THE ASSESSMENT OF FIRE HISTORY IN PLANTATIONS OF MPUMALANGA NORTH

by

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DECLARATION

I declare that the results contained in this thesis are from my own original work except where acknowledged, and that I have not previously in its entirety, or in part, submitted it at any University for a degree.

ABSTRACT

Fire is a threat to all forest plantations. As a result, growers are forced to take active measures to reduce the incidence and extent of fires in their plantations.

This thesis is an attempt to collate 846 fire records for eight Komatiland Forests (KLF) plantations in Mpumalanga North for the period 1950 to 1999. Up to now, these reports and the information therein, were not utilised by KLF for planning or for evaluating fire management practices. The only other studies in South Africa, using similar data, were conducted by Le Roux (1988) and Kromhout (1990).

A brief background of the forestry industry in South Africa, and in particular Mpumalanga is presented. The main text of the report covers a presentation on fire causes, extent of damage (both in area and in Rand value) and various aspects related to time of ignition and response times. A detailed analysis was done to identify possible relationships between the variables related to compartment, climate and different fire suppression activities.

A cause and frequency prediction model was developed that will assist fire managers in identifying and determining probabilities of fires per cause. Statistical guidelines regarding the planning of fire management around fires caused by honey hunters, lightning, work-related factors, and the activities of people (public, own labour, contractors) are presented.

Conclusions were drawn from the results of the analyses of the fire data, which covered a period of 47 years. Recommendations regarding guidelines for strategic fire management for the Mpumalanga North plantations were made. The main conclusions are:

- Statistics on previous fires are very useful in fire management planning as it supplies valuable information on fire causes, time of ignition, past performance related to response times, fire fighting times and damaged caused.

- The average area lost due to fires in the study area is 209.9 ha or 0.43% of the plantation area per annum.
- People-related fires (arson, smokers, picnickers, children and neighbours) caused most of the wild fires (48%), followed by lightning (22%).
- Some plantations performed poorly, with the occurrence of up to double the number of fires per 1 000 ha of plantation compared to other plantations in the same geographic area.
- There are definite patterns in the frequency of fires per cause with month of the year. These patterns are valuable for the development of strategies to manage fires caused by honey hunters, lightning fires and work-related fires.

SAMEVATTING

Brande is 'n bedreiging vir alle bosbou plantasies. Dit is dus noodsaaklik dat kwekers maatreëls tref om die voorkoms en omvang van brande in plantasies te beperk.

Hierdie tesis poog om 846 vuurverslae se inligting te ontleed ten opsigte van agt Komatiland Forests (KLF) plantasies in Mpumalanga Noord vir die tydperk 1950 tot 1999.

Tot op hede is min van die inligting wat in die verslae vervat is deur KLF vir beplanning- en evalueringsdoeleindes ten opsigte van brandbestuur gebruik. Die enigste soortgelyke studies wat op brandverslagdata in Suid-Afrika gedoen is, is gedoen deur Le Roux (1988) en Kromhout (1990).

'n Kort agtergrond oor die bosbouindustrie in Suid-Afrika en spesifiek Mpumalanga word gegee. Die tesis gee 'n oorsig oor brandoorsake, skade wat deur brande veroorsaak word (oppervlakte sowel as finansiële waarde) en verskeie aspekte rakende brandbestuur soos tyd van ontstaan en reaksietye. Data is volledig ontleed om moontlike verwantskappe te probeer vind tussen vak-, klimaat- en brandbestuursveranderlikes.

'n Oorsaak- en frekwensievoorspellingsmodel is ontwikkel wat brandbestuurders sal help om waarskynlikhede van brande per oorsaak te identifiseer. Statistiese riglyne ten opsigte van bestuursbeplanning vir weerligvure, brande deur heuninguithalers, brande as gevolg van plantasiewerksaamhede en ook brande deur mense (publiek, eie arbeid en kontrakteurs) is daargestel.

Brandrekords wat oor 'n periode van 47 jaar gestrek het, is ontleed. Afleidings wat uit die resultate gemaak is, kan benut word om riglyne daar te stel vir strategiese brandbestuur in Mpumalanga Noord plantasies. Die hoof gevolgtrekkings is:

- Statistiek van vorige vure is baie nuttig in brandbestuursbeplanning aangesien dit waardevolle inligting verskaf oor brand oorsake, tyd van

ontstaan, historiese werkverrigting rakende reaksietye en blustye, sowel as skade wat veroorsaak is.

- Die gemiddelde oppervlakte beskadig in die studie area is 209.9 ha, of 0.43% van die plantasie oppervlakte per jaar.
- Menslike aktiwiteite (brandstigting, rokers, piekniekvure, kinders en vure van bure) het die meeste brande veroorsaak (48%), gevolg deur weerlig (22%).
- Sommige plantasies het swak gevaar en het tot soveel as dubbel die aantal vure per 1 000 ha plantasie gehad in vergelyking met ander plantasies in dieselfde geografiese gebied.
- Daar is duidelike patrone gevind in die frekwensie van brande per oorsaak oor maande van die jaar. Hierdie patrone is nuttig vir die ontwikkeling van bestuurstrategie vir brande wat veroorsaak word deur heuningversamelaars, weerlig en werkverwante aktiwiteite (plantasie-aktiwiteite).

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Above all, to my Creator, for guiding me in selecting the noble profession of forestry, for giving me the insight to conduct this study and the perseverance to complete it.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

Pages

LIST OF TABLES

LIST OF TABLES (continued)

LIST OF FIGURES

LIST OF FIGURES

Pages

CHAPTER 1: INTRODUCTION AND STUDY GOALS

1.1 BACKGROUND

1.1.1 General

According to the annual statistics compiled by the Department of Water Affairs and Forestry (DWAF) on the forestry industry, the plantation area in South Africa for 2000/2001 was 1 351 760 ha and plantation area per province was as follows:

Table 1.1: Plantation area per province

Province	Plantation area 1999/2000 (ha)	%
Limpopo	64 534	4.8
Mpumalanga	540 709	40.0
North West Province	107	-
Free State	-	-
KwaZulu-Natal	525 154	38.8
Eastern Cape	148 919	11.0
Western Cape	72 337	5.4
Total	**1 351 760**	**100.0**

(DWAF, 2000/2001)

Therefore, plantation forestry in Mpumalanga accounts for 40% of the total plantation area in South Africa. The total area under commercial plantations in 2000/2001 was only 1.1% of the RSA area of 122.1 million hectares.

The statistics on plantations: "Commercial Timber Resources and Roundwood Processing in South Africa" collected annually by DWAF divides the country in twelve forest economic zones. The proposed study area falls within the Northern Regions zone (DWAF, 2000/2001). This zone consists of the area as shown in Table 1.2.

Table 1.2: Plantation areas in the Northern Regions zone

Northern Regions	ha	% of RSA	Private Ownership	Public Ownership
Limpopo Province	64 534	4.8	44 478	20 056
Mpumalanga North	250 940	18.6	155 282	95 657
Central Districts	19 545	1.4	14 155	5 391
Mpumalanga South	270 331	20.0	242 873	27 459
Total Northern Regions	**605 350**	**44.8**	**456 788**	**148 563**

(DWAF, 2000/2001)

These zones are based on provincial, physical, silvicultural, economic and historic considerations.

The study area, falling in the Mpumalanga North zone is situated in the Pilgrim's Rest magisterial district. The study area consists of eight KLF plantations covering a plantation area of approximately 50 000 ha (See Table 1.7).

The Mpumalanga North area within the Northern Regions zone is a very important forestry area and the total plantation area of 250 940 ha is utilised according to main products as follows:

Table 1.3: Mpumalanga North plantation area according to main products

Area	Main purpose	ha
Mpumalanga North	Softwood sawtimber	144 162
	Hardwood sawtimber	9 757
	Softwood pulpwood	27 896
	Hardwood pulpwood	36 034
	Hardwood mining timber	30 886
	Hardwood other	2 094
	Other	111
	Total	**250 940**

(DWAF, 2000/2001)

Plantations in Mpumalanga North are mainly managed for softwood sawlog purposes, (57% of Mpumalanga North) followed by hardwood mining timber (12.3%). The economic importance of the Mpumalanga North area is shown in Table 1.4 which shows the timber products sold from plantations (DWAF, 2000/2001).

Table 1.4: Timber products sold from Mpumalanga North plantations

Sawlogs and Veneer logs	1 534 311 m^3
Pulpwood	977 050 tons
Poles and Droppers	62 929 m^3
Mining timber	65 991 tons
Charcoal and Fire wood	42 474 tons
Other	9 063 tons

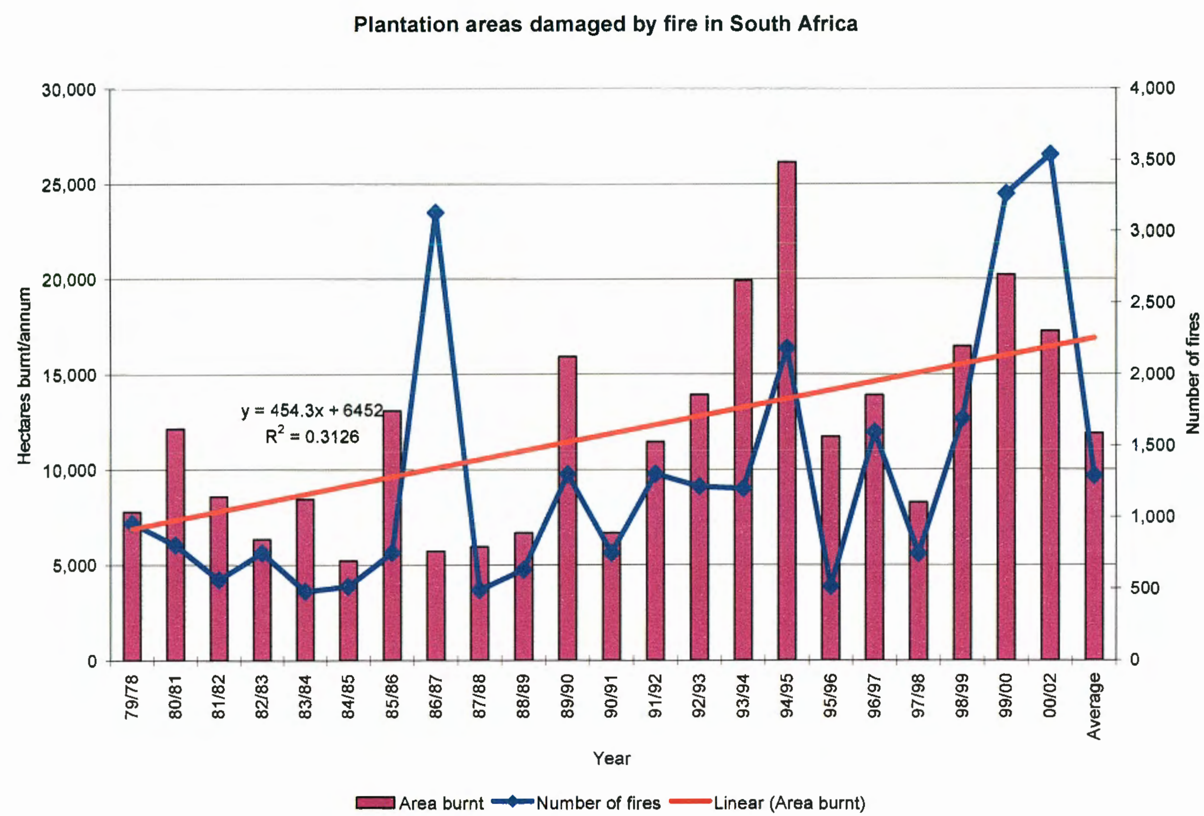
(DWAF, 2000/2001)

The total value of roundwood purchased for 2000/2001 for the South African forestry industry was R2 712 million (at mill cost of roundwood intake) and the value of sales of timber based products totalled R11 866 million. It is difficult to estimate the value of Mapumalanga North as sales volumes are not published per region. However, since the Mpumalanga North plantation area comprises 18.5% of the total South African plantation area, its proportion of the total sales will probably amount to approximately R2 195 million.

It is therefore critical that this valuable asset be protected, especially from fire damage. The forestry plantation areas damaged by fire in South Africa is provided in Table 1.5 (DWAF, annual reports). The average plantation area damaged per annum is approximately 12 000 ha. Areas damaged seems to follow the drought cycles such as the current droughts and the droughts of 1992 – 1994.

Table 1.5: Damage to plantations by fire

	78/79	80/81	81/82	82/83	83/84	84/85	85/86	86/87	87/88	88/89	89/90	90/91	91/92	92/93	93/94	94/95	95/96	96/97	97/98	98/99	99/00	00/02	Average
Area damaged	7,784	12,147	8,591	6,338	8,459	5,223	13,080	5,723	5,953	6,680	15,923	6,680	11,469	13,924	19,915	26,137	11,733	13,901	8,276	16,455	20,221	17,268	11,903
Number of fires	960	807	564	753	483	517	753	3,133	492	634	1,303	751	1,304	1,216	1,202	2,182	517	1,595	746	1,690	3,265	3,540	1,291



(DWAF annual reports)

Globally the pattern and occurrence of fires are very similar. Changes in weather patterns as a result of the El Niño phenomenon and global warming, is turning moist forests into drier habitats, and so increasing the flammability of forest vegetation, thus increasing the number, frequency, size, intensity and duration of fires (FAO, 1999, p. 3).

Fires, and specifically plantation fires, can result in major financial losses (De Ronde, 2001, p. 19) and measures must be put in place to manage the risk of wildfires. These measures can include fire prevention, a reduction in the frequency of fires and fuel management with the objective to alter fuel characteristics (hazard) (Greenlee and Sapsis, 1997, p. 13).

1.1.2 Introduction to Fire Management

Societies that are confronted with potentially destructive veld and forest fires establish fire management organisations to minimise the impact of fire on people, valuable assets, and the ecosystems about which they are concerned. Objectives are determined by the social, economic and political institutions that control it.

The extent to which objectives set by fire management organisations are achieved, depends upon:

- How well the fire and ecosystem processes and the impact of fire management are understood;
- The degree to which the social and economic impacts of fire are understood;
- The technology and resources society puts at the organisation's disposal;
- The knowledge, skills, and experience of the people in the organisation and;
- The challenges posed by nature.

(Martell, 2001, p. 527)

Global warming also results in more extreme weather conditions becoming more prominent and severe in the future. The 2003 fire season is a good example, with fire hazards reaching levels in certain forestry regions, never before recorded in South Africa.

Forest fire management is defined as the "activities concerned with the protection of people, property and forest areas from wildfire, and the use of prescribed burning for the attainment of forest management and other land use objectives, all conducted in a manner that considers environmental, social, and economic criteria" (Johnson and Miyanishi, 2001, p. 528).

Fire management programmes are designed to modify one or more of the following five basic elements of a fire regime, either directly or indirectly:

- Fire intensity,
- The season during which burning takes place,
- Fire size or extent,
- Fire type,
- Fire frequency

Preventive measures, for example, reduce fire frequency, whereas fire detection and suppression activities reduce final fire size. Fire prevention measures are effective when fire causes are clearly identified and remedied (Greenlee and Sapsis, 1987, p. 28).

Figure 1.1 provides a hierarchical view of a typical fire management decision-making process.

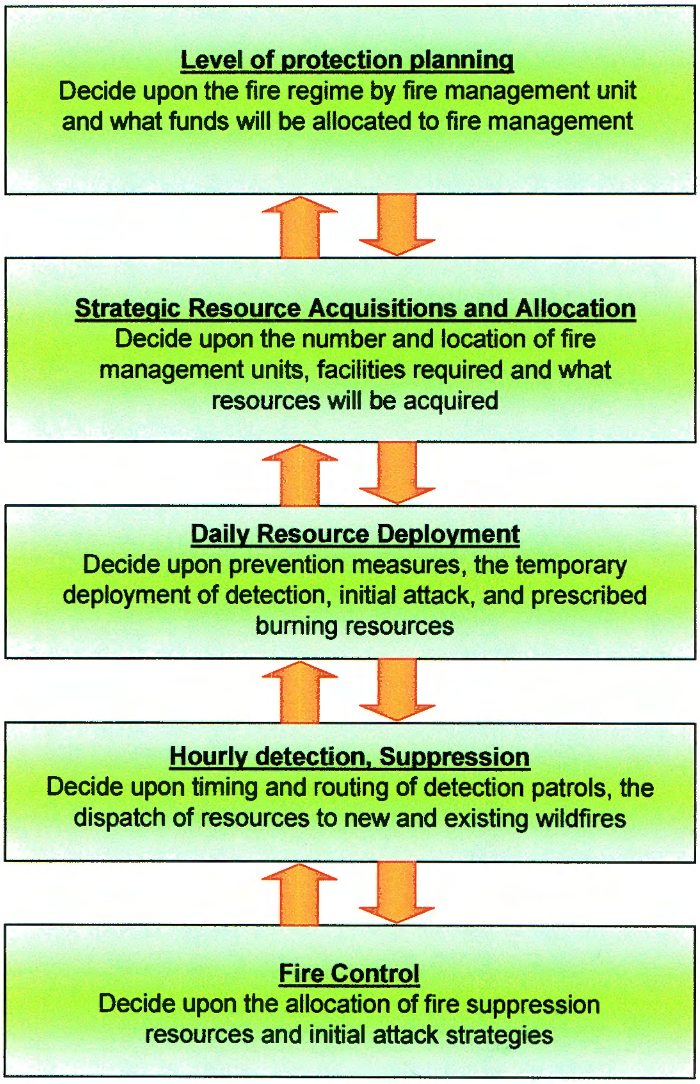


Figure 1.1: ***Fire management decision hierarchy (adapted from Martell) in Johnson and Miyanishi, 2001, p. 531)***

Assessing the social and economic impact of fires poses many complex problems and is a subject referred to as fire economics.

The effects of fire on timber plantations can be experienced in one or more ways, depending on the resistance of tree species to lethal temperatures, age of the trees, fire intensity and for what period of time the trees were exposed to high temperatures. De Ronde (2001) identified the following types of fire damage:

- Cambium damage
- Crown scorch
- Crown fire
- Root damage
- Secondary damage, e.g. pathogen attacks by *Rhizina*

In summary, fire management is a critical element in forest management in terms of its importance in sustainability of timber supply from plantations. Due to the constant increase in fuel load in plantations together with unfavourable climatic conditions during some months of the year, and a constant increase in human activities in and around forestry areas, efficient fire management is critical in the long term survival of the forestry industry.

1.1.3 Site description of the study area

1.1.3.1 General description

The study area comprised all of the timber plantations around the towns of Sabie, Graskop and Pilgrim's Rest that are managed by Komatiland Forests. The area is situated in the Mpumalanga Province on the eastern slopes of the Drakensberg Escarpment (Figure 1.2). Railway branch-lines run from Nelspruit through Sabie to Graskop and the area is well served by a network of all-weather roads.

Figure 1.2: Location of the study area

Tourists are attracted in ever-increasing numbers by the spectacular scenery of the area. There are several nature reserves, hiking routes, trout fishing opportunities and holiday resorts.

1.1.3.2 Forestry

In 1929 the Department of Forestry began its campaign of afforestation to provide employment in the depression years. Afforestation expanded rapidly and today it is by far the largest industry and employer in the area. Virtually all afforestable land has been planted up. The major growers are KLF, Mondi Forests, Sappi Forests and Global Forest Products (GFP). Figure 1.3 shows the localities of the eight KLF plantations in the study area as well as the two towns, Sabie and Graskop.

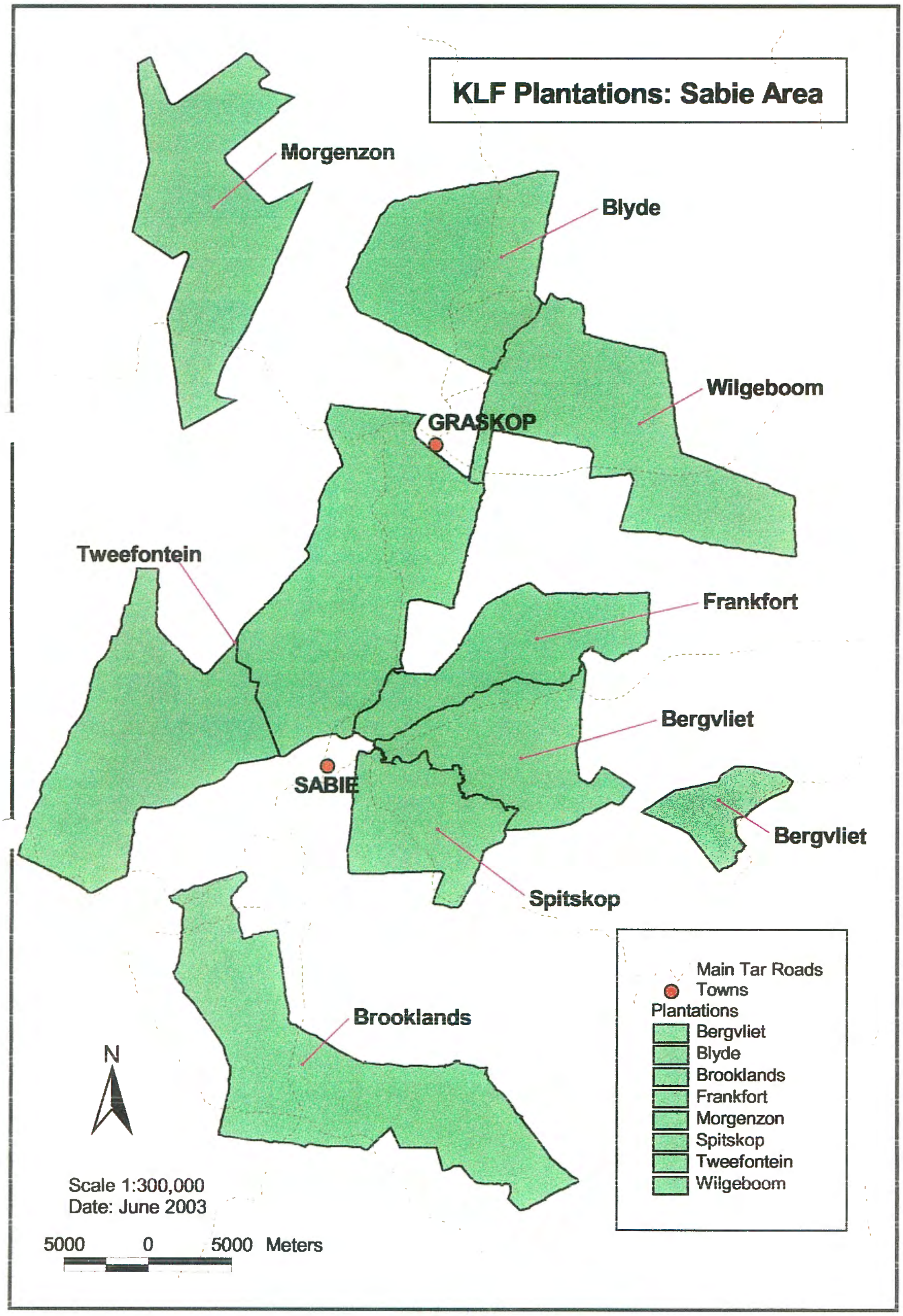


Figure 1.3: Map of the eight KLF plantations in the study area

1.1.3.3 Geomorphology

The edge of the Escarpment varies in altitude from 1 000 m near Rosehaugh in the south to nearly 2 000 m at Mariepskop, north of Graskop. The deep gorges, along which the edge of the Escarpment is shifted westwards and downwards (due to the westerly dip), were formed along lines of weakness caused by faulting or dykes, e.g. the Sabie and Mac Mac Rivers. The altitude of the Escarpment edge can thus vary greatly over relatively short distances, e.g. within 11 km there is a 1 600 m difference between Bakenkop (Spitskop Plantation) and Sabie Falls.

The main drainage systems are the Sabie and Mac Mac Rivers to the east and the Blyde and Treur Rivers to the north. The Sabie River has its source in the Mt Anderson range and flows east north east to the Lowveld.

1.1.3.4 Climate

1.1.3.4.1 Rainfall

The Escarpment falls within the summer rainfall area where most of the rainfall occurs between November and March. During this period rain is precipitated mainly in the form of thunderstorms and showers caused by convection in, and convergence of, tropical air masses. Light orographic rainfall associated with advection is also prevalent in the summer months, especially on the windward sides of the mountains and the Escarpment slopes. The small proportion of winter rainfall is derived mostly from orographic precipitation (Swanevelder, Van Huyssteen and Kotzé, 2001, p. 70).

On average, the Escarpment experiences a maximum of over 140 days per annum with measurable rainfall, including 60 to 80 thunder storms, which usually occur early in the rainy season (Weather Bureau, 1965, in Schutz, 1990, p. 31). Prolonged periods of rain, usually in the form of drizzle, are common.

Rainfall is generally reliable. In 58 years of recording at 24 stations in the Escarpment area, 78% of the annual falls occurred within about 20% of the normal rainfall (Weather Bureau, 1965, in Schutz, 1990, p. 31).

The regional climate is of the monsoon type in which three seasons can be recognised (Schutz, 1990, p. 31):

- The rainy season of summer and late summer (November to March)
- The cool dry season of autumn to early spring (April to August)
- The warm dry season of spring and early summer (September to October)

The strong seasonal nature of the rainfall at Tweefontein Plantation, which is typical of the area, is shown in Figure 1.4.

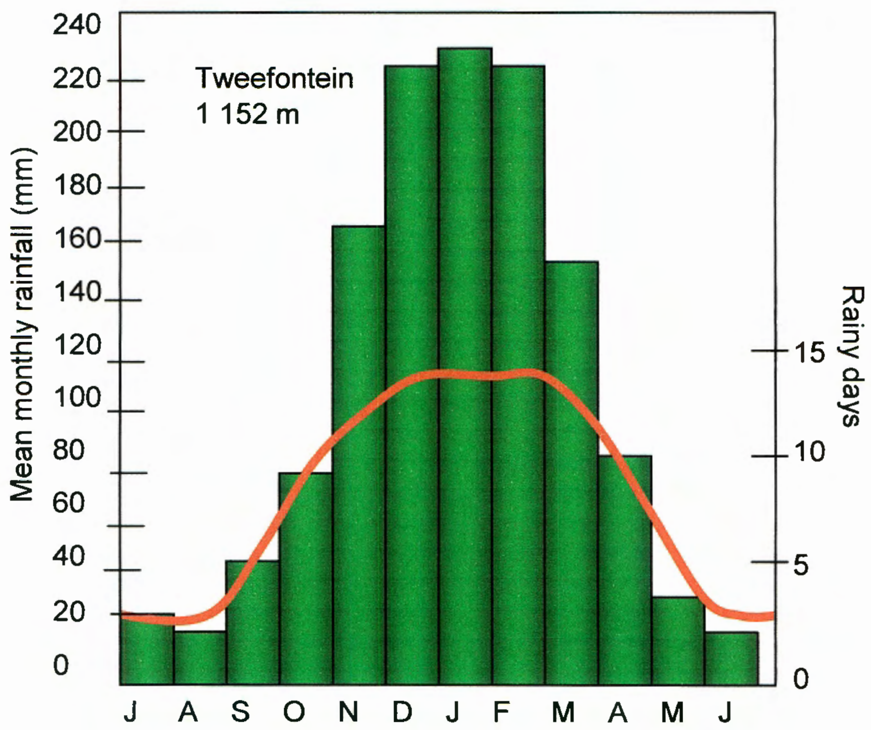


Figure 1.4: Mean monthly rainfall (histogram) and mean rainy days per month (graph) for Tweefontein Plantation (Schutz, 1990, p. 31)

Due to the broken topography, there is considerable variation in the mean annual rainfall within the study area (Table 1.6).

Table 1.6: Mean annual rainfall (from highest to lowest) for several stations in the Escarpment area (Schutz, 1990, p. 33)

Station	Rainfall (mm)	Period (years)	Altitude (m)
Kowynspas	2 027	6	1 445
Long Tom	1 853	17	1 525
Mac Mac	1 636	45	1 250
Mariti	1 594	29	1 115
Blyde	1 477	44	1 400
Frankfort	1 459	20	1 050
Spitskop	1 371	45	1 463
Bergvliet	1 320	40	981
Wilgeboom	1 297	50	1 032
Hartebeesvlakte	1 271	5	1 920
Tweefontein	1 258	45	1 152
Ceylon	1 248	44	1 075
Brooklands	1 201	43	1 234
Witwater	1 139	57	1 036
Rosehaugh	1 085	45	1 112
Morgenzon	881	29	1 615

Mean annual rainfall is highest along the Drakensberg Escarpment, increasing northwards to a maximum in the Graskop area. It is also high on the eastern slopes of the high mountains west of Sabie, but decreases northwards along these mountain ranges.

1.1.3.4.2 Other forms of precipitation

Mist is common in summer, usually above an altitude of 1 100 m. It plays an important role by reducing evapo-transpiration. Substantial contribution to soil moisture from fog drip has been widely reported, but the measurement of through-fall under a *P. patula* stand at a misty site on the edge of the Escarpment near Sabie has shown this contribution to be negligible (Schutz, 1990, p. 34).

1.1.3.4.3 Temperature

Temperature data for the region are scant. However, available information shows a direct relationship between temperature and altitude. Frost is prevalent in the winter months throughout the area, but frost-free sites are more common at low altitude. Frost is an important factor as it directly influences grass curing – an important aspect in grass fire behaviour.

1.1.3.4.4 Humidity

Humidity levels are correlated with precipitation, temperature and wind (Chandler, Cheney, Thomas, Trabaud and Williams, 1983, p. 69). The highest mean values for the area are recorded in February – March and the lowest in June – July with large fluctuations in July – August when the extremes may vary between 2% and 96% (Schutz, 1990, p. 36).

1.1.3.4.5 Wind

Schutz (1990) describes the winds as being south-easterly to easterly to north-easterly predominating during summer. These winds blow from the Indian Ocean and are often associated with anticyclonic systems, but can also be associated with cyclonic systems. Their persistence is often the harbinger of the steady rain, drizzle and mist so typical of Escarpment weather in summer. Winds which blow from the southerly to south-westerly sectors during early summer, especially in the afternoon, are often associated with thunderstorms. During winter these same winds are associated with cold fronts which are sometimes followed by mist and drizzle.

Violent bergwind conditions may occasionally occur. These winds become heated by compression as they drop over the Escarpment from the Highveld Plateau and are known to cause considerable physical and economic damage to timber plantations. The occurrence of such winds in the dry months of early spring constitutes a particularly serious fire hazard.

1.1.3.5 Vegetation

1.1.3.5.1 Indigenous

The study area spans two veld types of Acocks (1975), falling under his inland Tropical Forest Types, viz. the North-eastern Mountain Sourveld of the higher altitudes above the Escarpment, and the Lowveld Sour Bushveld of the lower altitudes east of the Escarpment (Veld Type 8 and Veld Type 9).

Indigenous forests are confined to fire-protected kloofs and southern aspects, but are relatively small in area. Forests were exploited for timber during the gold mining era (1840 – 1900) before exotic timber plantations were established. Virgin forest can still be found in inaccessible areas (Brink and Van der Zel, 1980, p. 13).

Grass species typical of the vegetation below the Escarpment are *Sporobolus* spp. and *Cymbopogon* spp., which occur mostly on disturbed sites, while *Loudetia* spp., *Themeda triandra* and *Panicum* spp. are common at higher altitude above the Escarpment (Schutz, 1990, p. 63).

