Appendix 2C - Table 4 : Pit rehabilitated in 1980



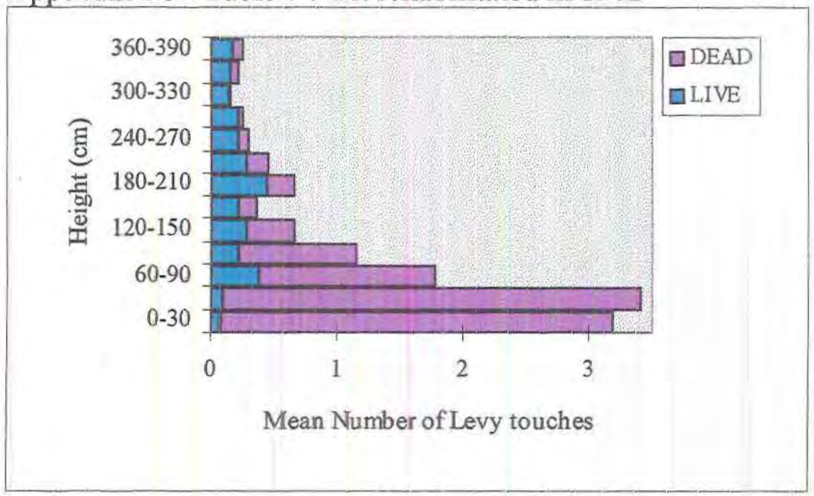
Appendix 2C - Table 5 : Pit rehabilitated in 1981 (burn site)



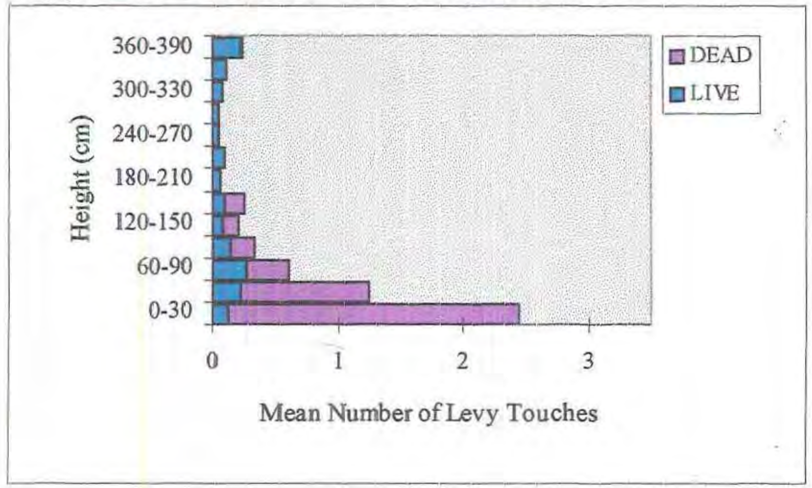
Appendix 2C - Table 6 : Pit rehabilitated in 1981



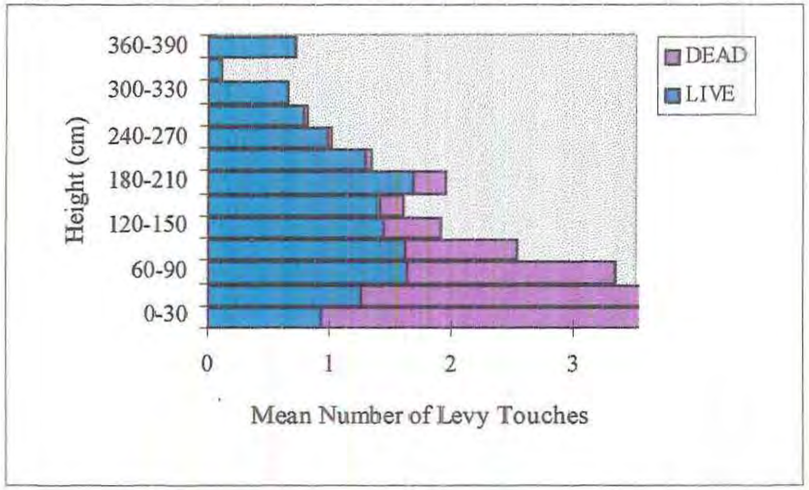
Appendix 2C - Table 7 : Pit rehabilitated in 1982