Exotic timber plantations have created conditions favourable for the growth and spread of some indigenous species. Pioneer high forest species spread rapidly under mature stands of pine, particularly on the better dolomite and granite sites.

Soil disturbance and the release of nitrogen from the mineralisation of organic matter following clearfelling often result in the rapid invasion of the site by the indigenous grass species *Setaria megaphylla,* one of the most serious weed species among newly planted pines and eucalypts. *Setaria* occurs mostly at lower altitudes but is spreading rapidly into the higher-lying areas (Schutz, 1990, p. 64).

1.1.3.5.2 Exotic

Commercial timber plantations are the major component of the exotic vegetation and were discussed in paragraph 1.1.3.1.2 (Forestry).

Several exotics have achieved prominence as weed species in commercial plantations, notably *Solanum mauritianum* (Bugweed), *Lantana camara* (Lantana), *Rubus* spp. (American bramble), *Caesalpinea decapetala* (Mauritius thorn), *Phytolacca octandra* (Inkberry) and various tree species such as eucalypts, wattle, blackwood, jacaranda and guava.

Weed species and competing vegetation, whether indigenous or exotic, are generally most serious at low altitudes.

1.2 DATA SOURCE

Komatiland Forests owns and manages twenty softwood sawlog forestry plantations in the Mpumalanga and Limpopo provinces. The study focussed on eight KLF plantations in Mpumalanga North as detailed records were only available for these plantations (See Figure 1.3 for a map of the area). Plantations are managed by a Plantation Manager who reports to an Area Manager. Plantation managers are responsible for fire management in their plantations and interaction with neighbours and local fire protection associations.

For each fire exceeding a certain size and magnitude in a KLF plantation a fire report form has to be completed. The following needs to be recorded: date of ignition, ignition time, fire report time, cause, weather conditions, area burnt and costs. According to Brown and Davis (1973) p. 264 individual fire reports are very important as they are primary sources of fire statistics.

Up to now, these reports and the information therein, have not been utilised by KLF for planning or for evaluating current fire management practices. As KLF is in the process of privatisation, this valuable source of information may be lost due to restructuring and staff changes (RAD, 1999).

"Armed with a few years of factual data, the analyst can pinpoint the major sources of damaging fires, their times and patterns of occurrence, and their trends over time. Special prevention programmes can then be designed to reduce particular risks."

(Chandler, Cheney, Thomas, Trabaud and Williams, 1983, p. 47)

Conducting a fire prevention programme without reliable information is like operating a ship without a rudder. It consumes energy but does not get anywhere (Brown and Davis, 1973, p. 264).

Some details of the KLF plantations in the study area are listed in Table 1.7.

Table 1.7: Average annual precipitation, average elevation and plantation area for the eight KLF plantations in the study area

Plantation	Planted area (ha)	Average elevation (m)	Average annual precipitation (mm)
Bergvliet	5 641	1 200	1 250
Blyde	4 324	1 580	1 400
Brooklands	9 505	1 200	1 160
Frankfort	2 917	850	1 200
Morgenson	3 129	1 800	1 800
Spitskop	3 677	1 375	1 200
Tweefontein	12 859	1 000	1 300
Wilgeboom	6 864	990	1 253
Total area: 48 916 ha			

(RAD, 1999)

Six hundred and seventy six reports of fires, which occurred during 1970 - 1999 in the area, were collected. In addition, a fire database, compiled by Mr G Hilligan, a student forester, for 179 fires from 1950 – 1970 was also used. As the basic information recorded differed substantially between the two databases, they were evaluated separately.

An electronic fire report capturing format was developed to enter the available information into a fire database (Sampson, Atkinson and Lewis, 2000). Great care was taken to record the data accurately as several plantations merged during the study period, resulting in new plantation, block and compartment numbers.

Climatic information recorded in the fire reports are scant and unreliable as foresters were not equipped to accurately record wind direction, wind speed, temperature and humidity at the start of a fire. To supplement the climatic data, weather records for the study area were obtained from the South African Weather Bureau. Unfortunately these data are also insufficient for a detailed analysis as weather stations at Graskop and Bushbuskridge only operated for a short period and the automated weather station at Friedenham (Nelspruit) experienced several lengthy breakdowns.

1.3 STUDY GOALS

For the study of plantation fire management in KLF plantations in the Mpumalanga Escarpment the following study goals were identified:

- To establish a theoretical basis on fire management to form a framework for evaluating fire management in KLF.
- To review the extent to which fire management is performed, using historic fire data.
- To identify possible strategies to improve fire management on the Mpumalanga Escarpment.
- To analyse historic fire report data to determine trends and patterns in fire occurrence, fire behaviour, causes and fire size.
- To develop a model based on historic fire data to assist in future management decision making.
- To compile guidelines for a strategic fire management plan format that will address the following objectives:
    - To protect human life, property and assets, as far as practicably possible, from the negative consequences of fires.
    - To control all veld fires, those in plantations as well as those in the process of threatening plantations, in the shortest possible time, in a manner which is determined quickly, safely and thoroughly, giving due regard to management objectives, environmental values and economy.

- To minimise the incidence of preventable fires (fires of human origin).
- To ensure that archaeological, historical and other cultural sites are conserved.

1.4 STUDY PLAN

Published data and company reports from Komatiland Forests were used in this study. Fire information obtained from the Fire Fighting Association (FFA) in Nelspruit was also incorporated.

Chapter 1 gives the background information regarding the study. This includes the objective of the study, the importance of the study and an overview of the study site. This is necessary in order to understand the context of the environment within which the current fire management practices are being evaluated.

Without a sound understanding of the theoretical issues related to fire management, this complex field cannot be explored. Chapter 2 focuses on the science of fire management, i.e. fire behaviour, climate and suppression.

Chapter 3 evaluates the historic fire information collected for eight KLF plantations. Relationships between different factors will be evaluated and any correlations investigated to determine factors which increase the risk of fire occurrence and also which factors contribute towards fires getting out of control.

A fire cause and frequency prediction model is presented in Chapter 4 which will be used, together with statistical inputs from Chapter 3, to develop a guideline for fire management planning. Chapter 5 presents the conclusion and future perspectives on fire management, specifically for the study area.

As wildfires continue to destroy valuable tree crops and infrastructure, this study is considered to be important to understand and evaluate the situation in fire management in the Mpumalanga Escarpment. The recommendations are aimed at making a positive contribution towards solving problems that have been identified, and to improve fire management within KLF.

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CHAPTER 2: A THEORETICAL OVERVIEW OF PLANTATION FIRE MANAGEMENT

2.1 INTRODUCTION

Establishing plantations increases the fire hazard in several ways. This may arise because the plantation species are more fire-prone than the vegetation they replace or due to changes in microclimate within the stand. However, by far the most important contributing factor to an increase in fire hazard is the dramatic changes in fuel loads as the plantations develop and are utilised (Chandler *et al.*, 1983a, p. 384 and De Ronde, 1988, p. 15).

Brown and Davis (1973 p. 48) identified the following factors affecting susceptibility to fire damage:

- Initial temperature of the vegetation
- The size of the critical tree portion exposed and its morphology
- The thickness and character of the bark
- Branching and growth habit
- Rooting habit
- Organic material covering the mineral soil
- Flammability of foliage
- Stand habit, e.g. canopy density, thinnings
- Season and growth cycle

Intensively managed forests should be backed by a proper fire management plan, as well as sufficient funds to implement the plan, to ensure that the asset (investment) is adequately protected.

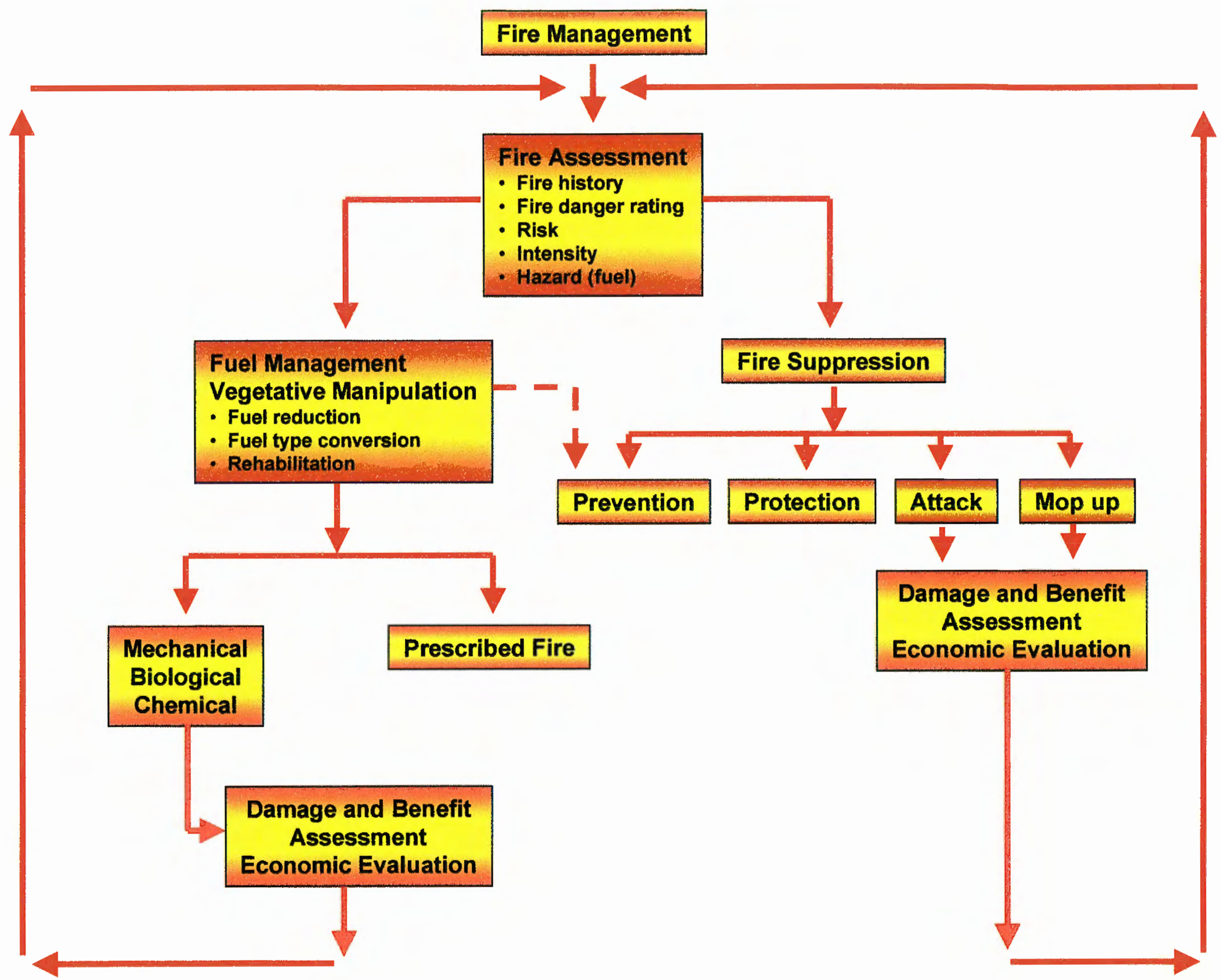


Figure 2.1: Fire management planning

From: Pyne, 1984 (p. 332)

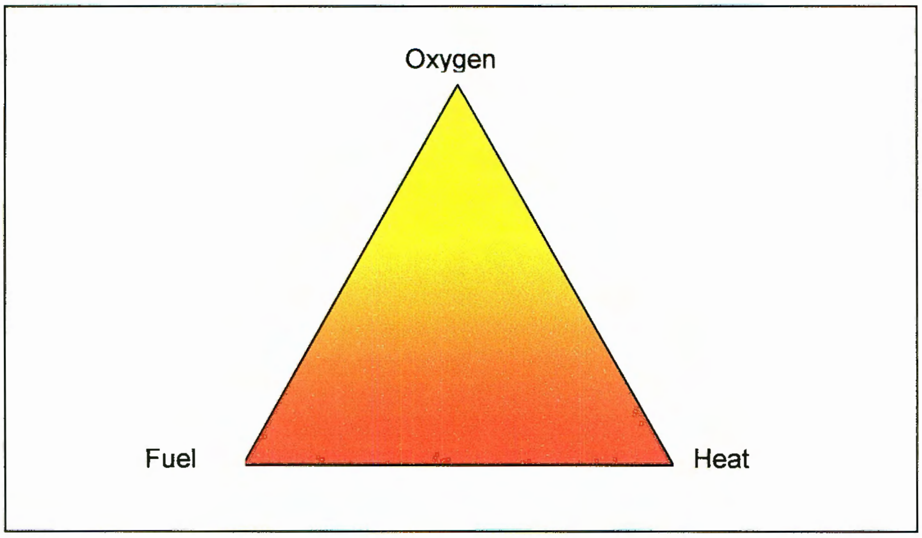
Fire management involves the management of fire fighters, the creation of plans to better organise fire fighters and the development of transportation systems to move them quickly to the scene of a fire (Pyne, 1984, p. 259).

The intention is to bring fire management in alignment with larger industrial and organisational goals (Figure 2.1). A degree of consolidation has resulted in the integration of fire suppression with fire management, of fire management with land management and of fire management institutions with inter-agency bodies having mutual programmes and shared resources (Pyne, 1984, p. 262).

Performance criteria that may be used are the following:

- Burned area and time of control – fire control programmes.
- Number of fire starts – fire prevention programmes.
- Elapsed time between start and initial attack – measure of organisational efficiency.

The combustion process can be considered as the interaction of three essential components: fuel, oxygen and heat. Combustion can proceed



(Heikkilä, Gronqvist and Jurvélius, 1993, p. 71)

Figure 2.2: Fire triangle

only when all three are linked together in a triangle (Figure 2.2). Fire control involves the removal of any one of the three components.

2.2 OBJECTIVES OF FIRE MANAGEMENT

The first thing to remember in attempting to formulate fire management objectives and policy is that fire management is not an end in itself. It is only a means to reduce the land manager's risk of loss due to fire damage and to increase the benefits from the proper use of fire (Chandler *et al.*, 1983b, p. 2).

At the foundation to all thinking about fire management objectives and plans is the fact that mankind has the ability to stop and start fires. Fire management can exercise some control over how fires start, how they spread and how they can be used for human purpose. Fires begin as point sources, which means that both prescribed fire and the control of wild fire are possible.

From its beginning fire protection has pursued a four-part strategy: to prevent unwanted ignition, to modify fire behaviour and effects by altering the environment in which a fire burns, to suppress wild fire and to exploit prescribed fire for use (Pyne 1984, p. 258).

As wild fires spread and intensify, fire effects, fire damages and fire suppression costs cannot be expressed as a linear function. Therefore, the secret to controlling fire is to stop small fires before they can make the transition into large fires (Sampson, Atkinson and Lewis, 2000, p. 7).

Fires and fire seasons are not distributed uniformly or in a simple binomial mode. Through the use of historical records, it is possible to determine a level of manning suitable to the regime, but it is not yet possible to determine which year will present abnormal problems for fire control. The result is a pattern for which averaged conditions are not a useful guide, as exceptional years or months account for most of the costs and damages (Pyne, 1984 p. 259). Fire management planning is a continuing process requiring annual revision as risks and hazards change and as better data are accumulated.

2.3 FIRE WEATHER

2.3.1 Introduction

Forests exist within the earth's atmosphere and are greatly influenced by changes in this atmosphere, both long and short-term. In general, these changing conditions of the atmosphere are known as weather and the terms used to describe it are temperature, wind, humidity and precipitation. It had become apparent to researchers looking into weather-fuel-fire behaviour relationships that whereas the basic relationships are relatively simple – the fuel absorbs moisture from precipitation and loses it during "dry" weather – there are many complex interrelationships and other influences that have a bearing on fuel moisture, hence flammability. Wind, for example, has distinct effects. Firstly, it plays an important role in drying rates of most forest fuels, and secondly, it has a very strong influence on the spread of fire once it has been ignited. In the drying influence of wind it was found that there are complex interrelationships with such other factors such as the relative humidity of the air surrounding the fuel, air and fuel temperatures, and the physical condition of the fuel (arrangement, density) to name a few (Chandler *et al.*, 1983a, p. 57).

Weather and climate affects forests fires in different but related ways:

- Climate determines the total amount of fuel available for combustion.
- Climate determines the length and severity of the fire season.
- Weather regulates the moisture content, and hence flammability of dead forest fuels.
- Weather has an independent influence on the ignition and spread of forest fires (Chandler *et al.*, 1983a, p. 58; Perry, 1990. p. 99).

2.3.2 Basic principles

The atmosphere can be divided into several layers, based primarily on their temperature characteristics (Schroeder and Buck, 1970, p. 3). The lowest layer is the troposphere where temperature decreases with height. This temperature structure allows movement of the air, resulting in clouds and storms and other changes that affect fire. The depth of the troposphere varies from about 8 km over the North and South Poles to about 16 km over the Equator.

Air in the troposphere is composed mostly of two gases. Dry air consists of about 78% nitrogen by volume and about 21% oxygen. Of the remainder, argon comprises about 0.93% and carbon dioxide about 0.03%. In addition to these gases, the troposphere contains a highly variable amount of water vapour – from near zero to 4 or 5%.

Water vapour has a profound effect on weather processes for without it there would be no clouds or rain. Variations in the amount of water vapour influence the moisture content and flammability of surface fuels (Schroeder and Buck, 1970, p. 3). Oxygen is essential for combustion. The troposphere also contains salt and dust particles, smoke and other industrial pollutants (Teie, 1997, p. 39).

The basic cause of winds is the movement of cold air from poles to the equator and warm air from the tropics back to the poles which are deflected due to the coriolis effect. The reason for the deflection is that the earth, rotating towards the east on its axis, turns underneath the moving air or body. This deflective force is called the coriolis force (Hurry, Henning, Hart, Irwin and Fair, 2001, p. 15).

When hot air rises it starts to turn (spiral) which may result in cyclones (depressions, low pressure systems). This weather phenomenon is associated with clouds and rain. Anticyclones are caused by downward moving air resulting in an increase in air pressure. These high-pressure systems are associated with fair weather.

Air has measurable mass and responds accordingly to the force of gravity. Atmospheric pressure varies with elevation, the higher the elevation, the lower the atmospheric pressure. Atmospheric pressure is measured in millibars (mb) and the pressure at sea level is normally within the range of 980 to 1 040 (Luke and McArthur, 1978, p. 49).

All energy, however, comes either directly or indirectly from the sun. The conduit for this action is solar radiation energy. The energy produced in the sun is by nuclear fusion, a process in which hydrogen is converted into helium. In the process, some of the sun's mass is converted to thermal energy.

The intensity of solar radiation received at the outer limits of the earth's atmosphere is quite constant (Schroeder and Buck, 1970, p. 11). However, the amount that reaches the earth's surface is highly variable depending on location, atmospheric conditions (e.g. clouds, moisture, pollution) and surface orientation or aspect (e.g. south, north).

On average, 50% of the sun's energy reaches the earth's surface, 20% is absorbed by the atmosphere (clouds, water vapour or pollutants) and 30% of the energy is reflected back into space (see Figure 2.3).

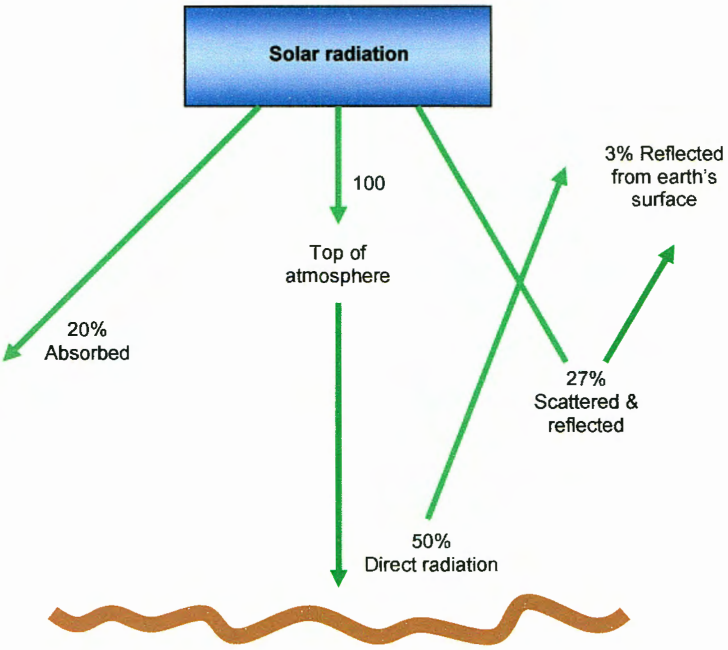


Figure 2.3: Distribution of incoming solar radiation during average cloudiness

(Teie, 1997, p. 40)

2.3.3 Temperature

The solar radiation which is absorbed, either by the atmosphere or by the earth, is converted back to thermal energy and thus warms the earth's surface. The earth's average temperature does not change, because the earth in turn radiates energy to the atmosphere and to space.

It is important to life on earth, and to weather processes, that the radiation received and those that are emitted by the earth, are of different wavelengths. Because of this difference, the atmosphere (especially the water vapour) acts much like the glass in a greenhouse.

The lag time is the period between when solar radiation strikes the earth and when the heat is radiated back out into space. According to Teie (1997, p. 43) this time varies both throughout the day and throughout the year. The greatest amount of solar radiation reaches the earth around noon, but the highest temperatures usually occur between 14:00 and 16:00 hours (Figure 2.4).

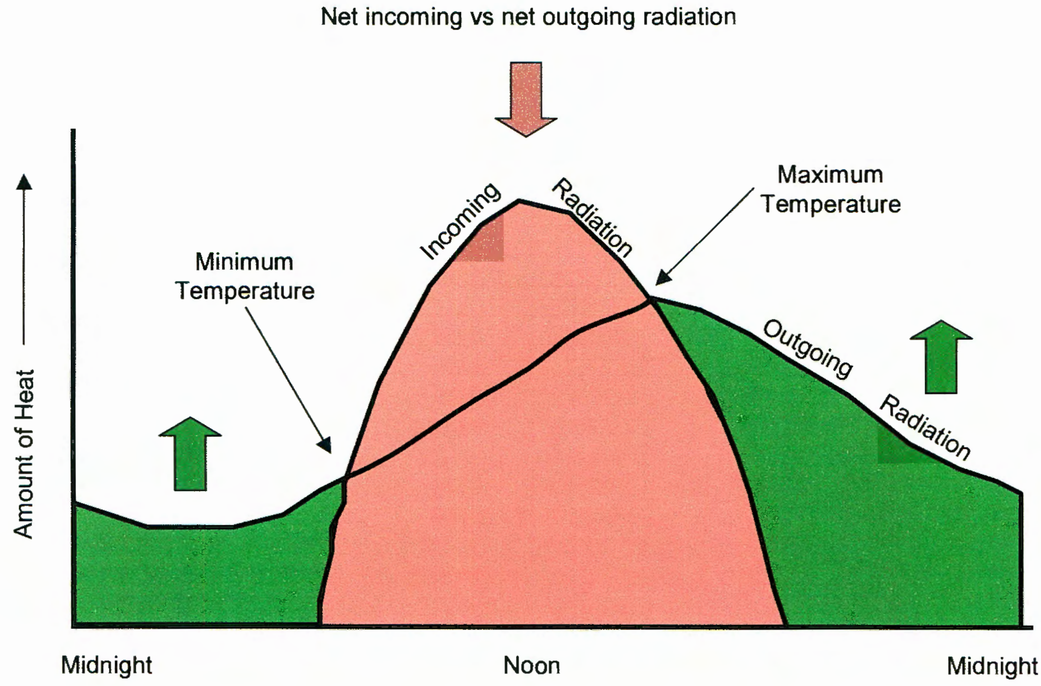


Figure 2.4: Net incoming vs net outgoing radiation

(Teie, 1997, p. 43)

Topography plays an important role in local surface temperature variations. Differences in topography cause local variations in the angle at which the sun's radiation strikes the ground surface. Both the steepness and the aspect of a slope affect surface heating and cooling. Accordingly, east-facing slopes reach their maximum temperature rather early in the day, while west-facing slopes attain their maximum temperature later in the afternoon (Schroeder and Buck, 1970, p. 22).

Water droplets in clouds and invisible water vapour in the air, also influence the cooling of the surface at night. Surface temperatures normally are much lower on clear nights than on cloudy nights. A blanket of smoke from forest fires, like clouds, causes significantly lower daytime surface temperatures, and higher night time temperatures, when skies are otherwise clear.

Strong daytime winds near the surface tend to prevent high surface temperatures. This air movement also transports moisture, increasing evaporation from moist surfaces and thus restricting the temperature rise. The temperature of the air is directly related to how much moisture the air can hold, but will be discussed further under the heading – "Atmospheric moisture", paragraph 2.3.4.

Air cooled at night, primarily by contact with cold, radiating surfaces, gradually deepens as the night progresses and forms a surface inversion. This is a surface layer in which the temperature increases with height. The cold air is dense and readily flows down slopes and gathers in pockets and valleys.

In all situations, according to Schroeder and Buck (1970, p. 30), vegetation moderates air temperatures within the vegetative layer, and the temperature distribution depends upon the nature and density of the vegetation.

Clear skies and low air moisture permit more intense heating at the surface by day and more intense cooling by radiation at night than do cloudy skies. The lower atmosphere tends to be more unstable on clear days and more stable on clear nights.

2.3.4 Atmospheric moisture

Water is always present in the lower atmosphere in one or more of its three states, e.g. gas, liquid or solid. A saturated volume of air contains all the vapour that it can hold. The vapour pressure at saturation is called the saturation vapour pressure. Saturation vapour pressure varies with the temperature of the air and is identical to the vapour pressure of water at that temperature. The higher the temperature the more water vapour a volume of air can hold and the higher the saturation vapour pressure.

Saturation is usually reached by the air being cooled until its saturation vapour pressure equals the actual vapour pressure. The temperature of the air at that point is called the dew-point temperature or dew point (Schroeder and Buck, 1970, p. 37).

The actual amount of water vapour in a given volume of air, that is the weight per volume, is called the absolute humidity. A direct relationship exists among the dew point, the vapour pressure and the absolute humidity. At saturation the dew point is the same as the temperature, the vapour pressure is the saturation vapour pressure and the absolute humidity is the saturation absolute humidity.

Because of these relationships the temperature of the dew point is a convenient unit of measure for moisture. Air temperature and dew point accurately define atmospheric moisture at any time or place (Perry, 1990, p. 121).

Saturation of surface air is a condition of favourable fire weather; that is, conducive to low fire danger. Less favourable are conditions of unsaturation which permit evaporation from forest fuels, increasing their flammability and the fire danger. Therefore, a very useful measure of atmospheric moisture is the relative humidity. It is the ratio, in percent, of the amount of moisture in a volume of air to the total amount which that volume can hold at the given temperature and atmospheric pressure. It ranges from 100% at saturation to near zero for very dry air.

Water vapour in the air comes almost entirely from three sources: Evaporation from water surfaces, evaporation from soil and transpiration from plants. Wind according to Schroeder and Buck (1970), p. 41, encourages evaporation by mixing moist air with drier air aloft.

Relative humidity is most important as a fire-weather factor in the layer near the ground where it influences both fuels and fire behaviour. Near the ground, air moisture content, season, time of day, slope, aspect, elevation, clouds and vegetation all cause important variations in relative humidity.

Schroeder and Buck, (1970, p. 43) state that a typical fair-weather pattern of relative humidity is nearly a mirror image of the temperature pattern. Maximum humidity generally occurs about daybreak, at the time of minimum temperature. After sunrise, humidity drops rapidly and reaches a minimum at about the time of maximum temperature. The daily range of humidity is usually greatest when the daily range of temperature is greatest.

Humidity may vary considerably from one spot to another, depending greatly on the topography. In mountainous topography the effects of elevation and aspect become important and humidities vary more than over gentle terrain. Low elevations warm up and dry out earlier in the season than do high elevations. North and south slopes have different relative humidities. In most mountainous areas the daily range of relative humidity is generally greatest in valley bottoms and least at higher elevations.

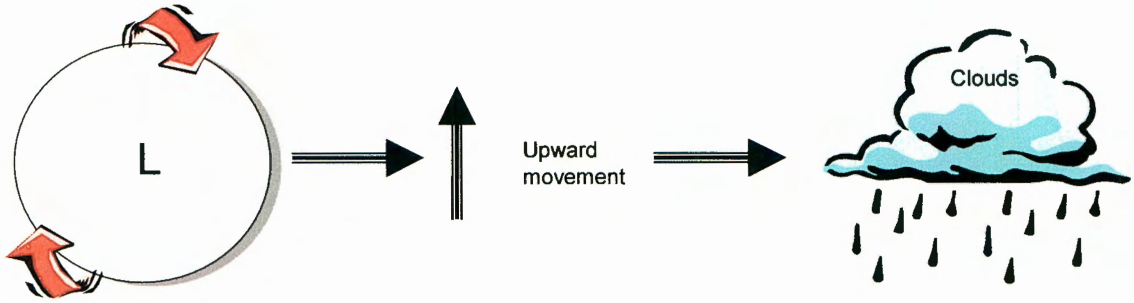
Clouds strongly affect heating and cooling and therefore influence the relative humidity. The humidity will be higher on cloudy days and lower on cloudy nights. Vegetation moderates surface temperatures and contributes to air moisture through transpiration and evaporation – both factors that affect local relative humidity. Under a closed canopy, humidity is normally higher than outside during the day, and lower at night.

2.3.5 Atmospheric stability

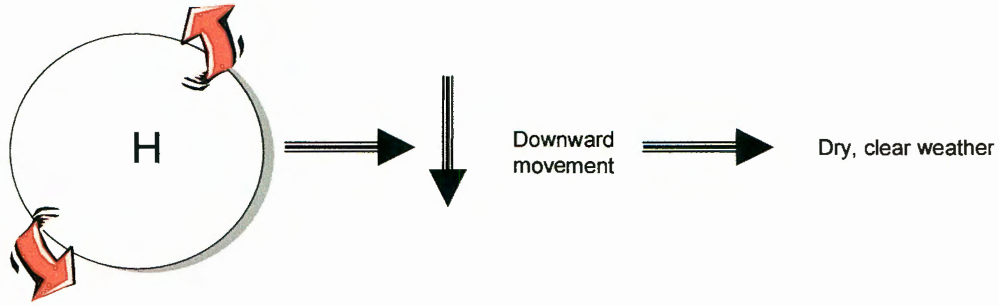
Atmospheric stability is defined as the resistance of the atmosphere to vertical motion (Schroeder and Buck, 1970, p. 50). A common process by which air is lifted in the atmosphere is convection. Surface heating during the daytime makes the surface layer of air unstable. After its initial inertia is overcome, the air is forced upward by the more dense surrounding air. Wildfire also may be a source of heat which will initiate convection (Olivier, 1982, p. 32).

Layers of air commonly flow in response to pressure gradients. In doing so, if they are lifted up and over mountains, they are subjected to what is called orographic lifting (Chandler *et al.*, 1983a, p. 71). In air masses, lighter air layers frequently flow up and over colder, heavier air masses. This is referred to as frontal lifting and is similar in effect to orographic lifting.

The airflow around surface low-pressure areas in the Southern Hemisphere is clockwise and spirals inward. Cold air moves towards the low pressure area (convergence) and upwards, resulting in clouds and rain, as indicated below.



The Coriolis effect is due to the earth's rotation in an eastern direction. As a result of the earth's rotation air movement is deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. Therefore, air movement to a low pressure system will move spirally around a low pressure area, approximately parallel with isobars. A line of low pressure is referred to as a trough. The pressure along the line is lower than the pressure on either side (Tolhurst and Cheney, 1999, p. 59), as illustrated below.



In high pressure cells the warm (hot) air moves down and outwards. In low pressure cells the direction is opposite. The downward moving air results in evaporation of clouds and dry weather. Ridges are lines of high pressure. “Bergwinds” are very dry, hot winds blowing from the interior seawards, occurring in the zone between anticyclones and cyclonic air circulation. Also called “foehn”-winds, a wind flowing down the leeward side of mountain ranges where air is forced across the ranges by the prevailing pressure gradient. The dryness and warmth of this air, combined with the strong wind flow, produce the most critical fire-weather situations known anywhere. The development of a foehn wind requires a strong high pressure system on one side of a mountain range and a corresponding low or trough on the other side (Schroeder and Buck, 1970, p. 101).

Air always moves in response to pressure differences, which are controlled by a combination of forces. These include the pressure-gradient force (air to move from high to low pressure), the coriolis force, an outwardly directed centrifugal force if air is flowing in a curved path and friction which opposes all air movement near the surface of the earth (Jenkins, Clark and Coen, 2001, p. 257).

2.3.6 Wind

Wind is air in motion relative to the earth’s surface. Its principal characteristics are its direction, speed and gustiness or turbulence (Davis, 1959, p. 145).

The two most important weather, or weather related elements affecting fire behaviour are wind and fuel moisture. Of the two, wind is the most variable and the least predictable. Wind aids combustion by increasing the oxygen supply, it aids fire spread by carrying heat and burning embers to new fuels, and by bending the flames closer to the unburned fuels ahead of the fire (Cheney and Sullivan, 1997; Rothermel 1995 and Schroeder and Buck, 1970).

When the wind is strong and sustained, a running crown fire may continue and spread for several hours, burning out entire catchments and crossing mountain ridges that would normally be barriers (Rothermel, 1995).

Wind direction is ordinarily expressed as the direction from which the wind blows. In mountainous country, though, surface wind direction with respect to the topography is often more important in fire control. Here it is common to express the wind direction as the direction towards which the wind is headed. Thus, an upslope wind is actually headed up the slope, while “offshore” or “onshore” are used to describe the directions towards which land and sea breezes are blowing. Thermal turbulence is associated with instability and convective activity and most pronounced in the early afternoon when surface heating is at a maximum. It is the reason why surface winds at most places are stronger in the afternoon than at night (Schroeder and Buck, 1970, p. 90).

2.3.6.1 Wind aloft

Veld and forest fires of low intensity may be affected only by the airflow near the surface. But when the rate of combustion increases the upper airflow becomes important as an influence on fire behaviour. It may carry burning embers which ignite spot fires some distance from the main fire. The winds aloft may be greatly different in speed and direction from the surface winds (Davis, 1959, p. 149).

As successive air masses move across the land the change from one to another at any given point is marked by the passage of a front. A front is the boundary between two air masses of different temperature and moisture characteristics.

The type of front depends upon the movement of the air masses. Where a cold air mass is replacing a warm air mass the boundary is called a cold front. Where a warm air mass is replacing a cold air mass the boundary is called a warm front.

The passage of a front is usually accompanied by a shift in wind direction. The reason for this is that fronts lie in troughs of low pressure. The wind behaviour during the frontal passage depends upon the type of front, its speed, the contrast in temperature of the air masses involved and upon local conditions of surface heating and topography. The passage of a cold front differs from that of a warm front as the wind change is usually sharp and distinct, and wind typically increases in speed and often becomes quite gusty (Flannigan and Wotton, 2001, p. 355).

Eddy formation is a common characteristic of both mechanical and thermal turbulent flow. Every solid object in the wind path creates eddies on its lee side (See Figure 2.5). The sizes, shapes, and motions of the eddies are determined by the size and shape of the obstacle, the speed and direction of the wind, and the stability of the lower atmosphere.

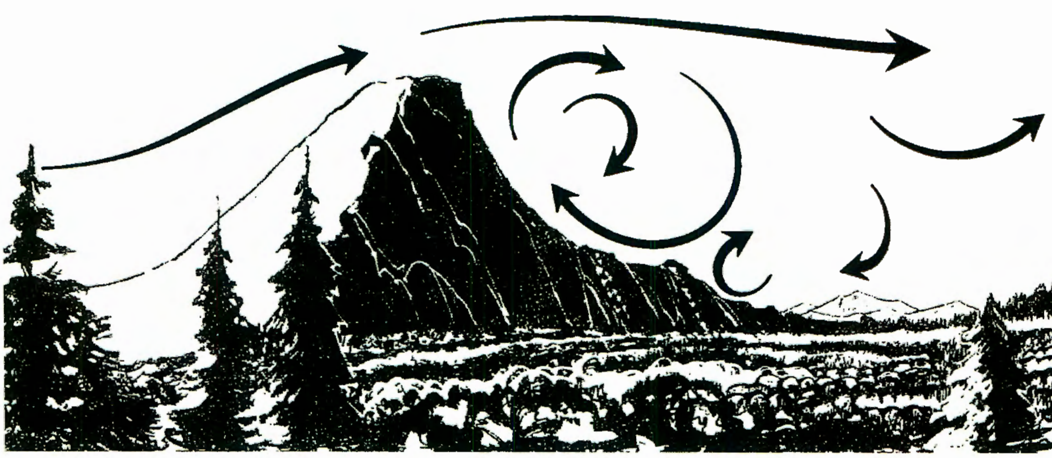


Figure 2.5: ***Large roll eddies are typical to the lee of escarpments or canyon rims. An upslope wind may be observed at the surface on the lee side***

(Schroeder and Buck, 1970, p. 98)

2.3.6.2 Effects of vegetation

Vegetation is part of the friction surface which determines how the wind blows near the ground. The leaf canopy in a forest is very effective in slowing down wind movement because of its large friction area (Figure 2.6). The drag of any friction surface is relatively much greater at high wind speeds than it is with low speeds. The reduction would vary considerably, however, among different species and types of forest.

Pine plantations are usually more effective than eucalypt forests and much more so than open savannah forests (Luke and McArthur, 1978, p. 60).

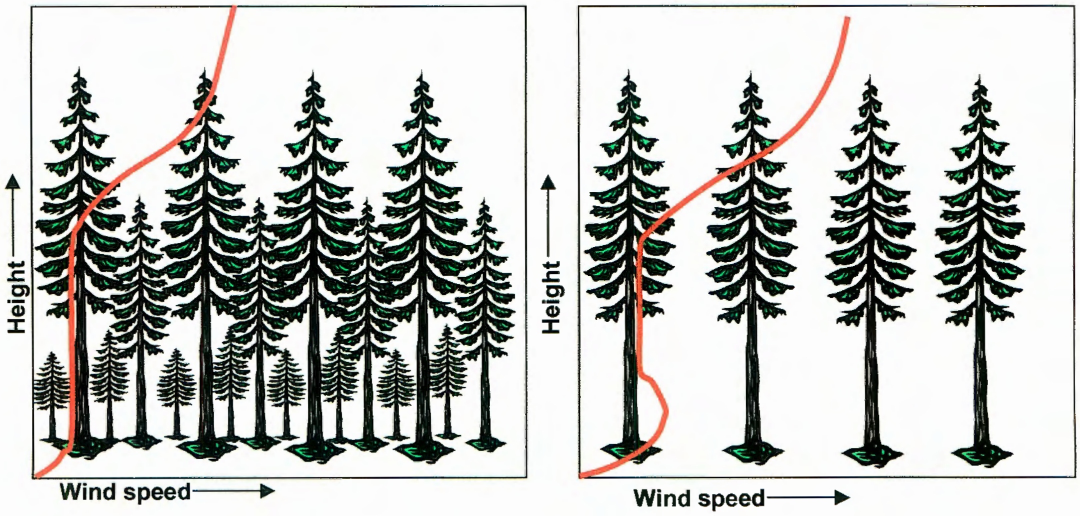


Figure 2.6: Vertical wind profiles in forest stands show that the crown canopy is very effective in slowing down wind movement
(Schroeder and Buck, 1970, p. 104)

Local eddies are common in forest stands and are found in the lee of each tree stem. These small eddies affect the behaviour of surface fires. Large scale eddies often form in forest openings, and edges of tree stands often cause roll eddies to form in the same manner as those associated with escarpments.

2.3.6.3 Slope and valley winds

Slope winds are local diurnal winds present on all sloping surfaces. They flow upslope during the day as the result of surface heating, and downslope at night because of surface cooling. Slope winds are produced by a local pressure gradient caused by the difference in temperature between air near the slope and air at the same elevation away from the slope (Perry, 1990, p. 80).

Upslope winds are quite shallow but their depth increases from the lower portion of the slope to the upper portion. Turbulence and depth of the unstable layer increase to the crest of the slope, which is the main exit for the warm air (Flannigan and Wotton, 2001, p. 357).

Downslope winds are caused at night when cool air near the surface flows down slope much like water, following the natural drainage ways in the topography. Down slope winds are very shallow and of a slower speed than upslope winds. Cool, dense air accumulates in the bottom of valleys, creating an inversion which increases in depth and strength during the night hours.

Orientation of the topography is an important factor governing slope– and valley-wind strength and diurnal timing. Upslope winds begin as a gentle up-flow soon after the suns strikes the slope. Therefore, they begin first on east-facing slopes after daybreak and increase in both intensity and extent as daytime heating continues. North and northwest slopes heat the most and have the strongest upslope winds. North slopes reach their maximum wind speeds soon after midday and west slopes by about mid-afternoon. Upslope wind speeds on north slopes may be several times stronger than those on the opposite south slopes.

The vegetation cover on slopes will also affect slope winds and, in turn, valley winds. Bare slopes and grassy slopes will heat up more readily than slopes covered with brush or trees. Upslope winds will therefore be lighter on the brush- or tree-covered slopes.

2.3.6.4 Whirlwinds

Whirlwinds are one of the most common indications of intense local heating. They occur on hot days over dry terrain when skies are clear and general winds are light.

Some whirlwinds last only a few seconds, but many last several minutes. Whirlwinds are common in an area that has just been burned over. The blackened ashes and charred materials are good absorbers of heat from the sun. Hotspots remaining in the fire area may also heat the air. A whirlwind sometimes rejuvenates an apparently dead fire, picks up burning embers and spreads the fire to new fuels.

The heat generated by fires produces extreme instability in the lower air and may cause violent fire whirls. They can pick up large burning embers, carry them aloft and then spew them out far across the fire line and cause numerous spot fires.

Fire whirls occur most frequently where heavy concentrations of fuels are burning and a large amount of heat is being generated in a small area (Schroeder and Buck, 1970, p. 123).

2.3.7 Clouds and precipitation

Clouds are visible evidence of atmospheric moisture and atmospheric motion. Those that indicate instability may serve as a warning to the fire-control man. Some produce precipitation and so become an ally to the fire-fighter.

There are two principle ways in which the atmospheric vapour pressure and saturation vapour pressure attain the same value to produce 100% relative humidity, or saturation. These are through the addition of moisture to the air, or, more importantly, through the lowering of air temperature.

The latter is accomplished in several ways. Rising of air, and the resultant adiabatic expansion, is the most important cooling method. The lifting may be accomplished by thermal, orographic, or frontal action. It produces most of the clouds and precipitation as shown in Figure 2.7.

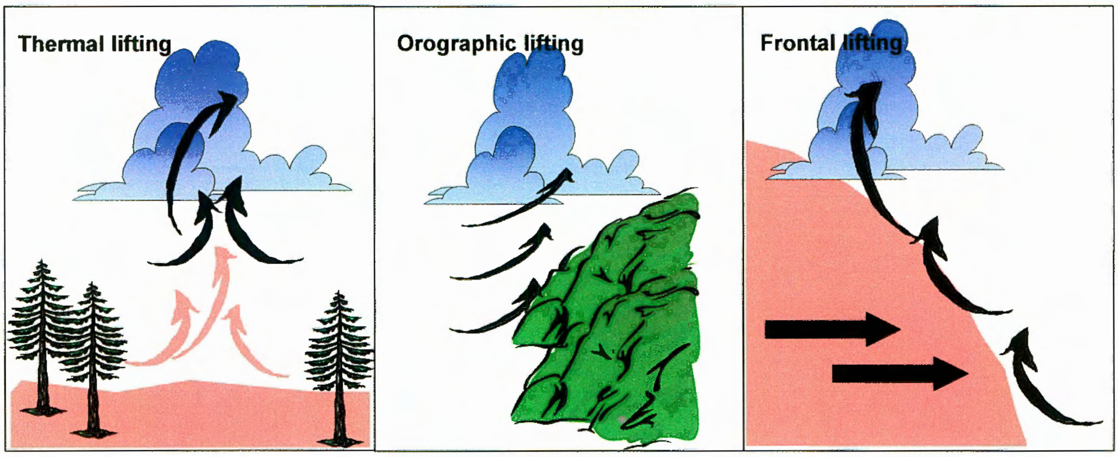


Figure 2.7: Illustration of the different mechanisms involved in air-lifting causing adiabatic cooling

(Schroeder and Buck, 1970, p. 147)

Local heating will result in thermal lifting. If the locally heated air contains enough moisture and rises far enough, saturation will be reached and cumulus clouds will form.

Frontal lifting, as air is forced up the slope of warm or cold fronts, accounts for much cloudiness and precipitation.

2.3.8 General South African weather conditions

Vegetation growing under almost any climate regime can burn under certain conditions, but the occurrence of fires is strongly dependent on the weather (Van Wilgen and Scholes, 1997, p. 27)

According to Swanevelder *et al.,* (2001 p. 73) the climate of Southern Africa is mainly influenced by three fundamental determinants:

- The influence of the sea. The oceans have a moderating influence on the weather. Cold polar air moving from the south is considerably tempered before reaching the cold water of the Benguela Current. The air above the east coast is warmer and less dense and therefore rises more easily. The warm water of the Mozambique Current and the cold water of the Benguela Current also have specific effects. The air above the east coast is warmer and less dense and therefore rises more easily.
- The central plateau of Southern Africa. The elevation of the plateau reduces the general temperature conditions considerably.
- The location of the subcontinent. The atmospheric pressure and wind systems of the southern hemisphere have a considerable effect on climatic conditions. The atmospheric circulation south of 20°S is dominated by subtropical anticyclones in the Southern Atlantic and Indian Oceans.

The land and water masses cause the subtropical high pressure belt to be broken up into separate cells of high pressure. A high pressure belt at approximately 30°S results in a fairly dry climate as the processes of rising, cooling and condensation and the formation of precipitation are seldom associated with a high pressure system.

Three cells of high pressure affect the weather process:

- The South Atlantic high pressure system (anticyclone) usually off the Namib coast. In the Southern Hemisphere circulation in an anticyclone moves anticlockwise and south westerly winds blowing towards the land tend to retain their moisture (blowing from a cooler to a warmer latitude).
- The south Indian high pressure system over the Indian Ocean fluctuates considerably in that it tends to move away from the coast during winter. The anticyclonical circulation causes north easterly winds to blow over the eastern parts of South Africa.
- The third high pressure cell dominating air movement over the land is sometimes called the Kalahari high pressure system.

To understand the full implications on the effect of this anticyclone, the subsiding air and stable conditions which are associated with anticyclones must be understood.

The surface winds are light and are usually easterly to the north of the high-pressure centre, changing to north-westerly to the south-west of the high pressure centre. The air subsides gently and the days are usually cloudless and warm when this system dominates. This pattern of airflow occurs particularly in winter together with the temperature inversion which occurs because of these stable conditions.

This inversion occurs over the coastal areas and is stronger and lower in winter and can stretch as far inland as the escarpment. The base of the inversion in winter is lower than the level of the plateau, with the result that moisture-bearing winds cannot penetrate over the escarpment into the interior. This results in dry winters in the interior.

During summer the anticyclone weakens and moves slightly southwards and the inversion layer lifts to above the level of the plateau (Hurry *et al.,* 2001, p. 38). South of these anticyclones there is a westerly wind belt in which the frontal depressions of the middle latitudes originate and move eastwards. Cold front systems reach the subcontinent of Southern Africa regularly. If the low pressure system is weak, its influence is usually limited to the coastal region. However, if the low pressure cell is well developed, and especially if it is followed by a strong Atlantic high pressure cell, the front can extend across the entire landmass of Southern Africa. This causes cold air to penetrate deep into the interior, accompanied by rain and sometimes snow.

The three high pressure cells, together with the cyclonic circulation to the south, account for the basic pattern of air movement over Southern Africa (Swanevelder *et al.,* 2001, p. 73).

Berg wind conditions in KwaZulu-Natal and Mpumalanga are the result of a high pressure that is centered over central South Africa and a cold front that is passing to the south of the land. Between these two systems there is a very strong subsidence of air.

The descending air is compressed and warmed up as it sinks lower over the escarpment, resulting in a flow of very hot and dry air moving from the interior towards the sea over the east coast. Bergwind conditions are usually followed by the moving in of a cold front, which results in sudden drops in temperature (Perry, 1990, p. 121).

2.4 FUELS

2.1.4 Introduction

Like weather, topography and fuels have a direct bearing on fire behaviour. Topography has a direct influence on how much solar radiation is absorbed by the surface of the earth because it determines the angle at which solar radiation strikes the surface. This in turn modifies the microclimate, which influences the type of vegetation (or fuel) in the area (Teie, 1997, p. 110). In forestry terminology “fuel” is defined as "any substance or composite mixture susceptible to ignition and combustion". (Chandler *et al.*, 1983a, p. 39).

Phytomass, or total fuel loading, is the amount of plant material, both living and dead, to be found above mineral soil. This definition of phytomass differs from that of **biomass**, often found in the ecological literature, in that roots and animal matter are not included, whereas dead plant materials are included (Chandler *et al.*, 1983a, p. 39).

Available fuel, refers to that amount of fuel available for burning in a particular fire, a value varying widely in magnitude with the environmental conditions on a site. The rate and intensity with which a wildfire will burn is influenced primarily by fuel density, fuel moisture content, fuel load and fuel availability. Fuel density, the average surface area to volume ratio (m^2/m^3), is very important and a high value will favour rapid ignition and often rapid spread of fires provided there is sufficient fuel to sustain combustion (Tainton, 1999). Other fuel variables can also play a role and will be discussed in paragraph 2.4.3.

Position on a slope also has an effect on fuel availability. There is usually more fuel at base and midslope sites than on the top of a ridge because of greater variations in temperature and relative humidity. According to Teie (1997, p. 110), this has a direct impact on the potential size of fires. Fires starting at the base of a slope have greater potential size than those starting midslope or higher up.

Aspect is the direction a slope is facing. Although the aspect is fixed, the amount of solar radiation received varies with the position of the sun. The impact of aspect on fire behaviour therefore changes throughout the day.

The amount and type of fuel available varies greatly depending on aspect. Northern aspects have lighter and more readily burning fuels with low moisture content. This is primarily because they receive the highest levels of solar radiation and therefore have the highest average temperatures. Fires on these aspects generally have the fastest rate of spread.

Fuels on a west facing slope are transitional between the light fuels of northern slopes and the heavier fuels of southern slopes. North and northwest aspects are the most vulnerable to fire. This is due to the fact that the fuels are usually lighter (easier to ignite), flashy (contributing to a faster burn rate), and warmer (again, easier to ignite).

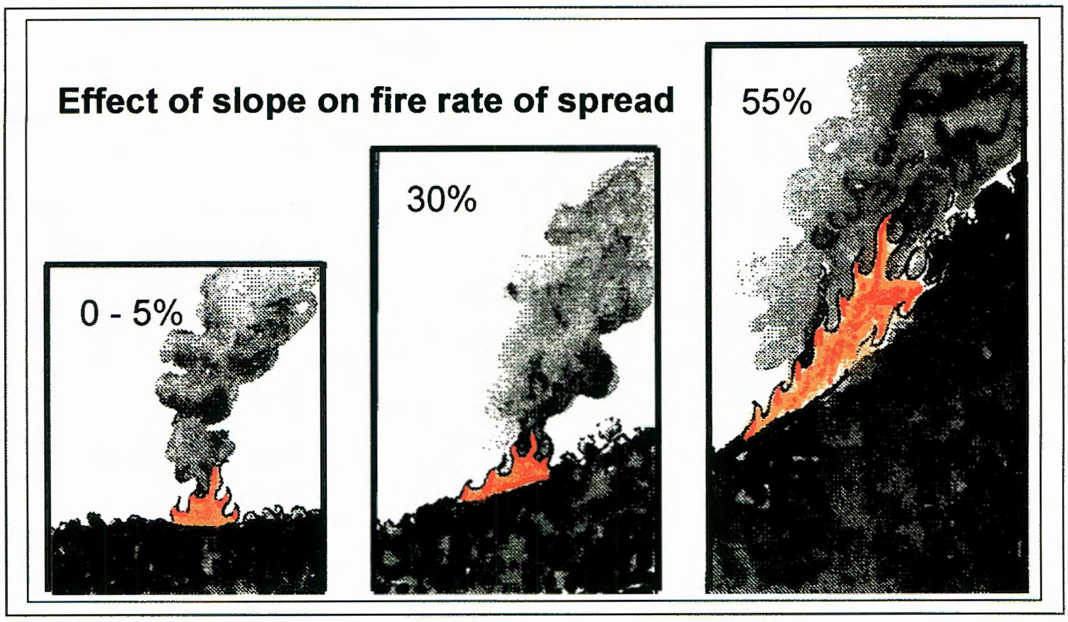


Figure 2.8: Slopes can play a significant role in the rate of spread of a fire.
(Teie, 1997, p. 114)

Slope contributes to preheating and ignition by "presenting the fuels" to a flame front. Slope, in effect, lifts the fuels to a position that places them closer to the flame, increasing the level of heating and making them easier to ignite (Figure 2.8). The steeper the slope, the closer the fuels are to the flame, and therefore the faster the rate of spread and the narrower the flame front (Perry, 1990, p. 82; Cheney and Sullivan, 1997, p. 29).

A barrier is a break in the fuel, or change in fuel type, that can slow or stop the spread of a wildfire. Barriers can be natural or man-made and some of the common barriers are:

- Rocks or bare soil conditions.
- Streams and moist soil situations.

- Roads and other infrastructure.
- Change in fuel type and fuel moisture conditions.
- Previously burnt areas.

Fuels can be divided into three groups or levels: ground fuels, surface fuels and aerial fuels. Each of these fuel levels has an impact on the ease of ignition and the combustibility of the fuels.

Ground fuels include duff, roots and rotten buried logs and usually do not play a major role in fire behaviour as they normally burn with low intensity. Fires usually start in surface fuels like grass, forest litter and brush. They are responsible for most fire spread and for "carrying fire" to the aerial fuels. Aerial fuels are those fuels that occur 1.8 m or higher in the vegetation. This includes limbs, leaves, trunks, and crowns of heavy brush and timber. The "tightness" of the aerial fuel canopy plays a role in how fires burn and will be discussed in paragraph 2.4.2.

As a physical and chemical process, a forest fire converts stored chemical energy into kinetic energy of heat and motion (Pyne, 1984 p. 89). Cellulose is the main component of plant fuels. Fire is an oxidation process involving a chain reaction during which the solar energy originally trapped by photosynthesis, is released as heat (Luke and McArthur, 1978, p. 24). This is explained by the following equations by Tainton (1999 p. 218):

$$Photosynthesis: CO_2 + H_2O + solar\ energy \rightarrow (C_6H_{10}O_5)n + O_2$$

$$Combustion: (C_6H_{10}O_5)n + O_2 + kindling\ temperature \rightarrow (CO_2 + H_2O) + heat$$

The prerequisites for this reaction to proceed are a high temperature and an ample supply of oxygen. The term "kindling temperature" in the above combustion equation indicates that combustion is neither a simple nor a spontaneous process. It requires the "activation energy" of an external energy source (Whelan, 1998, p. 10).

As an ecological process, fire is one variety of biological decomposition; it reassembles solid organic fuels into other forms. Yet fuel is not synonymous with biomass. Only a portion of total biomass, its phytomass, is potentially available as fuel, and not all of the phytomass is available for combustion.

Few studies of fire ecology could avoid considering the biota as a fuel complex and few fire management programmes have a separate work unit dedicated to fuel management (Pyne, 1984, p. 90). Through manipulation of the fuels fires can be prevented, fire intensity abated, fire control simplified and fire effects managed.

2.4.2 Fire intensity

Fire intensity is defined in terms of the rate of heat output per length of fireline or the rate at which a fire produces thermal energy. It is a function of the amount of fuel burnt in the flaming front of a fire, the calorific value of that fuel, taking into account the fuel moisture content, and the rate of spread of the fire. The limiting factor in fire intensity is the amount of energy stored in the fuel, and as a consequence, the greater the fuel loading, the more intensely a fire is likely to burn (Davis, 1959, p. 91; Cheney and Sullivan, 1997, p. 18).

Heat of combustion of a fuel was often expressed in British thermal units per pound (Btu/lb). (Values in Btu/lb can be converted to kJ/kg by multiplying by 2.33). In order to measure the intensity of the fire or the heat output from a standard length of a fire front, the total amount of flammable fuel in an area and the rate of a fire's spread must be taken into consideration (Luke and McArthur, 1978, p. 26). Fire intensity can be calculated from the equation:

$$I = \frac{Hwr}{600}$$

Where:	I	=	the fire intensity in kilowatts per meter (kW/m)
	H	=	the heat yield in kilojoules per kilogram
	w	=	the weight of available fuel in tonnes per hectare
	r	=	the rate of forward spread in meters per minute

Fire intensity was formerly expressed as Btu per second per foot, which may be converted to kW/m by multiplying by 3.46. By using the above formula, an estimate of fire intensity may be rapidly arrived at. For example, a fire spreading in light fuels of 5 ton/ha at the rate of 2 m/min would have a fire intensity of 266 kW/m, while a fire consuming fuel at a concentration of 20 ton/ha and travelling at 10 m/min would have an intensity of 5 300 kW/m.

Fire intensity is strongly related to flame height and flame depth, and is of great significance in fire control (Figure 2.9). For example, a fire with an intensity of 450 kW/m has a flame height of 1.2 m and a flame depth of around 2.5 m. It is spreading at 1.3 m/min. A much hotter fire spreading at 13.7 m/min in a 17.5 ton/ha fuel type in eucalypts will have a flame height of 15 m and a flame depth of 27 m. A fire in a 25 ton/ha fuel type spreading at 30 m/min will be a fully developed crown fire with a flame depth of at least 60 m (Luke and McArthur, 1978, p. 28).

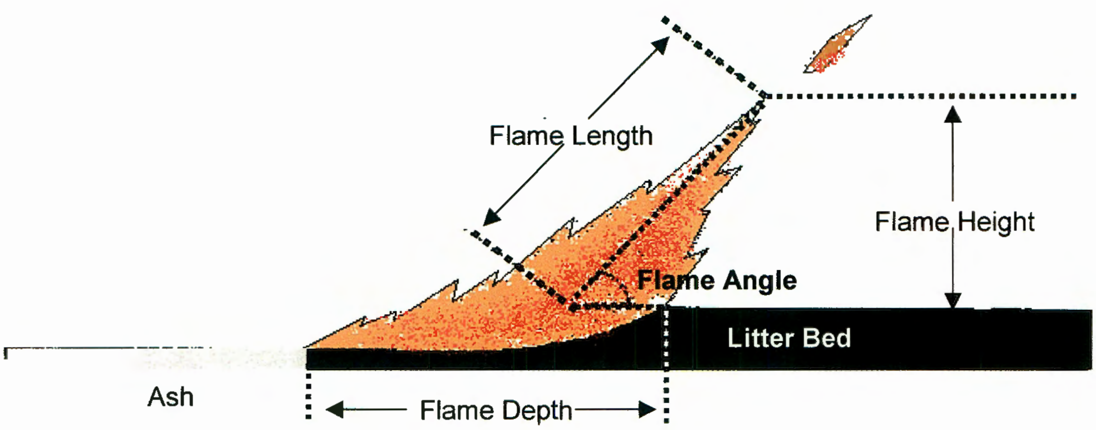


Figure 2.9: Diagrammatic example of flame descriptors

(Tolhurst and Cheney, 1999, p. 14)

Flames are usually described according to their height, length, angle and depth. **Flame height** is the average peak height of the flames measured vertically from the ground surface, excluding occasional flame flashes. Flame height is determined by the combination of the quantity and arrangement of the fuel, the fuel moisture content, wind speed and ground slope (Tolhurst and Cheney, 1999, p. 15). Estimation of flame height is quite subjective and a high degree of precision should not be expected.

Flame length is the length of the leading or fuel side edge of a flame measured from the ground surface and equals the flame height when the flames are vertical. Flame length is strongly related to fire intensity and the relationship between flame length and fire intensity depends on the structure of the fuel bed. Longer flames have a greater surface area from which to radiate heat and so pre-heat a much greater area of fuel ahead of it. Flame length will exceed the flame height if wind or slope are present according to Cheney and Sullivan, 1997, p. 17).

Flame angle is the inclination of the flame to the ground surface measured on the unburnt side of the flame front. Flame angle is determined by wind speed and ground slope. Flame angles will be less than 90° for fires running upslope and with a tail wind, increasing the radiative and conducted heat transfer to the unburnt fuels, increasing the efficiency of fire propagation and hence fire intensity. On the flanks of a fire, flame angle will be close to 90° as the direction of flank fires is usually perpendicular to the direction of wind or slope. At the back of the fire, flame angles are usually greater than 90° and this retards the rate of spread of the backing fire since more of the heat is directed away form the unburnt fuel.

Flame depth is the width of continuously flaming fuel behind the fire edge measured perpendicular to the fire edge. Flame depth is a function of the rate of spread of the fire edge and the **residence time** of the fuel, that is, the length of time for the fuel to burn with flaming combustion at a fixed location.

Residence time depends on the size of the fuel elements burning in the fire front and their moisture content (Cheney and Sullivan, 1997, p. 16). Under field conditions it is difficult to maintain burning at high moisture levels unless the logs are stacked closely to retain heat for continual drying.

The **burnout time** of fuel is the time taken for a particular unit of fuel to combust completely, including both flaming and smouldering combustion, into ash, heat and smoke (Tolhurst and Cheney, 1999, p. 14)

2.4.3 Fuel complexes and fuel cycles

Arrangements of fuel show patterns over space and time. In general, there are two ways to describe these arrangements (Pyne, 1984, p. 101), i.e. as biological systems and as physical systems.

The biological approach defines the fuel complex as a community of organisms. Organisms make up the fundamental units of composition, and the dominant species give their name to the whole complex - identified as a cover type, habitat type or fire type.

By contrast, fuel models describe biota strictly in terms of their relevant thermophysical and thermochemical properties. Particles are assembled into fuel bed, and fuel bed into fuel arrays or models (Pyne, 1984, p. 101).

When combined, fuel particles and cells show several degrees of organisation. A first order structure transforms elementary units into fuel bed. A fuel complex may contain several fuel beds. A layer of organic soils (ground fuels) and a fuelbed of foliage (aerial fuels) may form a bed of surface fuels.

Models of these fuel beds will emphasise slightly different parameters, and the fuel beds will be organised such that they burn with different fire behaviour characteristics (Figure 2.10).