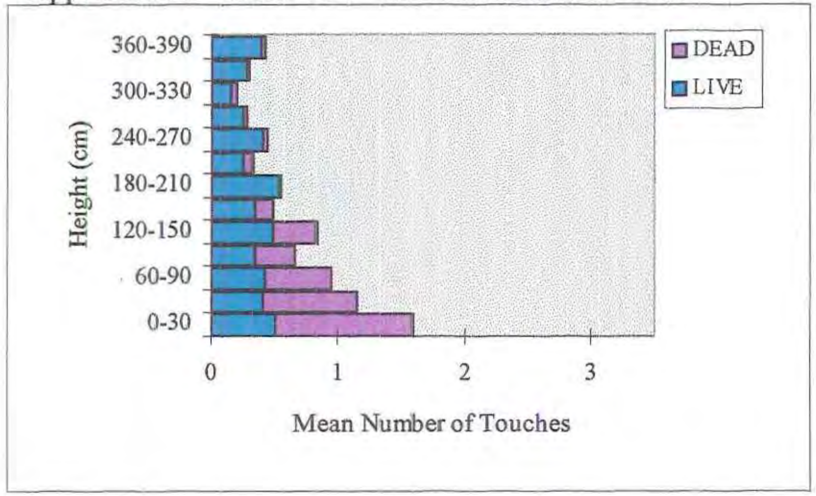
Appendix 2C - Table 8 : Pit rehabilitated in 1983



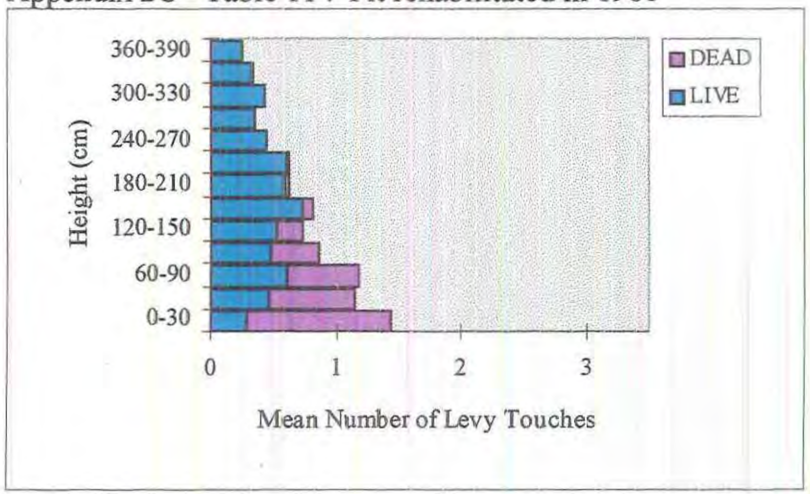
Appendix 2C - Table 9 : Pit rehabilitated in 1984



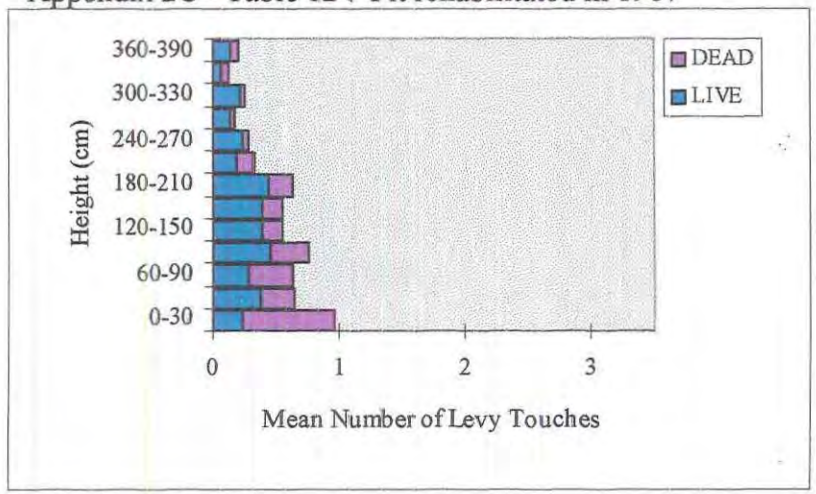
Appendix 2C - Table 10 : Pit rehabilitated in 1985



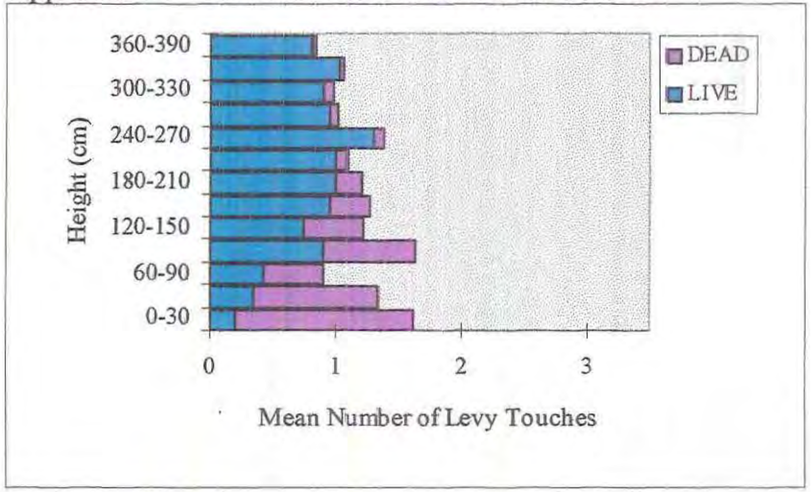
Appendix 2C - Table 11 : Pit rehabilitated in 1986