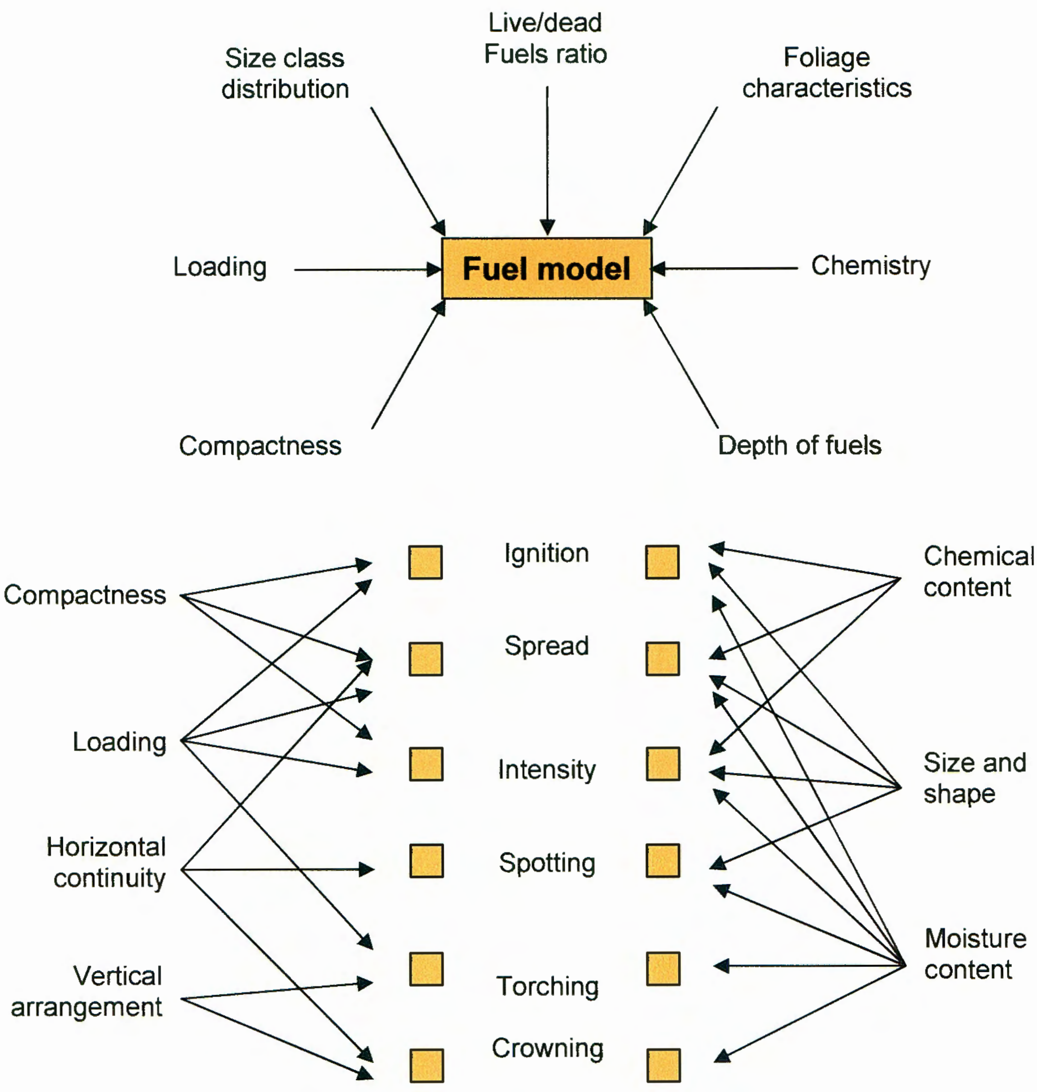


Figure 2.10: Fuel model considerations and characteristics

(Pyne, 1984, p. 102)

Fuels change in their amount and in their character. With each season come changes in the heat yield values of fuel particles, in the ratio of live-to-dead fuels within a complex and in the moisture content of both live and dead fuels (Pyne, 1984, p.103). Fuels change in their arrangement. Old fuelbeds acquire or lose loading, density and compactness. New fuelbeds are added, greatly expanding the range of available fuels (De Ronde, 1988, p. 13).

Fuel accumulate or diminish with regularity only in a few special environments. Examples include those fuel complexes dominated by brush or by single conifer species. As the species increases its proportion of fine available fuels, so increases the flammability of the biota (Pyne, 1984, p. 104).

Large fuel loads do not necessarily relate to more frequent or more intense fires. Fuels support fires but they do not cause them. Hazard must combine with risk, fuel with ignition, and fire with a suitable environment.

The following factors identified by Brown and Davis (1973, p. 192) are pertinent in estimating fire behaviour:

- Relation to time of day – more fires occur from late morning to mid afternoon due to heat.
- Available fuel.
- Fuel moisture and drought.
- Temperature.
- Wind speed.
- Topography.
- Atmospheric instability.

According to Teie (1997, p. 118), there are seven fuel characteristics that control fire behaviour in different ways (Table 2.1). Note how moisture content has the greatest effect on fuel behaviour.

Table 2.1: Fuel characteristics and their effect on fire behaviour

How the seven fuel characteristics affect fire behaviour						
	Fire behaviour components					
	Ignition	Spread	Intensity	Spotting	Torching	Crowning
Compactness	✖	✖	✖			
Loading	✖	✖	✖		✖	
Horizontal continuity		✖		✖		✖
Vertical arrangement				✖	✖	✖
Chemical content	✖	✖	✖			
Size and shape	✖	✖	✖	✖		
Moisture content	✖	✖	✖	✖	✖	✖

Fuel loading is the dry weight of a fuel (live or dead) in a given area. It varies greatly by fuel type and by area and can be separated into four size classifications. The size of the fuel affects how it will respond to various forms of moisture (rain, dew and relative humidity). Size also determines how quickly dead fuel will loose moisture. The four size classifications are:

- Grasses and litter: 0 to 0.5 cm in diameter
- Twigs and small stems: 0.5 to 2.5 cm in diameter
- Branches: 2.5 to 7.5 cm in diameter
- Large stems and branches: > 7.5 cm in diameter

(Teie, 1997)

The **size and shape** of the fuel are also critical factors in how fuels burn. The surface area to volume relationship is the ratio of the surface area of a fuel to its volume. The finer the fuel, the higher the ratio. The size and shape of fire brands affect how much spotting will occur and over what distances. Cones, bark plates and pine needles produce firebrands that can be lifted by convection columns and carried over great distances, and because of their size they will continue to burn for longer periods.

Compactness refers to the spacing between fuel particles. The closeness and arrangement of the fuel influences how easily it will ignite and how well it will burn. If fuels are very compact, there is less surface area exposed to the flames and the oxygen necessary to support combustion. A slower rate of spread can be expected (Booysen and Tainton, 1984, p. 213). Fuel bed depth is the average height of surface fuel that is available for combustion. Fuel orientation refers to the horizontal or vertical orientation of the fuel. Grasses and shrubs have a vertical orientation, and the fire intensity in this type of fuel increases with depth. Timber litter and slash are horizontal oriented fuels and slowly increase in depth as the load increases (Teie, 1997, p. 122).

The **horizontal continuity** or distribution of fuels has an impact on how a fire spreads; the rate of spread; and whether the fire will move along the surface or through the crowns, or both. Continuous fuel beds provide available fuels at the surface and in the crowns (Teie, 1997, p. 124).

The vertical arrangement and continuity of the fuels are very important characteristics and when there are fuels available for combustion throughout the vertical fuel bed, they are called ladder fuels.

2.4.4 Fuel moisture

2.4.4.1 Introduction

Fuel moisture content is the amount of water in a fuel. Fuel moisture is the one fuel characteristic that affects all the fire behaviour characteristics (De Bano, Neary and Ffolliott, 1998, p. 197).

Fuel moisture intersects the two most variable components of the fire environment, fuel and weather. Fuel moisture content (FMC) thus integrates many processes, and it influences all aspects of combustion and fire behaviour (Pyne, 1984, p. 90).

Protracted drought, accompanied by high air temperature and low relative humidity, set the stage for most bad fires by reducing the moisture content of all classes of forest fuels to abnormally low levels (Brown and Davis, 1973, p. 26).

Weather and climate affects forest fires in different but related ways:

- climate determines the total amount of fuel available for combustion.
- climate determines the length and severity of the fire season.
- weather regulates the moisture content, and hence flammability, of dead forest fuels.
- weather has an independent influence on the ignition and spread of forest fires.

(Chandler *et al.*, 1983a, p.33).

As absorbed water, moisture content affects the availability of fuels by increasing the heat sink at the expense of the heat source. More of the propagating flux goes towards distillation of fuel moisture, and less towards pyrolysis and combustion. As a vapour, fuel moisture inhibits combustion reactions through a combination of smothering in the reaction zone and of cooling within the flame. The processes of moisture exchange differ according to whether the fuel is alive or dead, to whether the moisture is liquid or vapour, and to whether the moisture gradient is large or small, a function of particle size, the intensity of the gradient, and the duration of exposure (Pyne, 1984, p. 90).

The exchange of fuel moisture is in some ways analogous to heat transfer. Both follow from a differential between the particles and their surrounding environment, heat and water travelling from regions of excess to regions of deficiency. Both act on the surface of the fuel particle. Those fuel particles with high surface-to-volume ratios and those fuel complexes with large proportions of fine fuels and high porosity for their packing will show higher rates of transfer. Large particles become moisture and heat sinks. Within a large particle, a gradient will develop between the surface and the interior. The rate of moisture transmission depends on the size of the initial gradient, the diffusivity of the particle, and the length of time the gradient persists.

According to Tolhurst and Cheney (1999, p. 39) fuel moisture content is the proportion of free and absorbed water in the fuel expressed as a percentage of the oven dry weight of the fuel. Fuels dried at 105 °C until no further weight loss occurs are said to be oven dried and have a moisture content of 0%. In the field, the driest dead plant material will get is a moisture content of about 3%.

Dead plant material can absorb water until it is about 30 – 35% moisture content at which point it reaches fibre saturation point; that is, any further addition of water will not be absorbed but exist as free water on the surface of the plant material. Live fuels usually have moisture contents between 50 and 300%. Pyne (1984, p. 90) gives a figure of 70 – 200% or more, although some succulent plants may have moisture contents as high as 1 000% (Tolhurst and Cheney, 1999, p. 38).

2.4.4.2 Dead fine fuel moisture

Dead fine fuel moisture content changes passively in response to past and present weather conditions. Depending on the position of the fuel bed, it responds to diurnal, seasonal and year to year variations in weather conditions (Tolhurst and Cheney, 1999, p. 39).

Dead fuels absorb moisture from precipitation, dew, soil moisture and atmospheric moisture. Dead fine fuel can absorb up to 35% of its dry mass in moisture. This value is called the fibre saturation point. When the exchange of moisture occurs with water vapour, the process is more complicated, involving adsorption rates that depend on the hygroscopic properties typical of cell walls. Driving the whole process is a moisture differential between the vapour pressure of the atmosphere and the vapour pressure of the fuel particle interior. When the vapour pressure of the atmosphere is greater, then moisture moves into the fuel; when the vapour pressure of the fuel is greater, then moisture moves out. The process begins with adsorption, or chemical bonding, to the cell walls. Water vapour becomes bound water. The bond is greater than the vapour pressure of the bound water, reducing the vapour pressure inside the particle and maintaining a high vapour pressure gradient between the particle and the ambient air. The adsorption process continues until the cell walls are saturated. For woody fuels this equals a fuel moisture of about 30% (Figure 2.11).

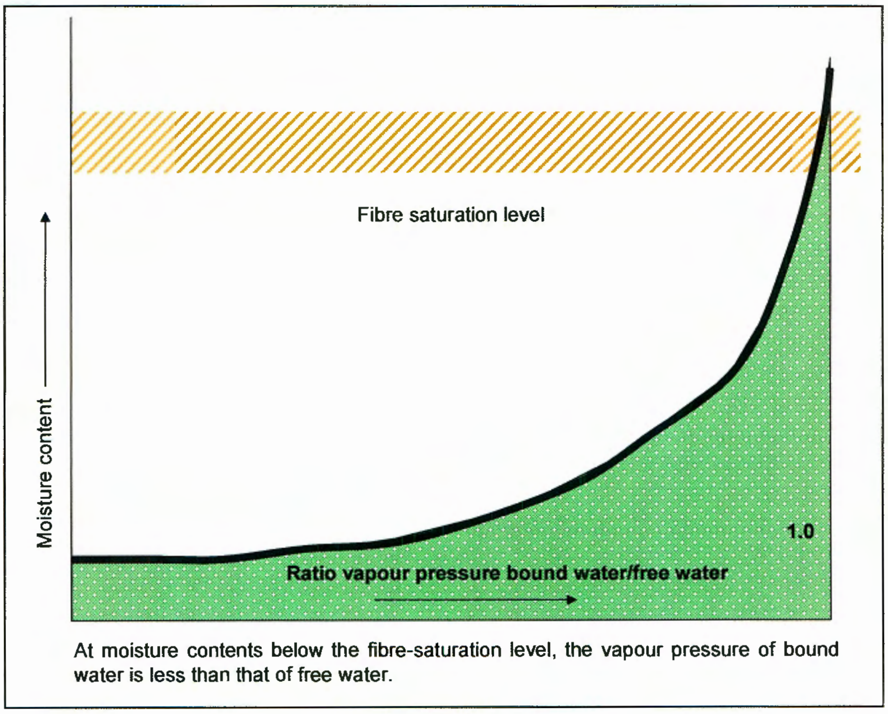


Figure 2.11: Vapour pressure and moisture content
(Schroeder and Buck, 1970, p. 186)

Prior to saturation, the vapour pressure of bound water is less than that of free water. At saturation the vapour pressures equal each other. Above fibre saturation point there is free water either in the cell structure or on the surface of the fuel particles. After wetting, free water will drain or evaporate quite rapidly. Below the fibre saturation moisture content the bound moisture will evaporate at a rate that depends on the atmospheric conditions and the structure of the fuel particle (Tolhurst and Cheney, 1999, p. 40).

If the atmospheric environment remains constant, the fuel moisture content eventually reaches a constant value called the equilibrium moisture content. Pyne (1984, p. 196) describes the condition of moisture equilibrium as when the vapour pressures outside and inside the fuel particle are equal (Figure 2.12).

The equilibrium moisture content for a particular fuel element depends on the relative humidity of the air and to a lesser degree temperature. The equilibrium moisture content reached by a fuel drying (desorption) under constant conditions will be up to

3% higher than the equilibrium moisture content reached by the fuel absorbing moisture (absorption) under the same conditions. The difference between the absorption (wetting) and desorption (drying) phases is called an hysteresis.

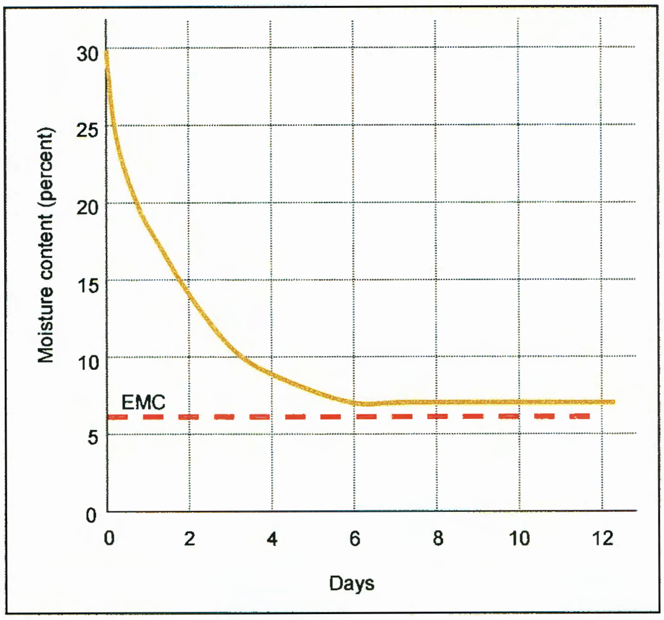


Figure 2.12: Equilibrium moisture content (EMC). A drying (desorption) curve for a 5 cm layer of litter for an EMC of 5.5%
(Schroeder and Buck (1970) in Pyne, 1984)

The relationship is itself variable: the different processes involved in drying and wetting proceed at different rates. The rate of exchange during the falling-rate period is logarithmic – 10 times as rapid when the fuel moisture is 10% than when it is 1%.

Because of the chemical bonding involved in adsorption, it is easier for a dry fuel particle to acquire moisture from a moist atmosphere than for a moist fuel element to surrender moisture to a dry atmosphere.

To simplify this variable rate of drying a time lag principle is used. For bound water, the approach to equilibrium follows a logarithmic scale for which the time required to reach equilibrium moisture content can be divided into periods. Each timelag (TL) period describes the moisture exchange to the amount of 63% (1 – 1/e) of the departure from equilibrium. The actual duration required to achieve equilibrium moisture content depends on the properties of the fuel, including its size and diffusivity, as is shown in Figure 2.13.

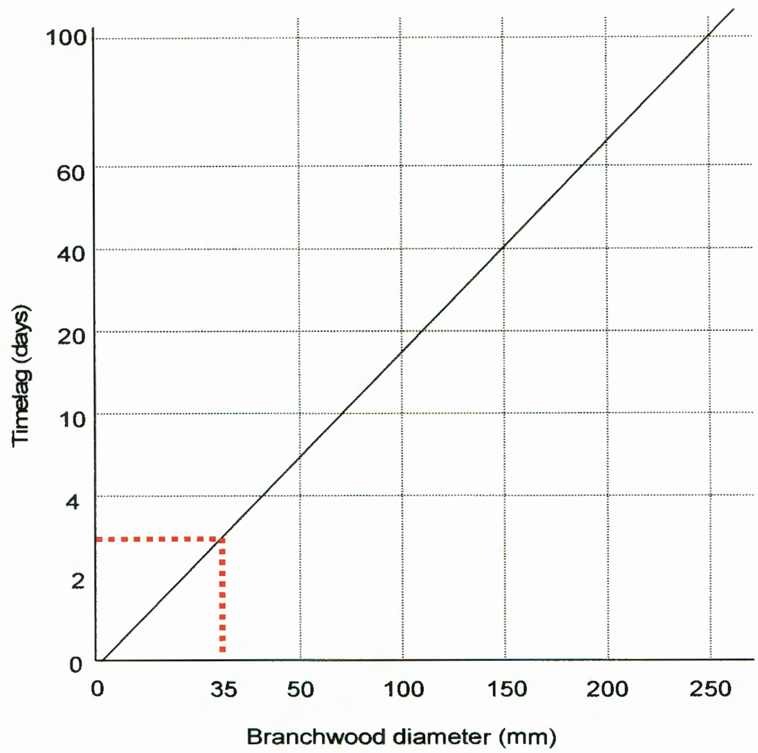


Figure 2.13: Timelag and fuel particle diameter
(Schroeder and Buck, 1970 in Pyne, 1984, p. 97)

Under laboratory conditions of 27° C and 20% relative humidity actual moisture content would be close to equilibrium moisture content after five or six timelag periods. For fine fuels, the change may take only minutes; for large fuels, days or weeks.

For purposes of inventorying fuel complexes and designing fuel models, four categories of fuel particles are recognised based on their timelag period (Pyne, 1984, p. 97): 1 hr TL, 10 hr TL, 100 hr TL and 1 000 hr TL. Time lag interval, or response time, is defined as the time required for dead fuel to lose approximately 63% of the difference between its initial moisture content and the equilibrium moisture content in an atmosphere of constant temperature and humidity.

Fuels are committed to one of these categories as a function of their diameter, in the case of particles, or their depth, in the case of fuel bed (See Table 2.2).

Table 2.2: Timelag fuel equivalencies

	Timelag classes			
	1 hr	**10 hrs**	**100 hrs**	**> 100 or 1 000 hr**
Timelag class interval	0 - 2	2 - 20	20 - 200	>200 or 200 – 2 000
Equivalent fuel dimensions:				
Roundwood	< 0.64 cm	0.64 – 2.5 cm	2.5 – 7.6 cm	7.6 – 20.3 cm
Litter	Surface	Surface to 1.5 cm	1.6 – 10.2 cm	10.2 – 30.5 cm

(Pyne, 1984, p. 98)

2.4.4.3 Dead coarse fuel moisture

The moisture content of dead coarse fuels such as fallen branches and logs does not respond rapidly to changes in the environment. These fuels can be classified according to the time it takes them to adjust to these changes. In Australia the moisture content of coarse fuels is related to the Keetch Byram Drought Index (KBDI) or the Soil Dryness Index (SDI) (Tolhurst and Cheney, 1999, p. 46).

The availability or flammability of these fuels depends on the seasonal dryness (as indicated by the KBDI or SDI), recent rainfall, the density and size of the fuel and the amount of finer fuels burning in the vicinity of the coarse fuel that will bring it to kindling temperature.

Moisture contents within course fuels often vary considerably depending on the location of the fuel in the forest and internal differences within the fuel (Figure 2.14). The figure illustrates differences in the patterns of variation in moisture content between logs of similar dimensions, as caused by differences in factors that affect moisture loss uptake or loss, such as position in relation to the forest floor and differences in the internal condition of the fuels themselves.

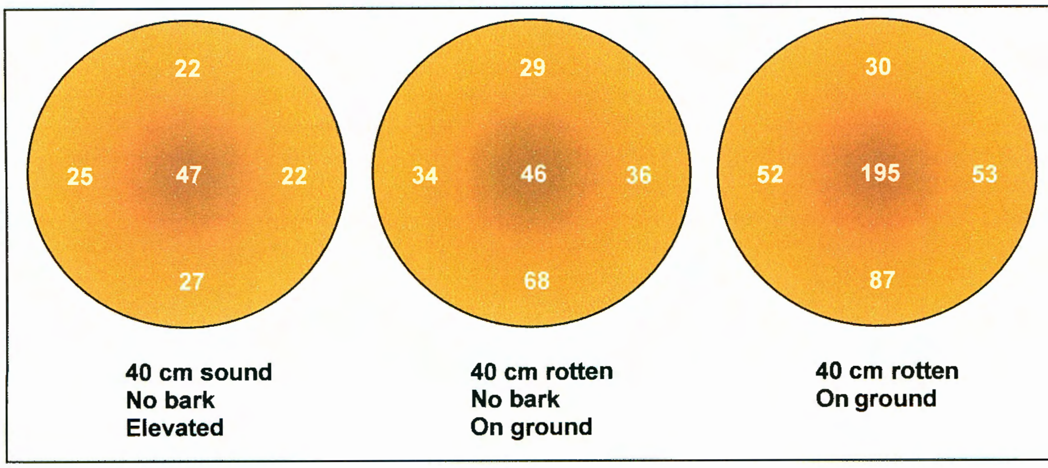


***Figure 2.14:* Average percentage moisture content at top, bottom, centre and sides of three logs subjected to the same weather conditions**
(Reinhardt *et al.,* 1991 in Tolhurst and Cheney, 1999)

Logs in contact with the ground are usually more moist at their base than ones elevated above the ground, but subjected to the same weather conditions. It is also evident that a partially rotten log may be more moist, while the top surface of the log differs little from that of sound logs. The heat capacity and conductivity of rotten logs cause rotten logs to ignite and burn more readily than sound logs (Tolhurst and Cheney 1999, p. 47).

2.4.4.4 Live fuel moisture

The live fuel moisture content is affected by internal physiological factors such as plant vigour, age and species as well as external physical factors such as seasonal and daily weather.

Although moisture gradients exist between the plant and the atmosphere, and between the plant and the soil, a variety of physiological processes intervene to keep plant moisture higher than it would be if the plant were dead. Trees are a mechanism of moisture exchange between soil and atmosphere, absorbing water from the soil by root systems and transpiring water to the air by their leaves or needles.

All live fuels show predictable changes over time. Moisture is highest with new foliage and at the onset of death or dormancy. The lifecycle of moisture for woody fuels is expressed in three stages: rapid growth, maturing growth and severe drought or dormancy. The annual cycle of moisture for herbaceous fuels follows three analogous stages: greenup, maturity and curing.

The important measurements of live fuel moisture include the fuel moisture (%) of live fuel particles and the ratios of live fuels (by volume). According to Tolhurst and Cheney (1999, p. 49) canopy fuel moisture content is important in higher intensity fires. Pines are particularly susceptible to crown fire development because of the low level of the canopies, particularly in young stands. The moisture content of leaves in the crown depends mainly on their age. The moisture level of new *P. elliottii* pine needles declines rapidly from around 200% ovendry weight (ODW) to around 130% ODW in older foliage. There is little seasonal variation in the moisture content of older foliage. A general rule of thumb with regard to living foliage moisture is that crown fire potential in conifers is high whenever needle moisture content drops below 100% (Chandler *et al.*, 1983a, p. 35).

Because fuel moisture content is so important to fire behaviour, many ways have been devised to measure or estimate it. The general approaches taken include: oven drying, chemical determination, mechanical strength, electrical meters, meteorological models, fuel analogues, remote sensing and burning leaf techniques.

Live fuels are thus a paradox. Moisture is a retardant, and the high moisture content of live fuels would seem to make them reluctant towards combustion. Yet because such fuels are living, they also contain chemical constituents (notably extractives and fats) whose heat content and flammability are high.

This is particularly true for the leaves and needles of woody live fuels. Some live fuels are thus both a heat sink, because of their moisture content, and a heat source, because of their thermo-chemistry. Conifer needles, according to Pyne (1984, p. 95), may show a strong tendency to ignite before and after their principal growth season, but once cast to the ground, their special combustibles leach or volatilise away.

Drought is a condition of moisture deficiency that is large in area and long in time. It induces moisture stress in live fuels and deepens the moisture gradients of dead fuels and fuel bed. The interpretation of drought indices is not easy (Pyne, 1984, p. 100). Drought is neither a necessary nor a sufficient cause for large fires. Droughts do not result in spontaneous combustion any more than large fuel accumulations do.

By drying out large fuels, a drought improves the total heat output: more heat is applied to combustion and more of the total fuel load is brought into the category of available fuel. Similarly, drought transfers live fuels to dead fuel categories, again transforming heat sinks into heat sources. Prolonged drought reduces the variability in the fuel complex as a whole; all fuel size classes become potential heat sources rather than partial heat sources and partial heat sinks. The differential moistures that characterise the fuel complex as a whole disappear. Instead of a mosaic of microclimates, the landscape is uniformly parched. The likelihood improves that ignition and low fuel moisture will coincide, and the prospects rise for making the transition to large fire status (Pyne, 1984, p. 101).

2.4.5 Fuel moisture and fire behaviour

Fuel moisture content (FMC) is important to fire behaviour for two main reasons. Firstly, it affects the rate at which the fuel will burn, and secondly, the moisture distribution in the fuelbed affects the amount of fuel available to burn (Tolhurst and Cheney, 1999, p. 38). The higher the moisture content of the fuel the greater is the amount of heat required to raise the fuel to ignition temperature.

Fuel moisture reduces the rate and efficiency of combustion so that combustion is incomplete as evidenced by increased production of smoke and increased residues. The heat released under these conditions is less than the heat of combustion and is referred to as the heat yield (Tolhurst and Cheney, 1999. p. 39).

Since the rate of spread of a fire is generally mostly dependent on the dead fine fuels, the moisture content of these fuels and the factors affecting them are critical to fire behaviour prediction. Figure 2.15 shows the relationship between rate of spread and fuel moisture content under a range of wind speeds with all other factors held constant.

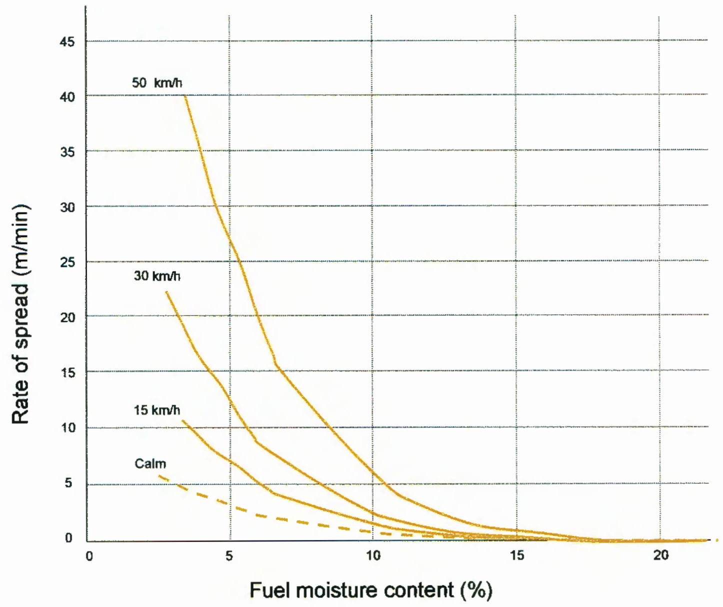


Figure 2.15: Relationship between fuel moisture content and forward rate of spread in open forest at various wind speeds measured at 10 m above ground level in the open with all other factors held constant
(From McArthur 1967 in Tolhurst and Cheney, 1999)

There is a rapid increase in rate of spread when the fuel moisture content falls below about 7% due to more efficient preheating of fuels and more efficient ignition. Tables 2.3 and 2.4 summarise the expected fire behaviour for different dead fuel moisture contents, and is critical to the success of prescribed burning operations. Generally, fuel in the sun will be considerably drier than fuel in the shade, fuel exposed to the wind will be drier than those in protected positions, and fuel moisture content is inversely proportional to the fuel temperature (Tolhurst and Cheney 1999, p. 43).

Table 2.3: A guide to fuel moisture content and fire behaviour in eucalypt forests (Tolhurst and Cheney, 1999, p.45)

Surface moisture content (% ODW)	Indicative fire behaviour (Eucalypt forest fuels)
<4	*Litter extremely dry.* Potential for extreme fire behaviour with intense short distance spotting and crown fire at moderate wind speeds
4 – 6	*Litter very dry.* Very rapid ignition from small smouldering firebrands. Fire behaviour could be severe, spotting likely, possible crown fire under strong winds.
6 – 9	*Litter dry.* Conditions may not be suitable for fuel reduction burning. Fuel very easy to ignite, spotting initiated by large smouldering firebands. High intensity fire may develop under strong winds.
9 – 13	*Litter is reasonably dry.* Eucalypt litter easy to ignite. Burning readily sustained. Fuel reduction may be carried out in light fuels under very mild weather conditions. Limited spotting from large flaming firebands.
13 – 16	*Litter just moist.* Eucalypt litter is moderately easy to ignite. Burning is sustained. A suitable range for fuel reduction when other conditions, particularly wind, are suitable. Spotting unlikely.
16 - 22	*Litter is damp.* Eucalypt litter is difficult to ignite. Burning difficult to sustain. Low intensity fuel reduction burn could be patchy. No spotting.
22 – 28	*Litter is wet.* Fuel very difficult to ignite. Burning very difficult to sustain.

Table 2.4: A guide to fuel moisture content and fire behaviour in pine plantations (Tolhurst and Cheney, 1999, p.45)

Fine fuel moisture content (% ODW)	Indicative fire behaviour (*P. radiata* forest fuels)
<7	Very intense wildfire possible.
7 – 10	*Elevated* dead needles carry fire of high intensity which is difficult to control. *Surface* needles carry fire of moderate to high intensity.
10 – 15	*Elevated* dead needles carry fire of moderate intensity (e.g. ROS >1 m/min). *Surface* needles easily ignited and carry fire of moderate intensity.
15 – 20	*Elevated* dead needles easily ignited and carry fire of low intensity (e.g. ROS up to 1 m/min). *Surface* needles ignite and carry slow moving fire (e.g. ROS <0.5 m/min).
20 – 25	*Elevated* dead needles will ignite and just carry a fire (e.g. ROS <0.2 m/min). *Surface* needles will just ignite and only carry fire with the assistance of wind.
25 - 30	*Elevated* dead needles will just ignite and carry fire only with the assistance of wind. *Surface* needles will not ignite.

Relative humidity is the most useful measure of moisture in the atmosphere for fire behaviour predictions because if reflects changes in the vapour pressure deficit (Figure 2.16).

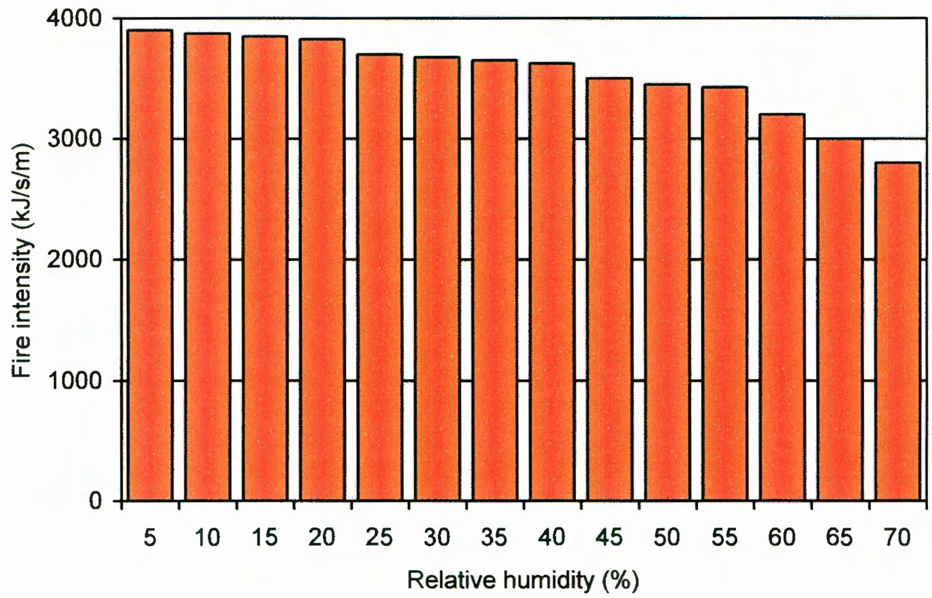


Figure 2.16: Effect of relative humidity on fire intensity
(Tainton, 1999, p. 225)

Relative humidity is a measure of the amount of water vapour actually in the air compared with the amount the air could hold if saturated and is therefore given as a percentage. It is therefore temperature and pressure dependent and strongly determines dead fuel moisture content.

Therefore to summarise: fuel moisture content affects ease of ignition, fire spread rate, fire intensity, smoke properties, fuel consumption, spotting and plant mortality or scorch. Fuel moisture is so important that it forms a foundation for many fire danger rating systems, such as McArthur's Forest Fire Danger Rating and the Canadian Forest fire behaviour prediction system. Furthermore, accurate prediction and measurement of dead fine fuel moisture content and an understanding of the adsorption and desorption cycle are central to the planning and conduct of prescribed burns (Tolhurst and Cheney, 1999). The effect of fuel moisture on fire intensity is shown in Figure 2.17.

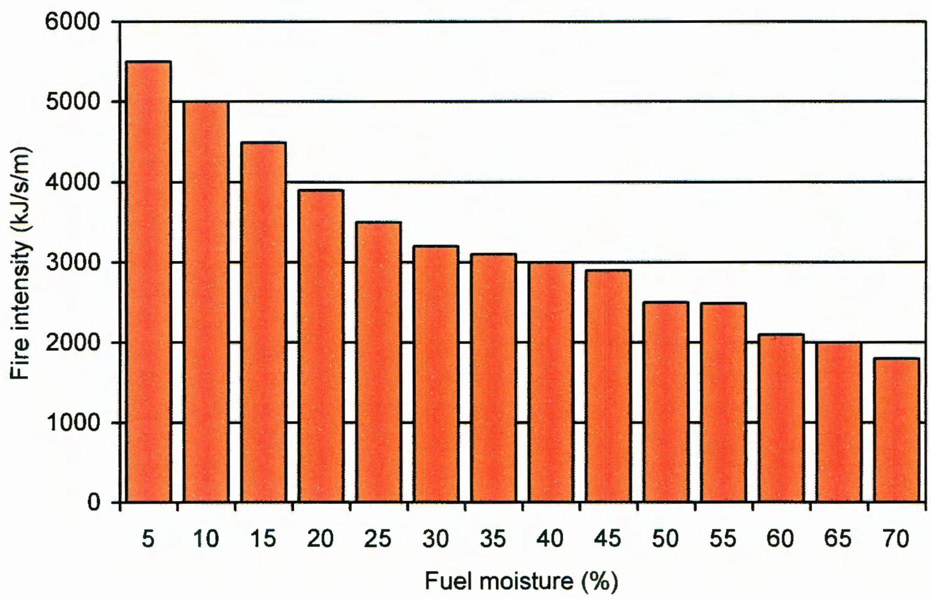


Figure 2.17: Effect of fuel moisture on fire intensity

(Tainton, 1999)

2.4.6 FUEL MODELS

A number of sophisticated models have been developed in the USA and Australia to predict the behaviour of fires, but they are probably too cumbersome for general field studies (Tainton, 1999). Simpler models based on general fuel characteristics such as particle size distribution and moisture content, together with terrain slope, relative humidity, air temperature and wind speed, are generally preferable.

Research in South Africa has concentrated on the effect of fuel and weather variables on the intensity of fires in savannah areas (Tainton, 1999, p. 222). In previous studies, attention has been focused on mainly fire intensity because of its close association with other fire behaviour parameters such as rate of spread, flame height and the temperatures recorded at different heights within the canopy of the vegetation (Tainton, 1999).

The function of fuel classification was to estimate fire behaviour, and the prediction of fire behaviour was fundamental to fire danger rating, fire suppression and fire planning. According to Pyne, (1984, p. 109) the fuels were originally typed according to whether grass, brush or timber dominated the biota.

By the 1930s the concept of cover type evolved into the concept of a fuel type. Each fuel type exhibited two primary characteristics: a rate of spread and a resistance to control. Each of these two traits could be assigned one of four values: Low (L), medium (M), high (H) or extreme (E). The Hornby fuel classification system underwrote extensive fire planning for the USA national forest system and the use of fuel type maps was widespread (Brown and Davis, 1973, p. 205).

Different strategies of fire control demanded greater refinement, and new developments in fire danger rating and fire behaviour modelling made new fuel classifications possible.

In the USA both the National Fire Danger Rating System (NFDRS) and the Rothermel fire model appeared in 1972. Both continued the process of transforming vegetative cover into fuel, and fuel traits into fire behaviour traits.

The quantification of fuels was underway and even biological approaches to classification followed suit. Biota were expressed as fire regimes and cover types as fire types, identifying complex ecosystems solely on their responsiveness to fire.

Generally, the average fuel models may be of three forms: static, dynamic and stylised. Static fuel models define fuel parameters for only a short period of time, such as a given fire season. Dynamic fuel models accommodate elements of growth and decay, predicting systematic changes in fuel parameters over the course of several years.

Stylised fuel models average the net growth and decay of fuel complexes into a characteristic ensemble. According to Pyne (1984, p. 111) two sets of stylised fuel models were developed. The NFDRS includes 20 fuel models, while the Northern Forest Fire Laboratory (NFFL) developed a slightly different set of 13 fuel models.

As biotic associations, both sets fall into four groups: grass, brush, timber and slash. As fuel complexes they are distinguished according to the distribution of fuel loads by size classes and by the depth of the fuelbed.

The effect of fuels on a fire, and of fire on fuels, can be summarised in terms of the three principal strata of fuels: ground, surface and aerial. The surface stratum is the most fundamental and it is customarily subdivided into four major biotic groupings: grass, brush, forest and slash. Pyne (1984, p. 115) states that behavioural characteristics of fires will differ according to structural properties of each group.

In the case of grass nearly all surface matter is available as fuel. In the case of brush, timber and slash the material available as fuel are 5 – 95%, 5 – 25% and 10 – 70% respectively (Figure 2.18)

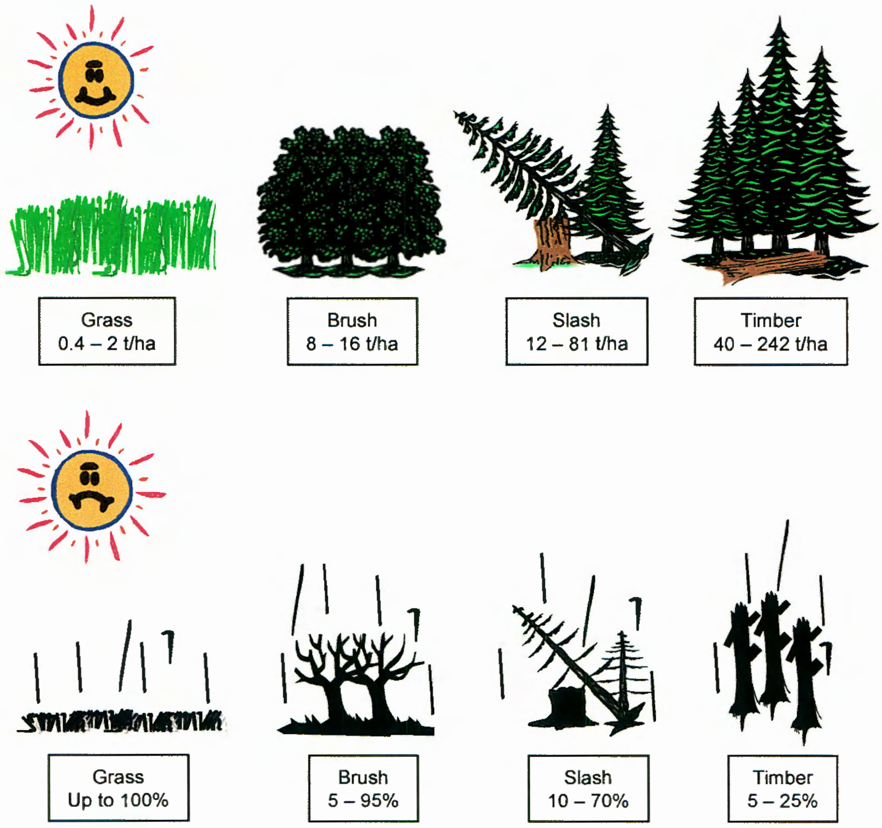


Figure 2.18: Fuel loading and fuel availability

(Pyne, 1984, p. 116)

Chandler *et al.*, (1983a, p45) states that although fuels are usually characterised as one of the "constant" factors in fire dynamics, they do change over time. The accumulation of dead fuel on the forest floor not only depends on the obvious factors of plant species, age and density, but it is influenced to a much greater degree by the climatic factors of temperature and moisture that determine the rate of decay of the material after it reached the ground.

2.4.6.1 Grasslands

All grasses, annual and perennial go through an annual life cycle where the plant germinates or produces new shoots, grows, flowers and dies. The life cycle is dominated by rainfall according to Cheney and Sullivan (1997). Grass curing is the term used to describe the process of dying and drying out (Van Wilgen, Everson and Trollope, 1990). The curing state of a grassland, expressed as the fraction of dead material in the sward, has a major effect on fire spread according to Cheney and Sullivan (1997).

Grasslands consist exclusively of 1-hr TL fuels; their principal structural parameters are fuel depth (grass height), fuel loading, and the rates of living to dead fuels. Its small diameter fuels and high surface-to-volume rates make grasses quickly responsive to heat and moisture transfer. Fire effects vary with the intensity of the fire, but the tendency is to consume virtually all-surface fuels.

Since the climate of the grassland biome is characterised by wet summers and dry winters, the moisture content of the fuel bed is normally high in summer. After the first winter frosts have killed the aboveground parts of the grass plants, the herbage dries out and will burn readily. In general, fires in the grassland biome are regular, occurring chiefly during late autumn, winter and spring. They are typically head-fires and are therefore intense and spread rapidly (Tainton, 1999, p. 229).

2.4.6.2 Brush

The fuels introduced as brush are small, loosely compacted, and available. All brush have in common that they enlarge the depth of the surface fuelbed and introduce a chemistry of flammable live fuels to compound with surface dead fuels.

The result can be a significant increase in fireline intensity and flame height, with further escalation into a stratum of aerial fuels, should a forest canopy be present (Pyne, 1984, p. 117).

2.4.6.3 Forest

Forest fuel complexes differ from pure grass complexes in having a mixture of fuel size classes, with proportionately heavy loads in the larger size classes.

Rate of spread is typically less than for grass and brush and the shielding effect of the forest further reduces effective wind velocity. Forest fires thus burn in complex ways, because it is a function of their mixed fuels.

Important physical attributes of fuel particles are density, thickness and surface/volume ratio according to Chandler *et al.*, (1983a p. 33). Fuel moisture also plays an important role in the relationship between foliage moisture and fire behaviour.

The fuelbed, the association of living and dead plant materials of various sizes and shapes that extend from mineral soil to the top of the vegetation canopy, have several properties that influence fire behaviour. (Chandler *et al.*, 1983a p. 39)

- Phytomass, or total fuel loading, is the total amount of plant material, both living and dead to be found above mineral soil. It differs from biomass in that roots and animal matter are not included. Fuel loading (synonymous terms common in the literature are fuel weight and/or fuel volume) is expressed in terms of mass per unit area, usually kilograms per square meter or tons per hectare.

- Assuming a constant heat yield, the intensity of a fire is directly proportional to the amount of fuel available at any given rate of spread of the fire front. This is illustrated in Figure 2.19.

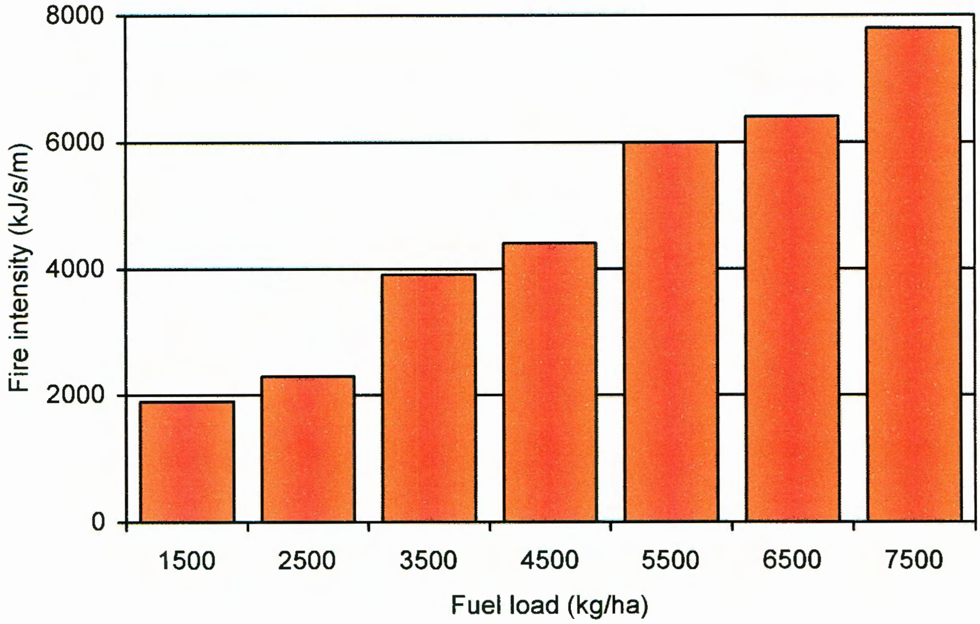


Figure 2.19: Effect of fuel load on the fire intensity

(Tainton, 1999, p. 222)

- Virtually all the crown loading tables correlate crown mass against species and diameter at breast height (DBH). Many use multiple regressions which include variables such as crown length, site index, stocking percent and crown width as well (Chandler *et al.*, 1983a p. 41).

- Size distribution of the living and dead materials is important in order to estimate available fuel loading. Dead fuels larger than 1 to 2 cm in diameter have little influence on a fire's rate of spread, although they do contribute to both convective intensity and reaction intensity. According to Chandler *et al.* (1983, p. 42) living fuels larger than 2 to 5 cm in diameter seldom burn at all but act as heat sinks, trapping energy that would otherwise be utilized to increase fire spread.

- Compactness refers to the tightness with which the individual particles are packed within the fuelbed. It affects both the air supply to the individual burning particles and the ease of heat transfer to particles in the bed ahead of the flame front. Compactness has an even more marked effect on combustion rates and flame heights. Logs, for example, burn best when tightly packed and will cease to burn if separated by much more than one diameter from each other. Fine grasses, on the other hand, burn best in loose arrays and combustion rates can be drastically reduced by compaction.

- Continuity is classified in both vertical and horizontal continuity within the fuel bed. The tendency of forest fuels to develop vertically stratified layers is so universal that the fuel strata in which they burn often classify fires e.g.:

  - Ground fuels are generally highly compacted and partially decomposed and consequently fires spread slowly with little or no flaming.

  - Surface fuels consist of the dead needles, twigs and other litter that have fallen and are by far the most common carriers of forest fires. According to Chandler *et al.* (1983a, p. 44) surface fires spread most rapidly in pine litter where the long needles, bundled in fascicles of two to five, tend to develop a deep, well aerated fuelbed. Grass fires spread more rapidly than fires in any other natural fuel because of its finely divided particles of low bulk density.

  - Midlevel fuels are those shrubs and trees either less than two meters in total height or taller plants that have branches and/or foliage within one meter of the ground surface. These plants are primarily important as a means of transmitting fire to the crowns of larger forest trees.

- Upper level or crown fuels consist of the foliage, twigs and smaller branches of the overstorey vegetation. Since crown fires only occur when conditions are dry (producing long flames) and windy, they are always intense, fast moving and extremely dangerous.

2.4.6.4 Slash

Slash is understood to include all the debris left in the forest as the result of cutting or agencies such as wind and fire. It comprises the tops, branches and unutilised portions of the trees felled, together with trees uprooted or broken off in the process or as a consequence of harvesting operations (Hawley, 1949, p. 309).

Intensive forestry practices may further increase fuel accumulation rates. Heavy uncommercial thinnings, which may be essential in some areas, lead to heavy loads of both fine and large fuel components. These residues make the task of fire suppression very difficult. Conifers contain resins and waxes and their needles and branches offer a large surface area for burning relative to their total mass (Chandler *et al.* 1983a, p. 385).

Integration of conservation, riparian zone management and weed control are all part of the plantation fuel mosaic. As changes occur in plantations, e.g. clearfelling, planting and thinnings, the fuel loads change and therefore the fuel mosaic.

2.4.6.5 Crown

Crown fires relate to surface fires in various ways. Crown fuels show a structure and chemistry that greatly influence the properties of a crown fire. The form of spread of a crown fire will depend on certain structural properties of the fuel stratum (fuel load and bulk density) and on chemical properties of the particles (foliage chemistry and fuel moisture). For active or independent crown fires to develop the crown fuel stratum must be dense, continuous, and live, and its fuel moisture low. To these preconditions must be added the presence of an intense surface fire (Pyne, 1984, p. 122).

Crown fires produce large flaming fronts, and fuel consumption within the front is complete for fine fuels (Refer to Table 2.2).
The net effect, however, is an increase in fuel load by the destruction of large stands of trees, as live fuels instantaneously become dead fuels.

2.4.7 Veld burning (Grassland)

The general objectives in both agricultural and conservation areas are to:

- Burn off unpalatable growth left over from previous season's growth which would be unacceptable as forage and which, if not removed, would tend to smother the plant.
- Control the encroachment of undesirable plants.
- Stimulate out of season growth to provide green feed when it does not occur naturally.
- Contribute to fire control by reducing fuel loads.
- Maintain or develop grass cover for soil and water conservation.

(Trollope, 1999, p. 228)

Grassland areas are prone to fire and support many plant and animal species which have evolved adaptations in response to fires. Fires are a natural phenomenon in these areas because Africa is prone to lightning storms and it has a fire climate including both dry and wet periods. During the dry period lightning induced fires can burn plant fuels that have accumulated during the wet rainy period (Tainton, 1999).

Factors affecting fire behaviour in grassland are primarily fuel density, fuel moisture content, fuel load and fuel availability. Tainton (1999) states that although most research work on grasses in South Africa were done in KwaZulu-Natal Drakensberg, grasslands have an homogeneous structure, and that the broad principles derived from these data should be widely applicable within the grassland biome.

2.4.7.1 Fuel density

According to Tainton (1999) the high values recorded in the Drakensberg (340 m^2/m^3) favour rapid ignition and rapid spread of fires (e.g. mean rates of spread of 0.37 m/s have been measured).

2.4.7.2 Fuel moisture

The moisture content of grassland fuels varies seasonally and has an important impact on the amount of fuel that will be consumed by a fire. In tracer belts, which are prepared in autumn when moisture content is approximately 70%, the amount of available fuel will be relatively low. This ensures a safe fire. In early winter, fire-breaks are normally burnt between 06h00 and 09h00 when the fuel moisture content is normally high, approximately 30%.

In mid-winter, fuel moisture contents decline to very low levels (<20%) during the day, giving rise to a high fire hazard. Frost or dew may raise it quite considerably in the early morning (Tainton, 1999).

2.4.7.3 Fuel load

In the Highland Sourveld approximately 2 000 kg/ha of fuel normally accumulates in the year following a fire. At the end of the second season, the fuel load will have more than doubled at about 4 700 kg/ha (Tainton, 1999). In low fire hazard conditions, fires in such fuels are readily controllable, but even under moderate fire hazard conditions they become uncontrollable. Therefore, many wildfires take place in two-year old grassland which, because of the presence of fully cured material from the previous season, will burn at any time. Tainton (1999) states further that by the fifth year, the fuel load increases to approximately 6 000 kg/ha and, after 10 years, to a maximum of 7 000 kg/ha.

Most of this fuel will be dead material, making it extremely flammable and a high fire risk. Beyond 10 years, the grasslands become increasingly moribund and the fuel load declines steadily to about 550 kg/ha after 20 years. At this stage the grasslands are invaded by woody species (Tainton, 1999).

2.4.7.4 Fuel availability

The proportion of the total amount of grassland fuel that will actually burn in a fire is largely dependent on its moisture content.

When annual winter fire-breaks are burnt, fuel moisture content is normally low and as much as 96% of the fuel will burn. In contrast, biennial spring fires, because of the higher fuel moisture content, will normally consume only between 70 and 90% of the total fuel load (Tainton, 1999).

2.4.8 Fire management of natural forests

Natural forests of South Africa are characterised by their fragmented distribution in the landscape and they have therefore large edge effects. Vermeulen (1999) states that a forest is not a fire-prone vegetation type and that only in exceptional circumstances and extreme weather conditions fires will penetrate into the forest. Fire, however, has an important ecological function in both fynbos and grassland ecosystems and thus also with regard to the maintenance of natural forest/fynbos and forest/grassland ecotones.

The scientific management of vegetation bordering forests, especially with regard to burning frequency, burning season and fire intensity is thus a prerequisite for the maintenance of a natural ecotone. According to Vermeulen (1999) the forest edge should not be artificially protected against these fires, as this will allow a heavy fuel load to accumulate on the forest edge. Furthermore, intense frequent fires could have pronounced effects on forest margins and result in the penetration of the forest edge (Tainton, 1999).

Protective measures could be necessary where the forest edge is heavily infested by invader plants, causing a too heavy fuel load and altering the structure of the forest edge. Especially small forest patches can be extremely vulnerable to wildfires. A too short rotation will not allow for the recovery of damaged ecotones before the next fire, while a too long fire rotation can lead to a high fire intensity, which could destroy small forest patches.

Where the forest borders unnatural vegetation, e.g. plantations, management activities will largely be aimed at the prevention of damage to the forest such as during harvesting operations and the eradication of invader plants.

Various guidelines exist with regard to afforestation of land bordering natural forest, and the establishment of buffer zones between forests and plantations (Vermeulen, 1999).

2.5 FIRE BEHAVIOUR

2.5.1 Introduction

The term fire behaviour is a general descriptive term to designate what a fire does and the manner in which a fire reacts to its environment, that is, to the fuels available for burning, climate, local weather conditions, and topography. The ignition, build-up, propagation, and decline of any large fire in forest fuels are components of a complex chain-reaction process (Brown and Davis, 1973, p. 183).

The fire environment includes all of the factors that allow a fire to start, burn and spread. According to Teie (1997, p149), there are sixteen primary factors that influence wildland fire behaviour (Figure 2.20). The fire's rate of spread, intensity, and other characteristics respond to these. Some of these can, in turn, be influenced by the fire itself.

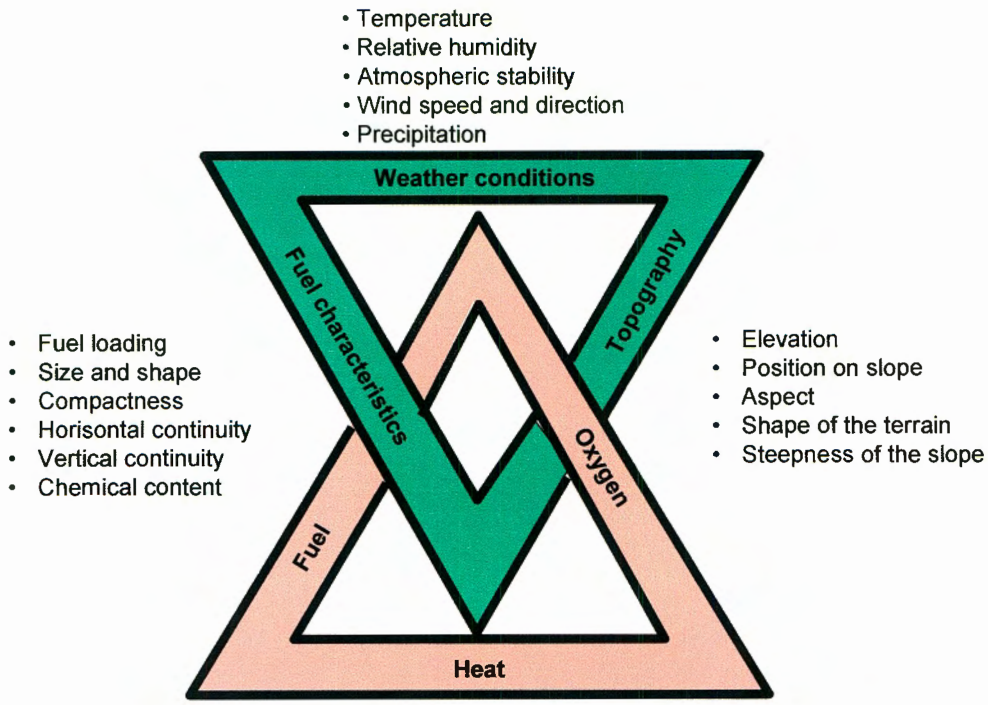


Figure 2.20: Wildland fire environment

(Teie, 1997, p. 150)

Typically, one part of a fire spreads more rapidly than the rest. Usually this is due to wind or slope or their joint effects. This creates a pennant like or fanlike pattern with the fastest-spreading portion at the apex or farthest point from the origin (Tolhurst and Cheney, 1999, p. 8). The parts of the fire's perimeter are separately designated as follows (Figure 2.21):

- Head or head fire, that part of the perimeter enlarging itself most rapidly.
- Flanks or side fire moving at right angles or obliquely to the direction taken by the head fire.
- Rear or base of the fire, spreading in the opposite direction to the head fire.

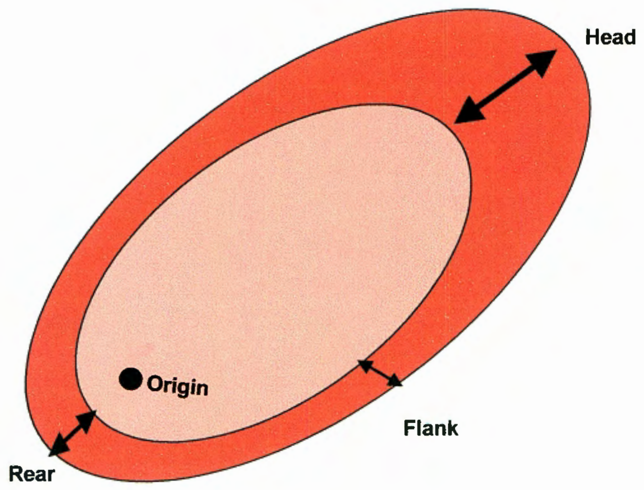


Figure 2.21: Typical pattern of fire spread

(Brown and Davis, 1973, p. 185)

2.5.2 Stages in the development of fires

When a fire starts in natural fuels it does not exhibit immediate violent reactions such as those observed when petrol ignites or explodes. A potential for intense fire behaviour may exist but fires cannot reach a steady state of progression appropriate to existing fuel, weather and local topography until the natural forces inherent to such conditions have been reinforced fully by those engendered by the fire (Luke and McArthur, 1978, p. 71).

When a fire is ignited on a slope or under windy conditions, air moves into the combustion zone preferentially from the downslope or upwind side, the flames are tilted upslope or downwind, and the fire rapidly assumes an oval shape as in Figure 2.21. Under the influence of wind (or slope), the hot gases from the upwind edge are swept across the combustion zone, contributing to the heating of fuels ahead of the burning edge (Figure 2.22).

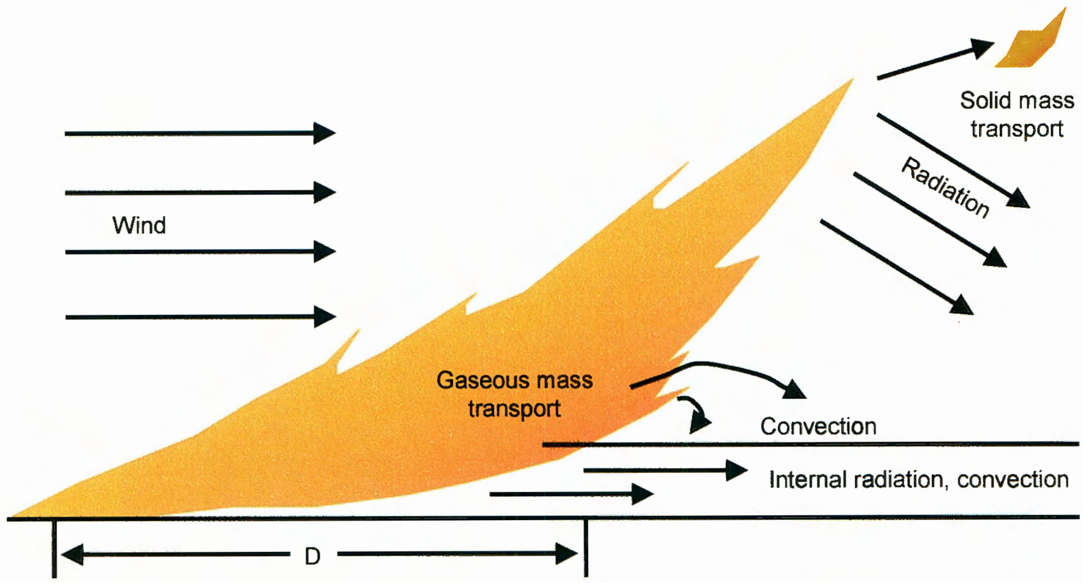


Figure 2.22: Schematic presentation of a wind-driven fire
(Chandler *et al.*, 1983a, p. 94)

Ignition in front of a wind-blown fire occurs rapidly and wind also increases the glowing combustion rate of residual charred material adding still further to the rate of production of hot combustion products (Chandler *et al.*, 1983a, p. 95).