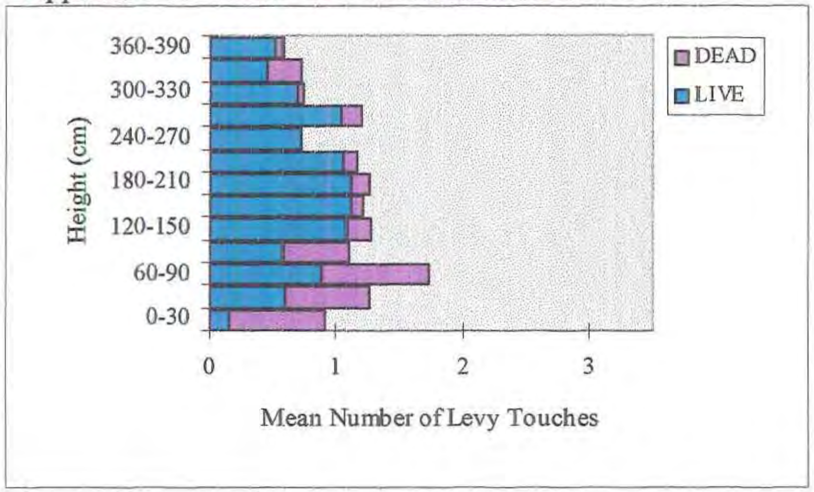
Appendix 2C - Table 12 : Pit rehabilitated in 1987



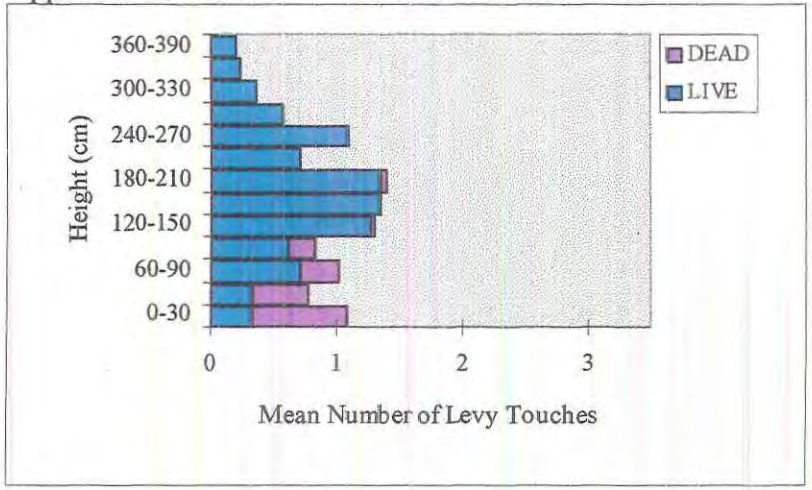
Appendix 2C - Table 13 : Pit rehabilitated in 1988



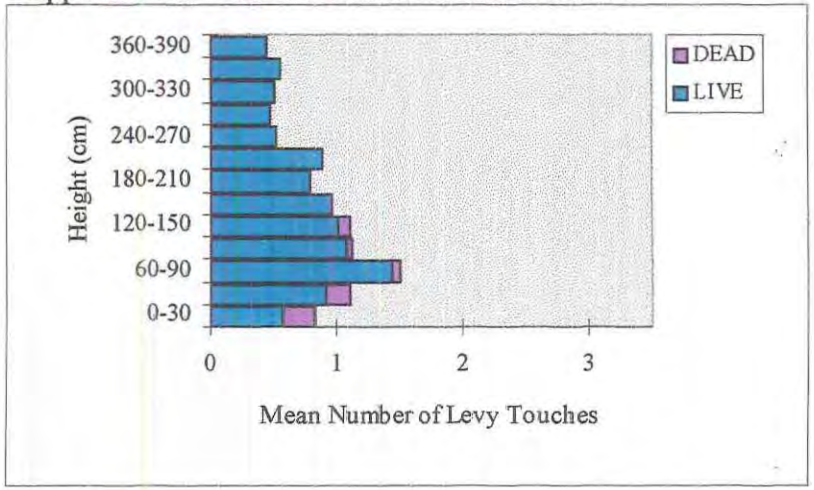
Appendix 2C - Table 14 : Pit rehabilitated in 1989



Appendix 2C - Table 15 : Pit rehabilitated in 1990



Appendix 2C - Table : Pit rehabilitated in 1991



Appendix 2C - Table 17 : Pit rehabilitated in 1992