2.5.2.1 Initial build-up

The first stage in fire development is a period of initial build-up during which the behaviour of the fire is dominated by environmental conditions. The suppression task is relatively easy provided fire fighters arrive early enough.

At first the pre-heating of fuel to ignition point is dependent on the relatively low rates at which heat may be transferred by radiation or convection from a small fire with low flames. Later the rate of build-up increases as more fuel is involved in both the vertical and horizontal dimensions. Finally, when the fire has reached a sufficient size, wind speed and convection, radiant heat become dominant factors as the fire passes into, and begins to exhibit the type of fire behaviour characteristic of the transition stage.

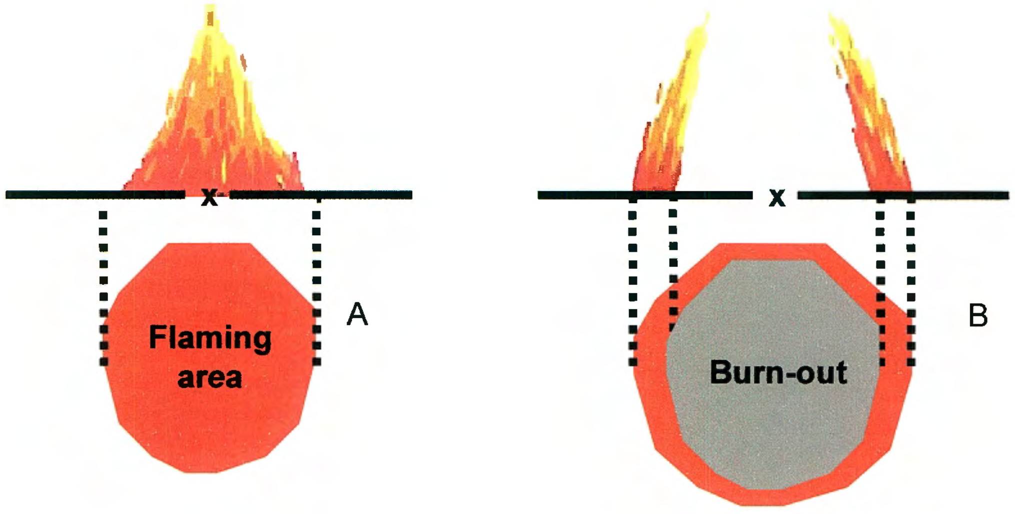


Figure 2.23: Initial stages of fire development under calm conditions on level ground

A Shortly after the start with flames drawing into the centre of the flaming area.

B After 10 – 15 minutes the fire has a doughnut shape and flames are leaning inwards.

(Luke and McArthur, 1978, p. 72)

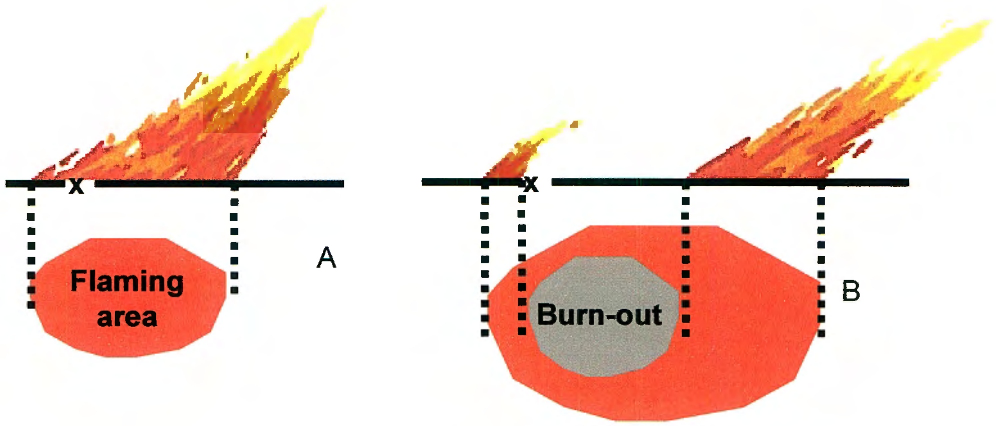


Figure 2.24: Initial stages of fire development under windy conditions or on sloping ground.

A Shortly after the start flames lean upslope or with the wind.

B After centre burnout the rear spreads slowly against the wind with low flame heights while the front begins to run with the wind.

(Luke and McArthur, 1978, p. 72)

The initial stage may last from a few minutes to half an hour or more, depending on such factors as the quantity, condition and arrangement of fuel and the influence of weather and topography. Fires burning under conditions of low fire danger show little tendency towards acceleration and therefore do not reach or barely reach the transition stage. During the initial build-up stage fires have certain characteristics which are typical of low intensity fires, namely a circular shape, narrow flame depth and flames leaning inwards from the perimeter (Luke and McArthur, 1978, p. 73) (Figure 2.23).

2.5.2.2 Transition stage

At the transition stage, convective activity begins to reinforce those forces nearer to the ground which normally regulate surface fire behaviour during the initial stage. According to Luke and McArthur (1978, p. 73) three criteria must be met to effect this transition.

The first relates to available fuel loading and burn-out time, and requires that the depth of the flaming zone should be large in relation to its length, and that the fire has achieved a dynamic head with the flames leaning towards the unburnt fuel, as depicted in Figure 2.24. The second requirement is that the flaming area behind the head should have reached a critical size conducive to the significant pre-heating of contiguous fuels. The third criterion is that the total rate of heat output should be sufficient to cause a significant perturbation in the surface wind field at and near the fire (Fendell and Wolff, 2001, p. 171).

When these criteria have been met either down draughts occur or wind speed into the rear of the fire increases noticeably. In forest fuels a transition from a surface fire to an intermittent crown fire is likely to occur, but is influenced greatly by the extent of the fuel loading (Luke and McArthur, 1978, p. 73).

2.5.2.3 The final stage

The final stage is marked by a well-developed or towering convection column. In forest fuels this almost invariably means that the spotting process is well developed. Suppression forces will have to face dangerous situations beyond or almost beyond their control capacity.

Some of the main factors influencing the acceleration of fires according to Luke and McArthur (1978, p. 75) are: the moisture content of fuels, fuel surface area and the distribution of fuel in the vertical plane, combustion rate and burn-out time of fuels, wind speed close to the ground, atmospheric instability, slope and the spotting process.

Because the effect of some of these factors is linked with diurnal regimes of temperature, humidity and wind, the time of day is important when considering the way in which a fire accelerates (Tolhurst and Cheney, 1999, p. 59). Fuel particle size also has an important influence on acceleration processes. Fires in fine grass fuels seldom take longer than five or ten minutes to accelerate and reach their steady state spread.

Because of the high rates of spread which can sometimes be exhibited by both forest and grass fires and the added complication of long distance spotting in forests or from isolated clumps of trees in grasslands, halting or slowing down the acceleration process during the early stages of a fire is basic to all fire suppression action.

2.5.3 Fuel characteristics

As discussed earlier, fuels play a major role in fire behaviour. According to Luke and McArthur (1978, p. 80) factors such as fuel quantity, fuel particle size, fuel distribution and fuel moisture content are some of the most important aspects in fire behaviour analysis.

2.5.4 Wind speed

As mentioned in paragraph 2.5.2, wind speed is one of the dominant meteorological forces which will take a fire from the initial spread phase into a dynamic spreading situation. Wind has the effect of changing the flame angle so that flames are driven into the unburnt fuel and provide more efficient pre-heating by radiation. In addition, burning embers are thrown ahead of the flaming fire front and accelerate the rate of fire spread.

Except at low and very high wind speeds, the rate of spread of a fire varies approximately as the square of the wind speed. Thus in a grassland situation rate of spread with a 15 km/h wind is only one-quarter of the spread under a 30 km/h wind. Figure 2.25 shows the different fire shapes with the influence of different wind speeds.

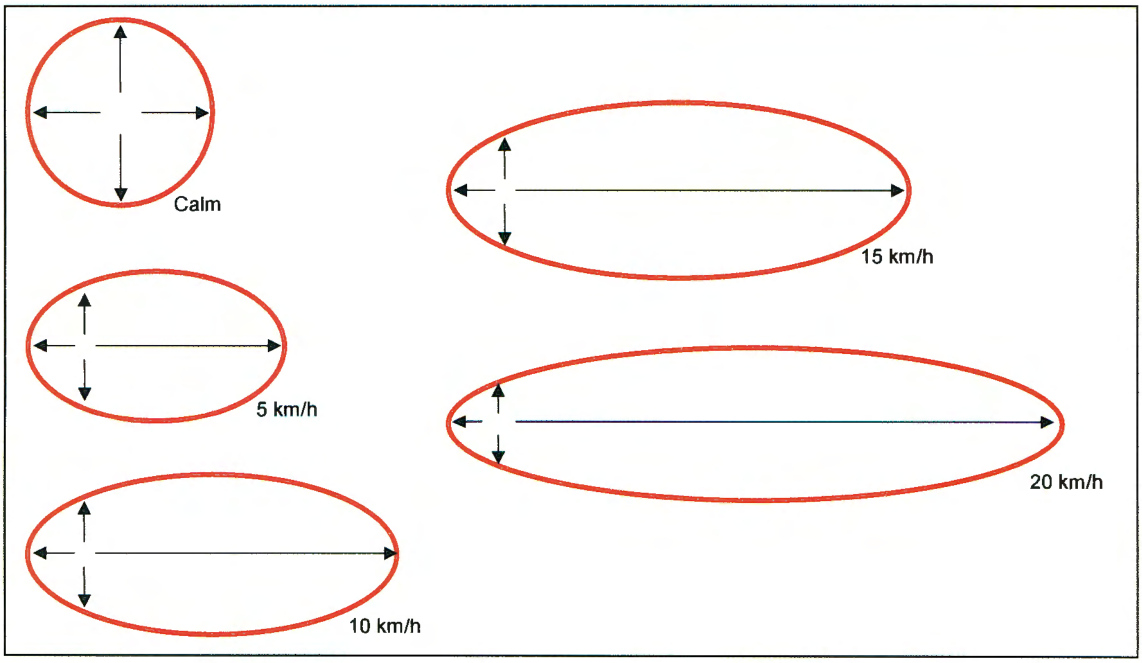


Figure 2.25: Diagrammatic representation of fire shape under the influence of different wind speeds as measured at 1.5 m above ground in the forest

(Tolhurst and Cheney, 1999, p. 16)

There appears to be a strong interrelationship between particle size, fuel distribution and wind speed and it is difficult to apply the same basic relationships to fine grass fuels as to heavier forest fuels. An added complication is that once the open wind velocity exceeds 50 km/h, the rate of forward spread in grasslands tends to decrease. According to Luke and McArthur (1978, p. 86) the reason for this is that the head fire becomes narrow and tends to be fragmented into a number of even narrower heads so that a deceleration process begins to operate.

In forests, wind speeds reaching the floor of the forests are considerably less than in the open and are largely determined by tree height and the density of trees and understorey vegetation.

Once again rate of forward spread in forest conditions, including both eucalypts and pines, appears to vary as the square of wind speed, except with very light winds of less than 3 km/h in the forest. However, fire spread continues increasing as open station velocity increases and does not show the same type of decrease beyond 50 km/h as with grasslands (Luke and McArthur, 1978, p. 87).

Wind speed is important not only with respect to rate of fire spread but it also has an effect on ignition probability and combustion rate. Strong wind speeds increase the changes of fires starting under certain circumstances, e.g. from rubbish dumps or other areas where fire occurred recently.

Although rates of spread are greatly increased with increasing wind speed, flame heights are reduced accordingly. This partly explains why crown fires do not always occur when wind speeds and rates of spread are high (Luke and McArthur, 1978, p. 95).

2.5.5 Slope

Slope, like wind speed, has a considerable influence on rate of spread, especially in the initial stages of a fire. Slope increases the propagating heat flux by exposing the fuel ahead of the fire to additional convective and radiant heat. The combined effect of wind and slope is to change the flames to a very acute angle so that once the slope exceeds 15° to 20° the flame front is virtually a sheet of flame moving parallel to the slope (Chandler *et al.,* 1983a, p. 94 and Heikkilä *et al.,* 1993, p. 85).

Data from experimental fires in eucalypts and grass fuels in Australia indicated that the rate of forward progress of a fire on level ground doubles on a 10° slope and increases almost fourfold travelling up a 20° slope. Luke and McArthur (1978, p. 95) state that a general "rule of thumb" used by the Californians is that fires burning uphill double their rate of spread going from a moderate (0 – 22°) to a steep slope (22 - 35°) and double again going from a steep slope to a very steep slope (35 - 45°). More dangerous fire behaviour is not the sole reason why suppression is difficult on steep slopes. Movement of mechanical plant and equipment is also difficult.

2.5.6 Atmospheric instability

A condition of atmospheric stability or instability can play a dominant role in determining fire behaviour both in grasslands and in forests. Deep layers of unstable air are prerequisites for the formation of an active convection column. This in turn can lead to strong thermal convection, increased wind speed near the ground due to indraught winds, long distance spotting and the formation of fire whirlwinds. Pronounced atmospheric instability day after day is one of the characteristics of an extended drought period and is often associated with cloudless skies and high solar radiation. Under these conditions fuel moisture contents drop rapidly from sunrise onwards and by 10h00 the chance of fires starting in grassland becomes high.

Fire whirlwinds are one of the most striking features of fire behaviour, especially on large stationary fires associated with slash or debris removal. Although fire whirlwinds are associated with intense burning rates and atmospheric instability, they can sometimes be triggered by mechanical turbulence even under milder atmospheric and burning conditions, provided there is ample fuel available for combustion.

Spotting distance is related to fire danger index and therefore to rate of spread, flame height and fire intensity (Luke and McArthur 1978, p. 102).

Spot fires which originate a considerable distance ahead of the main fire can be treated as separate fires. They can also place a tremendous strain on the suppression organisation. Once a spotting process is initiated, each successive surge of fire activity may be a little greater than the last and the fire appears to accelerate in a series of jumps and surges (Chandler *et al.,* 1983, p. 104).

2.5.7 Stationary fire behaviour

A stationary fire is defined as any fire burning within defined boundaries and generally lit by some form of area ignition techniques, either from aircraft or by ground parties (Luke and McArthur, 1978, p. 108).

The process of pyrolysis and ignition shows how a fire can be thought of as a chain reaction, with the initial ignition source providing the activation energy that permits ignition and self-sustainability of a fire. Flaming combustion at the fire front preheats adjacent fuel and provides the pilot flame to cause its ignition (Figure 2.26).

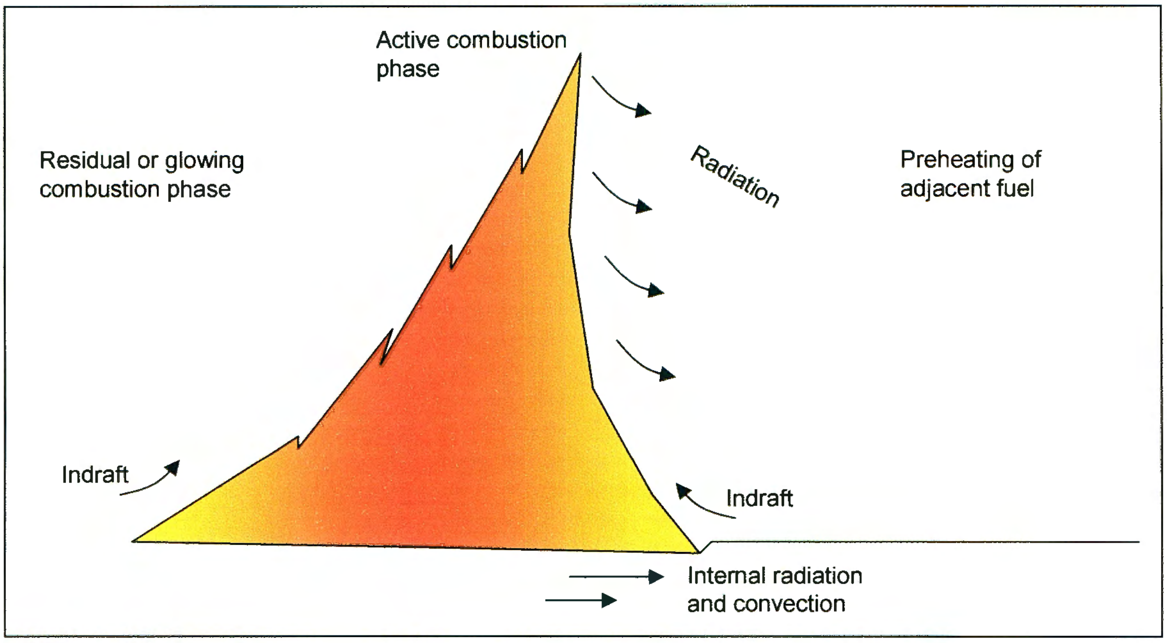


Figure 2.26: Flame profile of a fire on flat ground with no wind, indicating the region of pre-heating, flaming combustion and glowing combustion (Whelan, 1998, p. 11)

Stationary fires may be either high intensity fires associated with the burning of slash or low to very low intensity prescribed burning. During prescribed burning, indraught winds associated with low intensity burning are negligible as fire intensity is kept very low.

High intensity debris disposal burns are generally burnt under more severe meteorological conditions and frequently exhibit behaviour of mass fire such as intense and rapid combustion, strong indraught perimeter winds and flame flashes into the convection column (Hawley, 1949, p. 315).

2.5.8 Large fire behaviour

A large fire is any fire which has resisted the efforts of the initial attack force and generally burns at least into the following day. However, according to Chandler *et al.* (1983a, p. 97), the terms “small” and “large” fire have but little to do with fire size. They rather refer to the vertical height to which the fire affects the normal windfield. Large fires are said to “make their own weather” because they can noticeably alter the temperature, humidity and wind fields in their vicinity. The transition from a small fire to a large fire regime is typically sudden, 15 minutes or so at the most, according to Chandler *et al.* (1983a, p. 97). If the rate of forward spread remains constant, the area burnt in a large fire increases as the square of burning time. The spread, intensity and shape characteristics of large fires defy simple description. Any fire which remains uncontrolled for some days is likely to be subjected to considerable wind and other weather changes, fuel differences and topographic variations (Wolffsohn, 1980, p. 10).

If the initial attack fails during the first day, there is a need for a highly developed attack system and means of bringing in large numbers of men and equipment overnight with the objective of establishing control before the onset of the next day’s main burning period. The old concept of control by 10h00 the following morning is still very much applicable in present day fire control and is the only way to ensuring that a destructive large scale fire will not develop (McCarthy and Tolhurst, 1998, p. 29).

2.5.9 Fire behaviour warning signals

The degree to which fire behaviour is understood places a ceiling on the efficiency attainable in all fire control activities. In fire fighting there is a special premium on anticipating the behaviour of a fire as far as possible in advance. This need is met in part by forecasts of fire weather and by operation of a system of fire danger ratings. The following conditions are likely to generate a runaway fire.

Fuels: For a given rate of spread and heat yield, fire intensity will be directly proportional to the weight of available fuel. For the same fuel type, for example, when fuel loading doubles, rate of spread and flame height will also double (Chandler *et al.*, 1983a, p. 115). Heavy volumes of fine fuel mean a hot, fast-moving fire. In mixed fuels, the availability of kindling fuels and vertical arrangements conducive to crown fires become critical.

Fuel dryness: Fuel moisture content determines the ease of ignition, the amount of available fuel and the burning rate for each class of fuel. At fuel moistures below 5%, fires in fine and large fuels tend to spread at equal rates. At fuel moisture between 5 and 10%, fires in fine fuels spread more rapidly than those in large fuels. Above 10%, the rates tend to equalize again and at moisture above 15%, fires in heavy fuels will continue to burn and spread, whereas those in fine fuels will extinguish themselves (Chandler *et al.*, 1983a, p. 115). Under prolonged drought conditions, ground fuels and heavy fuels will also be dry, greatly increasing the available fuel and fire intensity. Fires then crown more readily and ground fuels burn more persistently (Luke and McArthur, 1978, p. 104).

Topography: Steep slopes greatly speed up the burning rate and the rate of spread of a small fire. Rate of spread doubles for every 10° increase in slope, while rates of spread increases tenfold on slopes above 35° (Chandler *et al.*, 1983a, p. 115). Except under drought conditions, moisture content of fuels on steep south and east exposures will be significantly higher than on north and west exposures. This results in a slower rate of spread of a fire front on such slopes.

Wind: Several of the more dangerous atmospheric conditions conducive to rapid fire spread can be forecast. Probably the most critical is the arrival of a dry cold front and typical "berg" wind conditions along the coast. Rate of spread will double for each four meters per second increase in windspeed. This rule is valid for fires in loosely compacted surface litter. Grass fires increase their rates of spread faster than this, particularly at higher windspeeds (Chandler *et al.,* 1983a, p. 115; Fendell and Wolff, 2001, p. 175).

Early spotting: A fire should be regarded as capable of developing extreme behaviour if in its very early stages it has a tendency to spot. Such spotting indicates the presence of susceptible fuels and of updrafts or whirlwinds capable of lifting up embers.

Dynamics of the convection column: After a convection column has formed, the blow-up may have already occurred or at least be well under way, so the characteristics of the column may be more significant from the standpoint of safety than of fire control tactics. Colour changes as well as motion are indicative of the onset of high-intensity burning. An increased burning rate means a drop in combustion efficiency, which, in turn, results in much darker smoke with a dense, solid appearance.

To summarise: If temperature increases, relative humidity decreases and fuel moisture decreases. When this happens, fuel temperature increases, local winds increase, atmospheric instability increases and cumulus cloud development increases (Teie, 1997, p. 153).

The British Columbia Basic Fire Suppression and Safety Student Workbook, (2000, p. 9) also refers to the 30/30 cross. The 30/30 cross describes the condition where the relative humidity drops below 30% and temperature rises to about 30°C. If this occurs on the fire line, a useful rule of thumb is to potentially expect extreme fire behaviour (See Figure 2.27).

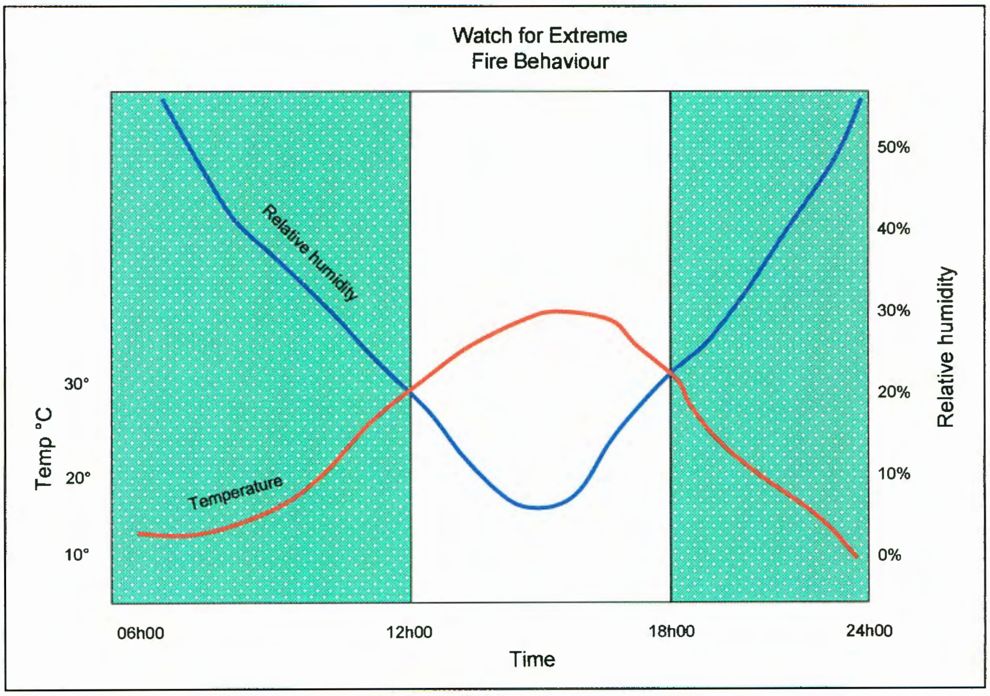


Figure 2.27: The 30/30 cross of extreme fire weather
(Basic Fire Suppression and Safety Student Workbook (2000 p. 9)

Teie (1997, p. 208) also mentioned the seven factors that constitute an extreme fire environment.

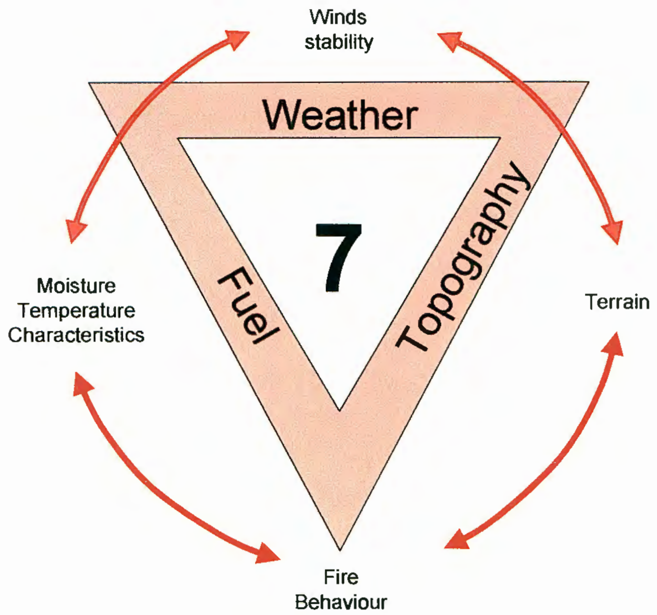


Figure 2.28: The seven factors within the wildland fire environment. These must be monitored throughout the fire fight
(Teie, 1997, p. 208)

The phrase "look up, look down, look around", refers to these seven characteristics. These are the things you should be looking for (Teie, 1997, p. 208).

2.6 FIRE EFFECTS

2.6.1 Introduction

Human perceptions of fire severity are influenced by features related to intensity, such as flame height, rate of spread, extent of the fire front and magnitude of the smoke pall (Whelan, 1998 p. 45). However, one fire is not necessarily like another with respect to its impact on the biota. Time between consecutive fires, or fire frequency, can thus have a marked impact on vegetation, independent of the fire intensity.

Other features of fire, in addition to intensity, include the time between fire (frequency), season of burning, the extent (or patchiness) of a fire and the type of fire. These features collectively constitute the fire regime (Whelan, 1998, p. 47).

It is important to fully understand the effects of fire in the forest. Such knowledge provides the economic basis for fire control and is a key consideration in both public and private forest policy, forest practices and overall forest management. According to Brown and Davis (1973, p. 45) it is also the essential prerequisite to beneficial use of fire for land-management purposes.

A forest fire does several specific things: Firstly and perhaps most obviously, it consumes woody material. Apart from physical removal of material from the forest, as in logging, fire is the only means of quickly removing large quantities of woody and other vegetative material. Secondly, it creates heat effects, as a result of which living vegetation and animal life are killed or damaged and the soil may be altered. Thirdly, it produces residual mineral products that may cause chemical effects, which are mostly important in relation to the soil.

Physical, biological and chemical changes in the forest environment are always involved. Some may be immediate and readily apparent, but others may be delayed and difficult to detect (Brown and Davis, 1973, p. 46).

2.6.2 Effects on plantations

Fire size does not always provide a useful means of assessing fire damage. Rate of spread, fire intensity, the nature of the improvements in the path of a fire and many other factors must be considered (Luke and McArthur, 1978, p. 119). Any tree can be killed by a fire of sufficient duration and intensity.

Because of low rates of spread and the greater efficiency of fire fighters under relatively mild weather conditions, the restriction of low intensity fires to small areas is comparatively easy. Damage under these circumstances is usually slight. When fire danger is very high or extreme, the chances of holding fires to small areas are greatly diminished and total damage is then often closely related to fire size. Fire behaviour in any ecological association and especially in coniferous plantations is largely determined by growth habits and fuel characteristics of the particular tree species, modified by peculiarities of local climate (McArthur, 1971, p. 16).

Several factors may affect the susceptibility of trees and forests to heat damage under natural conditions (Brown and Davis, 1973, p. 49):

- Initial temperature of the vegetation. The higher the initial temperature, the less additional heat is necessary to bring about lethal temperatures. This point is of importance in prescribed use of fire, since initial temperatures can be controlled by selecting the time of burning.

- The size of the critical tree portion exposed and its morphology. Young trees, leaves and small branches are easily killed because they can quickly be heated to a lethal temperature.

- The thickness and character of the bark. Of all the protective mechanisms of the tree, the bark is the most important. This is especially true near the ground surface where most fires occur.

- Branching and growth habit. Other things being equal, trees that self-prune readily and develop high and open crowns are more successful in escaping fire damage because they are less susceptible to crown fires and they accumulate less litter close to the stem. So the intensity and duration of fire immediately around individual stems are reduced. Persistence of dead limbs, especially if they tend to be draped with dead needles (e.g. *P. patula*), increases the flammability.

- Rooting habit. Roots have thin cortical covering and, if near the surface, are easily damaged by fire. Shallow-rooted species are frequently damaged by ground fires through root injury, even though the stem and crown are not affected.

- Organic material covering the mineral soil. The depth and character of the organic mantle on the ground may largely control damage by surface fires to the roots. If the mantle is fairly thick and the lower part does not burn, its high insulating ability will protect roots from damage.

- Flammability of foliage. Conifers especially are more flammable than deciduous hardwoods.

- Stand habit. Because of their greater liability to crown fires, coniferous trees that grow in dense stands or are commonly associated with abundant subordinate vegetation are more subject to fire damage than those occurring in sparsely canopied open stands with scanty subordinate ground cover. The volume and vertical distribution of available fuels, affecting crown-fire incidence and the duration and intensity of the fire are closely related to stand habit.

- Season and growth cycle. The seasonal stage of growth affects nett damage in three ways. Firstly, it greatly affects the total moisture content of the crown, which in turn affects its flammability. Secondly, succulent growth is more susceptible to fire damage. Therefore, growing tips and cambium are more easily damaged during the active growing stage than during the dormant state. Thirdly, the ability of the tree to recover is affected by the food reserves in the roots, which fluctuate with the season.

(Brown and Davis, 1973, p. 50; De Ronde, 1988, p. 47; De Ronde, 2001, p. 4; McArthur, 1971, p. 17).

Bark is a good insulator but bark thickness may be more important than texture of the bark. However, variations in thickness, due to the presence of furrows, may alter the capacity of bark to protect the vital cambium layer. Living cells are killed instantly when subjected to a temperature in access of 65°C. The cork cambium and vascular cambia are injured first because they are living meristems closest to the surface of the stem. When the temperature of the bark surface is raised to about 1 000°C, a temperature reached by the flaming of fibrous strands on the outer edge of the bark layer, death of the cambium is likely to occur if that temperature level is maintained for two minutes if the bark is 10 mm thick, six minutes for a thickness of 20 mm and about 14 minutes for 40 mm (Brown and Davis, 1973, p. 47).

The thick bark of some of the pines provides good protection from fire and some of them have peculiarities which enable them to survive fires when very young. Young *P. oocarpa* trees killed by a fire usually coppices vigorously, while *P. merkusii* and *P. tropicalis* go through a grass stage in their earliest years (Wolffsohn, 1980, p. 2).

In pines cambium damage give rise to semi-concentric rings, which only emerge when the logs are opened up during sawmilling or veneering. Leaf scorch may often be observed within hours after a hot fire. Raising the temperature of leaves to 55°C for three minutes, or to 60°C or more for a few seconds, is usually sufficient to ensure their death (Luke and McArthur, 1978, p. 122). Most eucalypts have considerable powers of recovery after defoliation, due to the presence of buds under the bark of stems and branches. Normally growth inhibitors, produced in the crown of a tree, keep these buds in a dormant condition. If the tissue which produces these inhibitors is killed, epicormic shoots will emerge from undamaged buds. According to Luke and McArthur (1978, p. 123), trees which have less than half their foliage scorched are not likely to produce epicormic shoots or to lose diameter or volume increment.

It is pointed out by Brown and Davis (1973, p. 57) that the fact that a tree is relatively fire-resistant does not mean that it is not susceptible to damage. Specific fire effects on trees consist of:

- Physical damage to the tree, which includes wounding of the bole.
- Damage by disease and insects induced by fire injury.

Apart from crown condition, visible fire damage may often take the form of dead epicormic shoots, exposed “dry sides” or boles hollowed by a succession of fires. Secondary damage effects in the form of occluded scars, gum veins and gum pockets or “pipes” caused by termites or rot, must await the conversion of the tree to timber. Loss due to quality degrade may then be as important as loss of volume when assessing total fire effects.

Both *P. caribaea* and *P. elliottii* are remarkably fire resistant pine species (McArthur, 1971, p. 19). Unlike most coniferous species they can withstand complete scorch of the green crown and still develop a new crown within a short period of time, provided the terminal shoot is not destroyed. However, when fully scorched, loss of increment occurs for one or more years depending on the intensity of the fire. Age, site quality and the seasonal conditions following the fire after crown recovery, all affect the subsequent growth of the stand, but generally increment rates will return to pre-fire levels within three years (McArthur, 1971, p. 22).

Brown and Davis (1973, p. 60) state that the most serious aspect of fire injury to living trees is that it often increases susceptibility to disease and insect attack. These relationships are exceedingly widespread, common and complex.

According to McArthur (1971, p. 20) damage resulting from prescribed burning generally has no adverse effect on subsequent growth of the stand and growth rates are frequently increased on sites with a low nutrient status. This is also confirmed by Wolffsohn, 1980, p. 27).

2.6.3 Effects of wildfires on the soil

Fire may affect the physical and chemical characteristics of the soil, indirectly influencing the composition or growth rate of the protective ground flora, water yield, water-holding properties and the capacity of soil to resist erosion (Luke and McArthur, 1978, p. 127).

Brown and Davis (1973, p. 63) mention the following factors controlling the effects of fire on soil:

- Frequency of fire: The frequency of fires is highly important as their effects are cumulative in varying degrees. A single fire may have a small effect on the soil but a sequence of two or more fires in fairly close succession may have substantial soil effects.

- Heat intensity and duration: Both these factors are determined by fuel type, topography and wind. This is supported by Neary *et.al.* 1999, p. 54. The component of fire severity that results in the greatest below ground damage to ecosystems, and hence recovery, is duration of the fire. Fast moving fires may be intense in terms of energy release per unit area, but do not transfer the same amounts of heat to the forest floor as slow-moving fires.

- Forest floor: The presence or absence of duff, humus and other unincorporated organic material in the forest floor and the amount of it consumed are of key importance in appraising soil effects. Changes in the organic layer also affect the chemical materials that infiltrate the mineral soil.

- Soil characteristics: The physical characteristics of the soil below the duff layer strongly influence the effects of fire. These include particle size, texture and structure, which in turn are modified in their effect by their moisture content and the organic content of the soil. According to Chandler *et al.,* (1983a, p. 171) the moisture contents of litter and duff layers are usually more important than the moisture of the mineral soil itself. If moisture gradients are so steep that the surface litter will burn but the lower layers of duff will not, the soil temperature, even at the surface, remains below 100°C with the result that there are virtually no effects on soil chemistry or physics.

It is generally considered that the temperature of the soil must reach at least 200°C before the physical properties of soil are altered. Heat penetration experiments by the FRI, Canberra, showed that while the temperature at the soil surface reached 350°C the maximum reading 13 mm below the surface was 90°C in a light prescribed burn (Luke and McArthur, 1978, p. 127). When a large windrow was burnt, the fuel flamed for 2.5 hours and glowed for 12 hours. Temperature peaks reached were 350°C at the soil surface after three hours, and 130°C at a depth of 50 mm after nine hours. Luke and McArthur (1978, p. 127) concluded that soil heating is of little importance under most Australian conditions when associated with a moving flame front. The extent of damage actually sustained depends on factors such as slope, type of vegetation, soil texture and the intensity and duration of rain after a fire, as well as fire intensity.

Investigations related to the re-establishment of burnt sites have focused on the sometimes spectacular mortality rates produced by *Rhizina undulata* (Germishuizen and Marais, 1980 and Allan and Carlson, 1998).

Burning which consumes only the upper portion of surface litter may have a slight and temporary effect on the capacity of the soil-litter complex to hold water and retard run-off. This may be advantageous or otherwise, depending on local circumstances. Benefits to soil structure could follow from the provision of physical and chemical conditions suited to the life cycles of micro-fauna in their role of breaking down surface litter (De Ronde *et.al.*, 1990, p. 224).

Soil heating may have a considerable influence on the chemical properties of soil. It is believed that the well-known "ash-bed" effect, which promotes rapid plant growth, is due mainly to an increase in the availability of phosphorus induced by heating effect of intense fires. Other nutrients, such as calcium, magnesium, sodium and potassium, are also released by burning, but they may rapidly leach from the soil (Luke and McArthur, 1978, p. 129).

Brown and Davis (1973, p. 76) give the following conclusions regarding effects of fire on soil:

- Specific effects are extremely variable, making generalisations difficult and often misleading. The frequency, duration and intensity of the fire, the presence or absence of an organic mantle and the amount of it consumed, and the character of the mineral soil must be considered.

- Direct heating effects are relatively minor in most situations. Soils are hard to heat with the result that only in extreme conditions direct heating is important.

- The depth of the organic mantle on the mineral soil and the amount consumed are extremely important. Where the organic layer is heavy and dry enough to burn, the effect on the underlying soil and on the site in general may be very destructive.

- Changes in micro-climate and vegetation following burning have significant soil effects, often more important and usually of longer duration than the immediate heat and chemical effects of burning.

- Physical soil effects, especially from repeated fires, are generally unfavourable. Erosion of unstable soils in hilly or mountainous areas is usually the most serious result.

- Chemical effects tend to be favourable but not strictly so, and are seldom a justification for burning.

- There is a tendency to over-emphasise the unfavourable effects of fire on mineral soil by stressing extreme situations in frequency and intensity of burning. It must be recognised that many fires have little overal effect on the soil one way or another. Only some are beneficial. This fact permits a fairly wide range of choice in using fire in particular situations as a tool in forest management without risking significant soil damage.

The regulation of stream flow and maintenance of water quality are important issues which must be considered when planning/controlling fires.

Severe fires, such as wildfire and slash pile fires, can sterilise the upper soil and change soil properties. However, re-inoculation by windblown dust and debris soon follows. When moisture is sufficient, microbial populations can increase for a few weeks until an equilibrium is reached (Chandler *et al.*, 1983a, p. 180).

Forest fires also affect air quality and emission rates are in an inverse proportion to the reaction intensity of the fire. Emission rates are about eight times higher during the smouldering phase of a fire than during the flaming phase. Chandler *et al.,* (1983, p. 193) also mention that because in head fires the flaming phase moves rapidly through the fuelbed, leaving a greater amount of fuel for residual smouldering, emissions from headfires are about three times more than those of backing fires where flaming combustion is less intense but more complete. As a rule of thumb, particulate emissions will be 10 kg/tonne of fuel burned for fuel loadings up to 5 tonnes per hectare for both backing and heading fires. For higher fuel loadings multiply (for headfires) or divide (for backing fires) by 0.2 times the total fuel loading.

Mop-up is critical in avoiding smoke pollution. Smouldering material has eight times the particulate emission rate of flaming fuel. Much of the smouldering occurs after the convective lift phase of the fire and smoke is adverted close to the ground. Smouldering often occurs during the evening and night hours when the atmosphere is at its most stable and there is a minimum of turbulence and dilution of pollutants (Ward, 2001, p. 62 and DeBano *et al*. 1998, p. 253).

2.7 FIRE BREAKS AND FUEL REDUCTION

2.7.1 Introduction

The concept behind fuel management is simple. To modify fuels (hazard) is to modulate fire behaviour, fire effects and the cost of fire suppression. It specifically focuses on preventing fires through control of the quantity, arrangement, continuity, ignitability, or burning rate of forest fuels. Though such measures are potentially costly, the principles and techniques come entirely within the scope of land-management actions on the ground.

Pinchot (1900) published the following about fire lines over a hundred years ago:

> *"Fire lines – strips kept free from all inflammable material by burning or otherwise – are very useful in checking small fires and of great value as lines of defence in fighting large ones."*

Fuel modification may come through a process of

a) reduction, in which the load of available fuel is decreased.
b) conversion, by which certain fuels are replaced by others with different flammability, and
c) isolation, through which large expanses of fuels are broken up with fuelbreaks or greenbelts.

Fuel quantity and fuel distribution are the major variables affecting fire behaviour in any area, and is an essential part of sound fire control planning to have the more difficult fuel types clearly indicated on management plans (McArthur, 1971, p. 25).

In forest fire terminology, hazard is defined as that part of the fire danger contributed by the fuels available for burning. It follows then that hazard reduction is synonymous with fuel treatment. Fuels can be modified in many ways to reduce hazard. (Chandler, *et. al*., 1983a, p. 87). Hazard reductions is best considered in terms of local reduction (firebreaks) or area reduction (Wolffsohn, 1980, p. 23).

Fuel may be isolated by barriers such as firebreaks or reduced in volume by burning or physical removal. Compactness of fuels may be increased by chipping/slashing. Their vertical continuity may be disrupted by pruning and the moisture content be increased by irrigation or removal of dead material. Fuel chemistry may be altered by species manipulation. Each of these methods of treatment has its advantages and disadvantages and each should be considered in developing a balanced fuel management programme (Chandler *et al*., 1983b, p. 88).

Brown and Davis (1973, p. 301) mention the following classifications, of which some will be discussed in more detail later in this chapter:

- Removal of all ignitable fuel in limited areas of special risk, e.g. around sawmill incinerators, rubbish dumps.
- Removal of all fuel in a strip close to or around the source of risk in order to confine any fire that may be ignited to a small isolated area, e.g. along public roads.
- Removal of fuel in a strip where the purpose is to exclude fire from a high-value or high-hazard area, firebreaks around a forest plantation are a typical example.
- Removal of fuels to reinforce natural breaks and to create new ones by which an area can be broken up into blocks to facilitate control of wildfires, e.g. internal firebreaks.
- Use of prescribed burning, when coarse and intermediate fuels are moist, to safely remove flash fuels from considerable areas.
- Breaking the vertical continuity of fuels and the horizontal continuity of tree crowns in coniferous stands by cultural measures such as pruning and thinning and the removal of undergrowth.
- The removal of dead trees that would throw spot fires if ignited.

The application of fuel (hazard) reduction measures requires decisions based on careful evaluation and planning. High risk and high fuel hazards cannot be allowed to persist where high values are at stake because of the near certainty of disastrous fire losses. It is often more feasible to treat the fuel than to reduce the risk to a safe point. Hazard reduction must be considered in relation to the fire control organisation as regards its detection efficiency, speed and strength of attack and protection costs. Hazard-reduction work is expensive (Davis, 1959, p. 263).

2.7.2 Fuels in commercial plantations

2.7.2.1 Introduction

When native vegetation is cleared for establishing plantations, the increase in sunlight results in an increase in low vegetation. Intensive forestry practices may further increase undisturbed fuel accumulation rates and especially conifers which contain resins and waxes result in fuels that are difficult to manage.

2.7.2.2 Fuel reduction

Fuel reduction is a generic term which describes programmes that seek to reduce fire hazard (fire intensity) through the diminution of available fuels. Fuel reduction programmes may be broadcast or site-specific, irregular or periodic (Pyne, 1984, p. 314). To be effective, reduction must keep pace with accumulation.

If fuels result from human activity – harvesting or road construction for example – then a programme of systematic reduction can be designed to follow upon it. If the fuels are the product of natural accumulation – periodic broadcast fire can keep fuels within acceptable limits. But fuels accumulate episodically too, and often in great quantities as a result of severe hail damage, windstorms or large fire. Phytomass suddenly becomes fuel.

McArthur (1971, p. 20) also states that young plantations, especially when associated with heavy accumulations of grasses, are extremely vulnerable to fire. The danger of large fire losses would be greatest in the first three years of a plantation (compartment).

A range of techniques for fuel reduction exists, according to Pyne (1984, p. 314). For broadcast fuels that accumulate as a result of natural processes – broadcast treatment is needed, and practically speaking this means fire. For activity fuels, limited to specific sites and one-time processing, prescribed burning, intensive utilisation of residue and conversion of the debris into chips could be selected.

Slash (plantation residue) must often be reduced to facilitate soil preparation and planting. Methods commonly used in South Africa include windrowing, stump shearing or chipping and roller chopping and burning. However, a “no burning” policy should be practised whenever possible according to Theron (2000).

Mechanical treatment may be a prelude to prescribed fire or it may, like increased suppression capabilities for the site, act as an alternative to it. The idea is that slash does not maintain its hazard forever. After a few years its potential flammability is greatly reduced by changes in the composition and bulk density of the fuel complex. Crushing slash accelerates this natural process of physical decomposition (Pyne 1984, p. 316).

Litter decomposition rates are slow and heavy accumulations of inflammable fuel builds up rapidly. Not only is the rate of fuel accumulation high but the distribution of the fuel near ground level produces a highly aerated fuel bed, leading to high combustion rates. *P. elliottii* and *P. caribaea* are also resinous and the persistence of dead stem needles for a considerable period of time creates a problem of "torching" when fires occur in these stands. "Torching" allows the fire to travel up the stem of the tree and is liable to cause high scorch heights and in some cases serious wounding of the tree if the fire persists for any length of time in resin pockets (McArthur, 1971, p. 25).

The heavy accumulation of fuel in *P. caribaea* and the species' inherent resistance to fire dictate that hazard reduction measures should become an integrated part of forest management. In practice it has been found that if fuel quantities can be kept below 12.25 ton/ha, severe fire suppression problems should not develop in coniferous plantations.

Brown and Davis (1973) also mention that fire hazard in an area increases greatly following timber cutting primarily because a large volume of the finer and potentially flammable fuels from the tree crowns lose most of their moisture and are concentrated on the ground surface. The increased hazard of slash disposal can be controlled by the following conditions, according to Brown and Davis (1973, p. 313):

- The quantity of slash created is affected by species, method of logging and utilisation of tree lengths.
- The distribution of slash is also a function of species and method of harvesting.
- The flammability of slash. There are substantial differences due to arrangements of the slash and slash that is flattened to place it in close contact with the ground, has a higher moisture content and kindling fuels are less effective.
- Duration of the hazard. Tree species and environments differ markedly in this respect.
- Micro-climatic changes resulting from more open land conditions. This includes higher surface temperatures, increased air movement near the ground and marked changes in surface vegetation. Together such changes may exert a larger total effect on hazard than the slash itself.

- The size of the area clearfelled. In general, the larger the area, the greater the total hazard.

After exploitation, site preparation by ploughing should be considered for the combined silvicultural and hazard reduction benefits which may be derived from it (Wolffsohn, 1980, p. 25).

2.7.2.3 Fuel conversion

The concept of fire management through fuel type conversion is a tested, venerable one, according to Pyne (1984). By and large, however, broadcast conversion solely on the grounds of fire control is rarely justified. Even when the cover type remains forested, the conversion from one dominant species to another is common, for example pine to eucalypts. Where reforestation or afforestation takes place, the increase in flammability may be large.

Breaking the vertical continuity of fuels and the horizontal continuity of tree crowns in coniferous stands by silvicultural measures, such as pruning and thinning, is another important aspect of fuel conversion. McArthur (1971) is of the opinion that pruning is one of the basic requirements of sound plantation fire control management.

According to McArthur (1971) the difference in fire behaviour and rate of spread between pruned and unpruned plantations is well documented. As a general rule of thumb, rates of spread are at least double in an unpruned plantation compared to those in a pruned plantation for a given set of meteorological conditions. This suggests that suppression difficulty would be increased by a factor of four or five in the unpruned plantation.

2.7.2.4 Fuel isolation

Fuel isolation is to segregate high hazard fuels from high value resources, or to break up the continuity of high hazard fuels. In fuel reduction, the objective is to prevent the site from becoming a source for fire. In fuel isolation the objective is to prevent fire from entering or leaving the site.

If the objective is to make fuel complexes more manageable on a larger scale, then fuels can be isolated into predetermined blocks through selective modification along strips – fuel breaks or green belts (Pyne, 1984, p. 317).

The term "firebreak" can be used to include natural firebreaks, such as gallery forest and artificial features such as roads which, though they may function as firebreaks, are not primarily designed for this purpose. Permanent firebreaks are designed to protect the edge of the forest from fires starting outside it, to isolate places of high risk or hazard and to break up a forest so as to restrict the spread of fires within it (Wolffsohn 1980, p. 23).

A fuelbreak is a strategically located wide block, or strip, on which a cover of dense, heavy, or flammable vegetation has been permanently changed to one of lower fuel volume or reduced flammability. It also differs from a fireline and firebreak on which all vegetation is removed down to mineral soil.

Fuelbreaks are never designed to stop fires but to allow suppression forces a higher probability of successfully attacking a wildfire. The amount of technology directed at the fire, and the requirement for firefighter safety, both affect the efficacy of fuelbreaks in the suppression effort.

Firebelts (firebreaks) serve a variety of fire control purposes – improving access to remote areas, creating lines for indirect control according to pre-attack blocks, and as safety zones for firefighters. However, firebreaks have several limitations.

The fundamental paradox is that they are most justified for the control of large fires, for which indirect attack methods are appropriate. But large fires require wide fuel breaks, increasing installation and maintenance costs, and large fires do not propagate solely along the surface. No fuelbreak can be wide enough to halt the long-range spotting that will almost certainly accompany high-intensity fires.

Firebreaks consist of one or both of the following elements:

- A fuel-free strip, usually established mechanically;
- A strip in which the type or quantity of fuel has been so modified that it will ignite less readily or, if it ignites, will not burn so intensely or produce so many airborne firebrands as the adjacent species. This may be achieved by silvicultural means, by grazing, by prescribed burning or by a combination of these (Wolffsohn, 1980, p. 23).

The location of firebreaks is determined largely by risk. Firebreaks directed at specific risks are generally established at the following locations:

- At the edge of the forest. If, adjacent to the forest, there are areas of hazardous fuels in which fire control is absent or inadequate, a perimeter firebreak is most desirable.
- Around populated centres. Fires from burning rubbish, children playing with matches, etc. constitute main risks.
- Around sawmills and especially around piles of sawmill waste, whether it is intended to burn these or not.
- Along roadsides.
- Around agricultural fields on which burning is to be done for site preparation or for stubble removal.
- Around areas of particularly hazardous fuels.

The minimum width is that required to prevent ignition by direct radiation, the maximum is not well defined but should be greater than the potential horizontal length of flame to be expected at the head of a fire (Brown and Davis, 1973). When fire danger is high, and fire is burning in heavy mixed fuels, particularly up slopes or with a strong wind, this width can become prohibitive for a constructed firebreak. However, the effective width can be increased at least 50 percent by reducing the angle between the axis of direction of spread and that of the firebreak as illustrated in Figure 2.29.

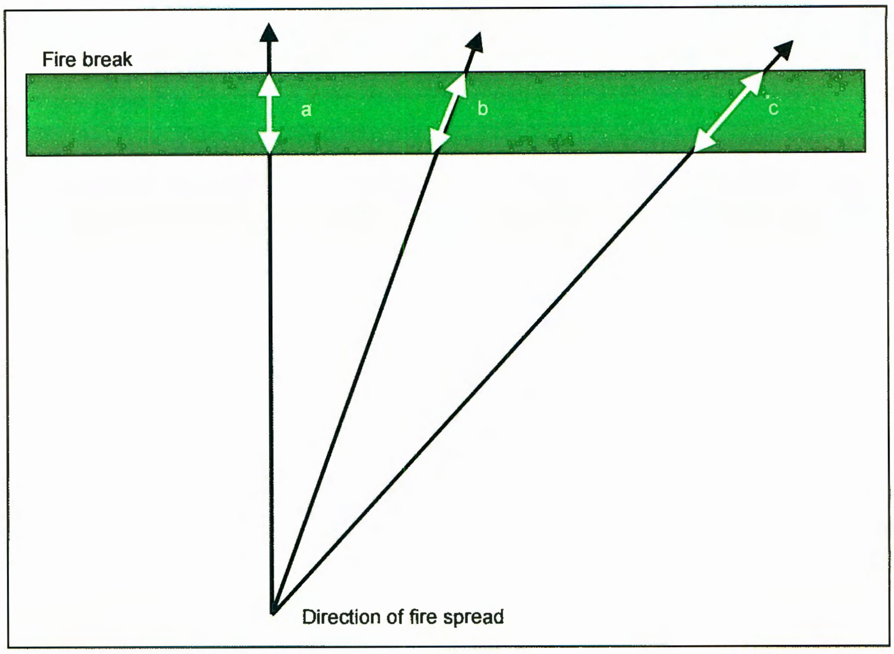


Figure 2.29: ***Effect of angles of approach of a fire on effective width of a firebreak***

(Brown and Davis, 1973)

All barriers, artificial or natural, need to be taken into account in planning control strategy. Roads, streams, water bodies, swamps, interspersed agricultural lands, cover types of naturally low flammability and topography all may constitute important natural barriers to the spread of fire in particular situations.

Where the terrain is hilly or undulating, firebreaks are best sited on the tops of ridges and it is better that they should not run at right angles to steep contours. Accessibility should be considered in siting a firebreak and, where possible, the functions of road and firebreak should be combined.

A greenbelt is a slightly different version of the fuelbreak and is especially relevant for the boundary between forests and suburbs (urban-interface). Orchards, parks, golf courses are all examples of greenbelts that can combine open space, recreational use, or agricultural production with fire protection (Agee *et. al.,* 2000, p. 55).

Also in South Africa, new settlements are deliberately located in natural areas, plantations, etc., and generally resist extensive modification of the vegetative cover.

In these circumstances, fuel management is the only reasonable foundation for fire protection.

Additional to this, building codes can specify non-flammable roofs, fire codes can promulgate standards for clearing debris from around structures, and fuelbreaks or greenbelts can form a protective perimeter around the area (Pyne, 1984).

The crucial question is how much fuel modification should be done and where to reduce total hazard to a tolerable level measured in terms of the ability of a fire control organisation to cope with fires that may occur.

2.7.2.5 Prescribed burning

The use of fire in land management has many applications. The term "prescribed burning" refers to the use of fire to achieve planned land and resource management objectives. Prescribed burning is conducted at certain times of the year, and aims to achieve specific heat intensities and rates of spread according to the desired management objectives (Higgs, 1995). Prescribed burning generally is done for: fuel management, flora and fauna management and in commercial forest management.

The skilful combination of lighting pattern, timing, use of topography, weather and fuel conditions is the key to successful prescribed burning (Tolhurst and Cheney, 1999, p. 79).

Prescribed burning by backfire is carried out by enclosing the area with firebreaks, cleaning a series of parallel lines at right angles to the wind direction and the starting with the line furthest to leeward, lighting a strip fire along the windward edge of each internal line. These lines are called control lines by Tolhurst and Cheney (1999, p. 9).

Once an adequate width has been burned along the leeward edge, and all smouldering material in it has been extinguished, burning can continue with only a very small force at each end of the fire front to prevent it escaping to the flanks (Wolffsohn, 1980, p. 26).

Prescribed burning is a complex tool. Proper diagnosis and detailed planning is mandatory before every burn. An incomplete assessment of any factor in a plan can lead to serious loss of property and life with serious liability questions.

A first burn is normally done with a backfire so as to avoid excessive damage to the young trees. Moreover, since a backfire moves more slowly and generally produces higher temperatures at ground level than a headfire, it is more efficient in litter consumption. The decision to burn depends on the size of the area to be burned, prevailing weather, objectives of each burn and the availability of resources.

The ignition pattern chosen is critical to the success of a prescribed burn. The fire intensity can be reduced by a factor of five compared to a line of running fire. Tolhurst and Cheney (1999, p. 80) also mention that the ignition pattern often needs to be varied according to the weather, fuel and topographic conditions within a single burn (Figure 2.30).

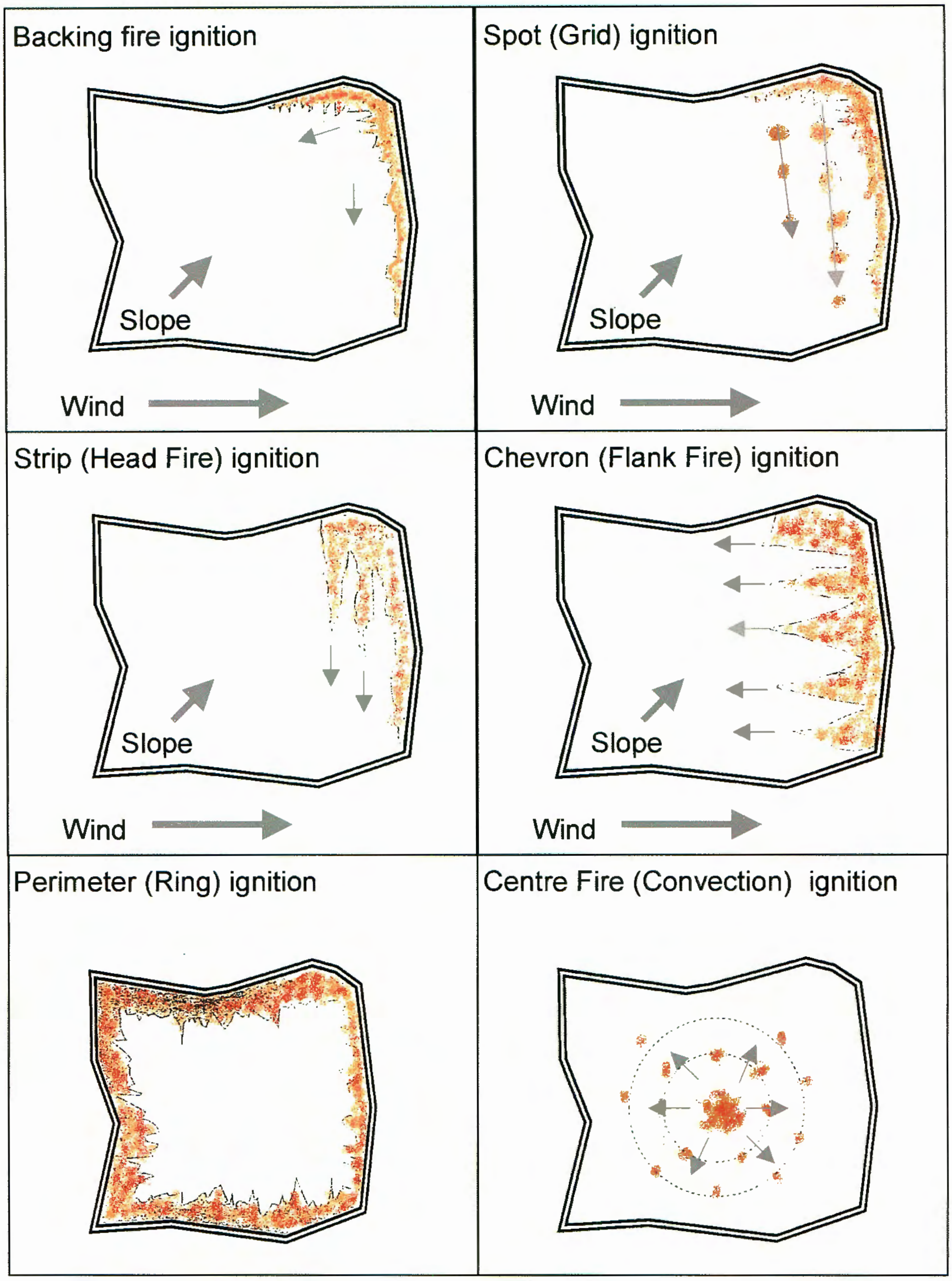


Figure 2.30:* *Some common ignition patterns used for prescribed burning. Small arrows show the direction of lighting, not the direction of fire spread

(Tolhurst and Cheney, 1999, p. 82)

Fire was once considered a cheap form of site preparation for fuel reduction, but this is no longer true. The requirements for fire-breaks, staff and machinery, and the risk of damage to surrounding stands are often unacceptable (Maclaren 1996, p. 115). There are at least three environmental consequences of fire. The first is air pollution from smoke and its effect on road safety, human health, tourism and the lifestyle of local residents. The second effect of burning is the flux of released nutrients to rivers, which can persist for several months or even years. The third consideration is the long-term effects on the soil. While there are undoubtedly gains in short-term productivity from burning, long-term fertility can be reduced. According to Maclaren (1996, p. 116) nitrogen, sulphur and phosphorus are volatilised and lost from the site. Other nutrients are converted to more mobile forms which can be lost to the waterway.

In a prescribed burning study in the USA with *P. elliottii* and *P. taeda* the following results were obtained regarding soil fertility:

- Burning was found to have had no deleterious effect on organic matter or nitrogen in surface mineral soil.
- It consistently increased the amount of available phosphorus.
- Exchangeable potassium was not altered by burning treatments.
- Exchangeable calcium concentrations increased slightly after burning.

(McKee, 1982)

Because of the greater exposure and hence more rapid drying near the edges of pine stands, it is often desirable to burn the portions near the edges with a lower intensity fire than that used in the remainder of the stand. Further, wind eddies near edges may result in unexpected fire behaviour and, for this reason such places should be burned cautiously. Wind exerts a very important influence and burning should not be carried out on days of changeable wind speed or direction. Burning should also be avoided on calm days since flames will then rise straight up and are likely to do considerable damage to the crowns. Although increasing wind speeds produce faster rates of spread and higher intensities in headfires, they also flatten the flames, thereby reducing temperatures in the crowns (Wolffsohn, 1980, p. 26). According to

Wolffsohn (1980) winds of 6.4 to 16 km/hour measured near ground level, is recommended for backfires. For headfires winds of 3.2 to 8 km/hour are recommended.

Some grass species like *Setaria chevaleiri* are stimulated by fire and grow and spread very prolifically after fire. Occasionally, burning stimulates growth of fungi such as *Rhizina undulata* that may attack and kill *Pinus* seedlings.

When the area is burnt about six months before planting at the beginning of the dry season, the risk of seedling mortality from fungi is reduced. However, if left unplanted this long, the advantage of cleared land is lost because weed species colonise the burnt area very rapidly (Zobel, Van Wyk and Stahl, 1987).

Mortality is much influenced by weather conditions at the time of burning, the season of burning and the interval between burning and re-planting (Poynton, 1977, p. 327). Prescribed burns are also undertaken in older plantations, especially with species that can withstand fire, such as *P. caribaea* or *P. elliottii* (Zobel, Van Wyk and Stahl, 1987; and De Ronde, 1982).

P. taeda and *P.elliottii* at maturity suffers little from ground fires (Poynton, 1977, p. 486). Although prescribed burning is at present only applied on a limited scale, research programmes proved beyond doubt that selective application could provide the required results without harmful effects to the trees and ecosystem (de Ronde, 1994).

The immediate effect of fire on the appearance of a burned-over area is always unfavourable, but the longer-term effect of fire is quite often a more attractive appearance. It eliminates dead material, clears out heavy undergrowth and creates forest openings.

A good cleanup of slash fuels carries value far beyond the direct advantage of fire fighting as it enhances all recreational value and is favourable to game and forage. As stated by Brown and Davis (1973), maintenance of a favourable forest environment through control of fuel hazards depends primarily on the landowner.

The degree to which he assumes this responsibility reflects the quality of his stewardship.

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CHAPTER 3: STATISTICAL ANALYSIS OF THE FIRE DATA

3.1 INTRODUCTION

A comprehensive analysis of fires in privately-owned plantations in South Africa was done by Le Roux (1988), covering a 6-year period (1979 – 1985) and 1 596 fire reports. Later a similar study was done by Kromhout (1990) on 1 607 fires over a four year period (1985 – 1989).

As Komatiland Forests is in the process of privatisation, historical fire reports may be lost due to restructuring and personnel changes. For this reason all the fire reports in the KLF Mpumalanga (Sabie) office were collected and entered into a database.

The fire risk for the study area is average compared to other forestry regions in South Africa and Van der Sijde (2000) found the average annual area burnt per 1 000 ha plantation to be 4.2 ha for the period 1994 – 2000. Le Roux (1988) stated it to be 3.3 ha, compared to 11.2 ha for the Natal Midlands and 5.5 ha of the Southern Transvaal Highveld, while Kromhout (1990) reported the average annual area burnt per 1 000 ha plantation for the Sabie area as 1.36 ha. These figures will change considerably after the severe fires experienced during the 2003 fire season.

In the present study records of 846 fires have been captured for eight plantations in the Mpumalanga Escarpment area. The data used represented fire information collected over a period of 49 years (September 1950 to November 1999). No records exist for 1951 and 1952.

The fire reports are divided into three subsets as the information collected differed over the four decades, due to format changes.

Subset 1 contains the majority of the fire reports and consists of 576 fire reports, all in commercial plantations (1970— 1999).

Subset 2 is all the fires that occurred in open areas, catchment management areas or indigenous forests where no compartment details could be attached to the incidence. Ninety one fires were recorded in open areas (1970— 1999).

Subset 3 consists of a separate collection of fire reports as was compiled by a student forester in Mpumalanga, G Hilligan in 1974. Unfortunately the data collected differed so much from subset 1 information that the data had to be grouped separately. This subset has 179 fire reports and the main differences from Subset 1 are that no compartment number was recorded for this data set, as well as response time, fire fighting time or compartment details (1950—1970).

Database	Number of fires recorded
Subset 1 (Main)	576
Subset 2 (Open land)	91
Subset 3 (Hilligan)	179
Total	**846**

Some of the data variables had to be grouped into categories for easy processing and in order to develop workable management processes. The categories developed were:

Cause of fire: Lightning
Honey hunters
People related (smoking, picnickers, arson and "unknown")
Work related (burning of fire breaks, tracers, warming fires)

Fire season:	High	(July – October)
	Low	(November – February)
	Medium	(March – June)
Time of day:	Morning	(03h00 – 09h59)
	Day	(10h00 – 17h59)
	Night	(18h00 – 02h59)

3.2 STATISTICAL ANALYSIS OF HISTORIC FIRE RECORDS

3.2.1 Plantations included in the study area and number of fires

The KLF plantations for which fires were recorded are as follows:

Table 3.1: Number of fires per plantation

Plantation name	Number of fires recorded
Bergvliet	147
Blyde	47
Brooklands	172
Frankfort	50
Morgenzon	36
Spitskop	70
Tweefontein	245
Wilgeboom	79
Total	**846**

During the period 1970 to 1999 several amalgamations and plantation merges took place and for record purposes the old and current plantation details are given in the following table:

Table 3.2: Old and current plantation names

Old plantation name	Current plantation name
1. Frankfort	1. Frankfort
2. Blyde	2. Blyde
3. Brooklands	3. Brooklands
4. Rosehaugh	Brooklands
5. Tweefontein	4. Tweefontein
6. Mac Mac	Tweefontein
7. Wilgeboom	5. Wilgeboom
8. Mariti	Wilgeboom
9. Ceylon	Tweefontein
10. Bergvliet	6. Bergvliet
11. Witwater	Bergvliet
12. Spitskop	7. Spitskop
13. Long Tom	Tweefontein
14. Morgenzon	8. Morgenzon

From Table 3.2 it can be seen that the original 14 KLF plantations around Sabie were now consolidated into eight plantations. From the number of fires recorded (Table 3.1), it is clear that Tweefontein had the highest fire incidence followed by Brooklands and Bergvliet.

3.2.2 Compartment and plantation block details

Compartment numbers were recorded where fires started in subset 1, not for fires in open areas or the data collected by Hilligan (subsets 2 and 3).

As plantations were merged in the past, compartment numbers also changed. For this reason the new compartment number had to be recorded to correlate with the current COMPAS plantation database. Compas is a computerised plantation management system used by KLF for calculating plantation volumes. Plantation, block and compartment details changed as in Table 3.3.

Table 3.3: Old and current plantation block numbers

	Rosehaugh		**Brooklands**	
Block Numbers	A		H	Block Numbers
	B		J	
	C		K	
	D		L	
	E		M	
	F		N	
	G		O	
	H		P	
	J		R	
	Mariti		**Wilgeboom**	
Block Numbers	A		F	Block Numbers
	B		G	
	C		H	
	D		J	
	E		K	
	F		L	
	Witwater		**Bergvliet**	
Block Numbers	A		G	Block Numbers
	B		H	
	C		J	
	D		K	
	E		L	
	Rietfontein	**Frankfort**	**Bergvliet**	
Block Numbers	A	C		Block Numbers
	B		D	
	C		F	
	D	D		
	Mac Mac		**Tweefontein**	
Block Numbers	A		J	Block Numbers
	B		K	
	C		L	
	D		M	
	E		N	
	Long Tom		**Tweefontein**	
Block Numbers			X	Block Numbers
	Ceylon		**Tweefontein**	
Block Numbers	A		P	Block Numbers
	B		R	
	C		S	
	D		T	
	E		U	
	F		V	
	G		W	

3.2.3 Species

Although 846 fire reports were collected, very little information could be derived regarding species. Given the fact that the main species planted are pines, e.g. *P. patula* and *P. elliottii,* it is not surprising that it correlates with the number of fires per species, as shown in Table 3.4.

Khaya nyasica and *Gmelina arborea* were only planted for a few years and clearfelled due to poor growth. Several other species also occur in very small quantities, e.g. *Populus* and *Quercus.* Many of the pine and eucalyptus species are also no longer planted on a commercial scale in Komatiland Forests (Marked with a * in Table 3.4)

Most fires started in *P.patula* compartments, followed by *P.elliottii* and *P.taeda*. This corresponds with the area planted per species. Thirty eight fires (5.7%) occurred in temporary unplanted areas. A total of 9 866 ha was damaged by 846 fires over the 47 year period. The extinguishing cost to suppress the 846 fires amounted to R5,3 million. The 2001 cost (a Production Price Index (PPI) was used in calculations and is discussed in more detail in paragraph 3.2.7).

Table 3.4: Fire frequency, area burnt and extinguishing costs per species

Species	Fire frequency	Area burnt (ha)	Cost (R)	Area planted (ha) as in July 1998
Cupressus lusitanica *	1	0	363	0.74
Eucalyptus cloeziana	6	3	8 265	21.73
Eucalyptus fastigata *	5	4	215 392	38.22
Eucalyptus globulus *	2	0	1 383	0.65
Eucalyptus grandis	71	267	602 199	4 460.56
Eucalyptus obliqua *	2	0	1 031	0
Eucalyptus paniculata *	4	0	6 896	26.75
Eucalyptus radiata *	2	13	7 429	0
Eucalyptus saligna *	5	15	12 145	0.61
Gmelina arborea *	1	0	87	0
Khaya nyasica	1	0	676	5.06
Pinus cubensis *	2	0	1 251	4.31
Pinus elliottii	108	461	630 829	16 166.59
Pinus greggii	1	2	6 430	208.37
Pinus oocarpa *	7	1	2 087	147.38
Pinus palustris *	2	0	1 356	0
Pinus patula	203	1 492	1 792 695	17 471.66
Pinus pseudostrobus *	5	7	18 094	45.35
Pinus roxburghii *	1	11	13 663	0
Pinus taeda	100	219	424 290	8 016.86
Pinus teocote *	3	0	12 728	0
Populus deltoides *	5	7	18 513	30.47
Quercus serotina *	1	0	250	8.01
Temporary unplanted	38	410	739 852	565.18
No species information	270	6 951	832 500	-
Grand Total	**846**	**9 866**	**5 350 403**	

* No longer commercially planted

The fire data in the Hilligan subset (179 fire reports) and the information in the Open land subset (91 fire reports) were grouped into the no species information column in Table 3.4.

3.2.4 Number of fires and area burnt per year (1950 – 1999)

Table 3.5: Number of fires and area burnt per year

Year	Area burnt (ha)	Number of fires
1950	19.9	10
1953	4.2	2
1954	4.6	7
1955	2.2	9
1956	0.6	6
1958	2.4	1
1959	0.9	8
1960	1.8	8
1961	9.2	4
1962	168.5	12
1963	14.2	7
1964	158.7	15
1965	105.6	29
1966	7.5	22
1967	2.2	12
1968	75.5	13
1969	1.9	6
1970	8.3	10
1971	114.7	5
1972	536.4	11
1973	163.5	15
1974	63.2	21
1975	11.5	15
1976	8.2	17

Year	Area burnt (ha)	Number of fires
1977	428.8	20
1978	3,040.8	27
1979	52.5	21
1980	31.0	27
1981	1,216.8	35
1982	624.9	53
1983	115.5	45
1984	7.0	16
1985	24.3	27
1986	87.7	46
1987	362.4	24
1988	15.4	23
1989	6.2	18
1990	147.7	20
1991	35.1	17
1992	13.8	15
1993	21.1	11
1994	1,515.5	27
1995	278.5	27
1996	81.7	21
1997	181.0	31
1998	90.8	25
1999	2.3	5
Total	9 866.3	846

The total area burnt over the 47 year period is 9 866.3 ha or 209.9 ha per annum on average. The worst year was 1978 when 3 040 ha was destroyed, or 30% of the total burnt area (Table 3.5). The average number of fires per annum was 18 and the highest number of fires per annum was 53 fires in 1982 (which resulted in a total burnt area of only 624.9 ha). The area burnt and number of fires per annum are shown graphically in Figure 3.1.

The analysis of the number of fires per year showed that there is a positive trend. The following table shows the ANOVA results for the linear regressions:

Table 3.6 Analysis of variance of the frequency of fires per annum

Source	n	R^2	MSE	F	p
Number of fires	47	0.27	98.62	17.23	<0.05
Area burnt	47	0.029	263 952	1.35	0.25

Although the trend is positive for the number of fires per annum, the fit of the linear model is relatively poor as shown by the low R^2 value. The low R^2 is a result of the high fluctuations in fire frequency over time. The analysis of the area burnt per year showed that the linear model is not significant due to the high variation over time.

3.2.5 Date of fires

The date represents the exact date on which the fire occurred. From the date other variables were derived, e.g. day of the week and month.

3.2.5.1 Number of fires per day of the week

Table 3.7: Number of fires per day of the week

	Fire report				
Day of week	**Main**	**Hilligan**	**Open land**	**Total**	**%**
Monday	89	37	16	142	16.8
Tuesday	93	21	11	125	14.8
Wednesday	81	18	12	111	13.1
Thursday	75	21	8	104	12.3
Friday	69	19	16	104	12.3
Saturday	99	29	7	135	15.9
Sunday	70	34	21	125	14.8
Total	**576**	**179**	**91**	**846**	**100**

The data were analysed to see if any pattern exists between the number of fires and the day of the week. From the information in Table 3.7 no clear relationship is evident. The highest number of fires occurred on Mondays and lowest on Thursdays and Fridays. Number of fires per day of the week compared to different causes will be discussed in paragraph 3.2.6.4.2.

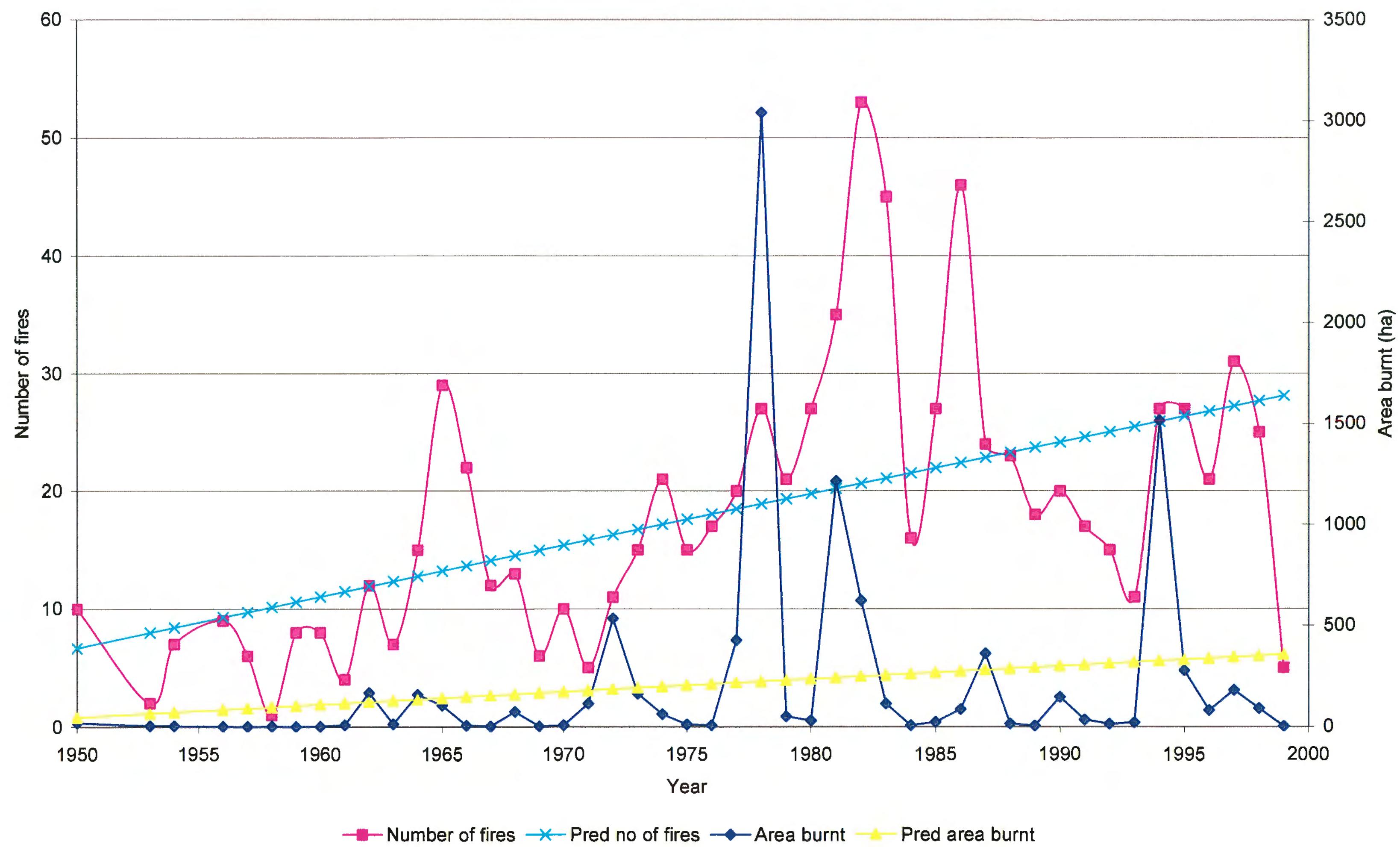

Figure 3.1: ***Number of fires and area burnt per year in study area***

3.2.5.2 Number of fires per month of year

From the date of the fire incident the number of fires per month could be calculated. From Table 3.8 it is clear that there is a very distinct fire season in the study area. About 66% of the total number of fires occurred in the four months, June, July, August and September.

Table 3.8: Number of fires per month of the year (1950 – 1999)

Month of the year	Total number of fires	%
January	22	2.6
February	18	2.1
March	17	2.0
April	14	1.6
May	53	6.3
June	123	14.5
July	140	16.6
August	128	15.2
September	166	19.6
October	85	10.1
November	56	6.6
December	24	2.8
Total	**846**	**100**

A complete table of areas burnt and number of fires per month and per year is provided in Table 3.28. The studies by Le Roux (1988) and Kromhout (1990) showed higher frequencies for both June and July than for September. These results may have been influenced by a high percentage of fires from own burning operations during these months.

The month of September had the highest fire incidence and in paragraph 3.2.6.4.3 month of year was evaluated against different causes. This is possibly due to dry thunderstorm developments before the beginning of the summer rains.

3.2.6 Causes of fires

3.2.6.1 Introduction

Effective fire prevention begins with the identification of problem areas. The exact causes of fires are of great importance since management's actions must address them in order to reduce the risk and impact (Alexandrian, Esnault and Calabri, 1999, p. 35). As in other parts of the world, where a small percentage of fires are of natural origin (especially lightning), the South African Forestry environment is also marked by a prevalence of human-induced fires. Natural causes include lightning and friction due to trees or other objects rubbing together (Luke and McArthur, 1978 and Goldammer, 1990, p. 77).

Natural causes represent only a small percentage of all fires in South Africa (8 — 12%), depending on the geographic area. Soares (1989) in Goldammer (1990, p. 77) analysed 1 754 reported fires in Brazil from 1983 to 1987 and concluded that only 2.1% of the fires were natural, i.e., lightning-caused. Le Roux (1988) found that 12.1% of fires studied were attributable to lightning and Kromhout (1990) calculated lightning to cause 8% of plantation fires. Fuel condition, weather, degree of fire danger and time of day have some relevance in the determination of the actual ignition agency. When factors of this kind are considered in conjunction with a broad assessment of fire causes throughout a region, it becomes possible to devise the general rules and controls which should apply in the months when damaging fires are likely to occur (Reifsnyder, 1960, p. 835).

More specific determinations of causes and the circumstances associated with the starting of fires are desirable when the fire prevention requirements for a district are considered. Motivation may be related to the occupation and ages of persons who cause fires. Even the day of the week could be important. Maps showing the origin of fires help to draw attention to certain patterns of occurrence. Fires frequently occur at the edges of roads, and knowledge of this may be more important than determining the actual means of ignition, whether by matches, cigarettes or other means. By a careful analysis of all such data, local foresters should be able to deal more effectively with the problems of their own areas (Luke and McArthur, 1978, p. 148).

Brown and Davis (1973 p. 264) also mentioned that effective control of each source of risk requires knowledge of how it operates locally and of when and where it is most likely to start fires. To develop such knowledge, analysis of past fire experience in each geographic region is needed. This depends on records of how, why, when and where fires started in the past (Grut, 1965, p. 32).

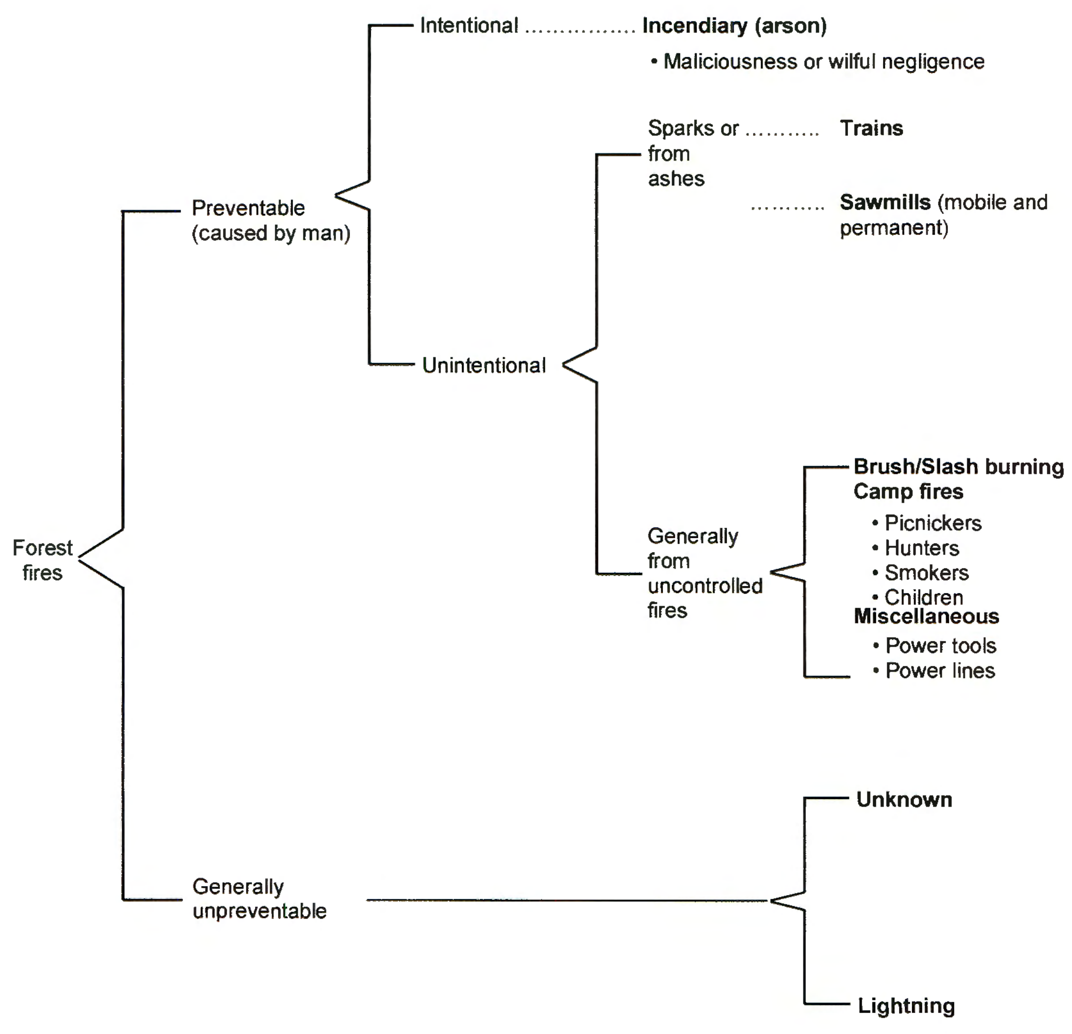

Figure 3.2: Classification of causes of forest fires (Adapted from Plummer, 1912, p. 64)

3.2.6.2 Wildfire causes

The identification of the cause of problem fires is not as simple as it seems. Although statistics help, their effectiveness are limited due to the inaccuracy of the fire investigation and by the processing of information. Causes may be divided into the three main headings: natural causes, deliberate lighting and accidental causes (Luke and McArthur, 1978) and Plummer (1912). Refer to Figure 3.2. A study by Van Wilgen (1981) on fires in fynbos, indicated that they can be divided into wildfires, prescribed fires and burning of fire breaks in natural vegetation.

Forest fires started in other ways than by natural causes may also be classified according to the degree of culpability of the person responsible as malicious, wilful, negligent and accidental (Gordon, 1955).

Malicious fires: Malicious fires or arson is a felony and is not usually dealt with by the forest laws but under the general criminal law of the land. However, forest arson is often carried out in isolated areas, where the chance of witnesses observing the act is slim, and such offenders are rarely caught.

Malicious fires are sometimes acts of revenge, and the prospect of retaliation by incendiarism may profoundly influence the methods by which a forest policy can be carried out. Such fires may be started through the concerted action of a community as a protest against unpopular measures, or on account of real or imaginary grievances of an individual against the forest or member of the forest staff.

In times of unemployment, malicious fires may be set with the object of creating work and trade through harvesting of burnt timber, or even in order to obtain wages from putting out the fire. Where grazing is permitted within a forest area, fires are sometimes set with the object of improving the pasture.

Wilful fires: The expression wilful is used to cover conflagration started deliberately, but without an intention to destroy property. Such fires are commonly started in pursuit of game, to improve the grazing or for the collection of honey.

Negligent fires: This term is used to distinguish cases in which, although the fire itself has been deliberately lit, its subsequent spreading was not intended. Instances are camp and cooking fires, cigarette ends and casual matches.

Accidental fires: Fires can be called truly accidental where neither the original fire nor the subsequent conflagration can be attributed to the deliberate act of anybody. The vast majority of wildfires are caused by carelessness or negligent actions, by burning under unsafe conditions or by inadequate clearance from combustible materials or fuels (Ford, 1995, p. 82).

Although the securing of accurate information about fire causes is often difficult, fire protection organisations cannot hope to develop their prevention work adequately unless efforts are made to obtain as complete a set of data as possible. Even if the circumstances leading to a fire are not known precisely, evidence of its probable cause is preferable to describing it as being of unknown origin (Luke and McArthur, 1978, p. 148).

3.2.6.3 Grouping of fire causes

3.2.6.3.1 General

Classification of causes into groups will differ from country to country, even between forestry companies within a country (Chandler *et al.* 1983, p. 52; Sneeuwjagt, 1998, p. 2155 and Alcázar, *et.al.,* 1998, p. 2379).

According to Brown and Davis (1973, p. 264), eight major cause categories of forest fires have long been used in fire statistics in the US Forest Service. These are campfires, debris burning, incendiary, lightning, lumbering, railroad, smoker and miscellaneous. However, major changes to this classification were adopted after 1964. Railroad fires, which had shrunk in importance, were included in a broader category termed **Equipment**. This includes all fires due to use of machines. The term **Forest utilisation** was substituted for lumbering and was broadened to include harvesting of any forest product. Campfires and debris burning were discontinued and **recreation** and **land occupancy** were substituted.

Causes of problem fires can be categorised according to the list of the US Forest Service (Davis, 1959 and Brown and Davis (1973) as is shown in Table 3.9).

Table 3.9: Grouping of causes of fires: US Forestry Service

Equipment	A fire resulting from use of equipment.
Forest Utilisation	A fire resulting directly from timber harvesting, harvesting other forest products except use of equipment, smoking, and recreation.
Incendiary	A fire wilfully set by anyone to burn vegetation or property not owned or controlled by him and without the consent of the owner or his agent.
Land Occupancy	A fire started as a result of land occupancy for agricultural purposes, industrial establishment, construction, maintenance, and use of rights of way and residences except use of equipment and smoking.
Lightning	A fire caused directly or indirectly be lightning.
Recreation	A fire resulting from recreation use except smoking.
Smoking	A fire caused by smokers, matches, or by burning tobacco in any form.
Miscellaneous	A fire of known cause that cannot be properly classified under any of the other seven standard causes. (Fires of unknown origin are classified under most probable cause and not under Miscellaneous).

The classification of a fire cause as "miscellaneous" is not very useful and is often over-used. With conscientious reporting practices, it is reasonable to expect from the reporter to speculate on the most likely cause, since he is in the best position to analyse the evidence. But when reporting is done by someone other than the "man who was there", the statistics for cause of fires may become distorted as there is a tendency to classify too many fires for which the cause is uncertain into any broad category (Brown and Davis 1973, p.266).

3.2.6.3.2 Causes of fires in the South African Forestry Industry

Within the forestry industry in South Africa a standard fire report form is used and fire groupings of causes are as follows:

- Mechanical
- Own burning activities
- Human element
- Natural causes
- Unknown

Table 3.10 provides the list of 27 fire causes as used by the forestry industry:

Table 3.10: Causes of fires: South African Forestry Industry

Mechanical	Own burning	Human element	Natural cause
Trains	Fire breaks	Arson	Lightning
Chainsaws	Brushwood burning	Contractors	Static electricity
Power lines	Crop residue	Cooking fires	Falling rocks
Power tools	Refuse dumps	Warming fires	
Welding	Sugar cane	Honey hunters	
Blasting	Veld/grazing	Children	
Heavy equipment	Flare-up	Picnickers	
Firearms	Trace burning	Neighbours	

(FFA, 2003)

Le Roux (1988) and Kromhout (1990) identified the following four main causes of plantation fires in South Africa:

Fire cause	Le Roux (1988)	Kromhout (1990)
Incendiarism	19.9%	25%
Burning	13.0%	12%
Honey hunters	10.8%	10%
Lightning	12.1%	8%

Fire causes in the study area will be discussed in paragraph 3.2.6.4.

Accuracy of primary cause of ignition is important when investigating the fire. With training and experience the fire investigating officer will be able to state the cause as being "definite" or "probable".

The National Fire Protection Association in the United States adopted a reporting system, which requires 24 mandatory items to be reported for each forest fire incident. In addition, 18 additional items are listed as desirable of which the **degree of certainty** of form of heat of ignition is one. This includes :

a) **Certain**: Form of heat of ignition is established by admission, statement of reliable witness or physical evidence. This category is intended to cover cases where form of heat of ignition is established beyond doubt.

b) **Reasonably Certain**: Form of heat of ignition is established by strong circumstantial evidence. This category covers cases where form of heat of ignition is reasonably certain, but witness statements or physical evidence present may not be conclusive.

c) **Most Probable**: Form of heat of ignition is established by weak circumstantial evidence, by process of elimination between two or more possible forms of heat ignition or by fire history of the area and experienced judgement of the investigator.

d) **Undetermined**: No definite clues or could have started from any one of several probable forms of heat of ignition or fire not investigated (Chandler *et al.,* 1983, p.47). A high percentage of unknown causes of fires may point to less intensive investigations into the causes of fires (Ford, 1995, p. 79).

3.2.6.3.3 Land owners, farmers, and the rural population

In most countries, agricultural burning, such as in shifting cultivation, grazing and fires to control vermin and insects, together with the many variations of rubbish and debris burning, are major causes of wildfires (Williams, 1993, p. 22 and Gboloo, 2000).

This type of wildfire is often the result of a failure to select the proper time, place and method of burning or in the supervision and control of the burning operation. In order to minimise the number of escaped fires caused by agricultural burning there should be local regulations which would require that:

- A burning permit must be obtained.
- Burning should be carried out only in designated areas.
- Burning should be carried out only during certain weather conditions.

When outdoor fires are allowed, the public should be educated to know the following:

- Burn only during safe conditions, for example, when there is little or no wind and after rain if possible.
- Obtain a permit from the local fire authority or forest fire headquarters.
- Start the fire in a safe place, not too close to the forest or veld. Clear all hazardous material from around the fire area.
- Burn at a safe time and never on a windy day. Generally, the early morning or the late evening is the best time.
- Before starting a large outdoor fire there must be stand-by fire suppression equipment and men available to prevent the fire from spreading.

3.2.6.3.4 Cigarette smoking

One of the major causes of wildfire is the careless smoker. Picnickers, campers, hikers, fishermen, hunters, tourists, or local residents who smoke while in a veld, forest or grassland area can, through carelessness, cause a disastrous fire. To reduce the number of wildfires caused by smoking each smoker should be made aware of the danger and precautions to be taken (Heikkilä *et al.*, 1993, p. 55).

For instance, some very simple basic rules for smoking could be:

- The prohibition of smoking while walking or working in a forest area during the fire danger season.
- Smoke only in designated safe places where there is no hazardous fuel. These areas should be next to a stream or lake, on sandy soil or on a roadway.
- Crush the butt-end of the cigarette against a bare rock or into sandy soil.
- Use a cigarette lighter or make sure that the match is extinguished before discarding it.
- Use the ashtray in the vehicle.

Smokers caused 8.6% of plantation fires in the Sabie area according to Le Roux (1988) and 12% according to Kromhout (1990).

3.2.6.3.5 Campfires

Campfires are a frequent cause of wildfires in those areas where camping, hunting, hiking, fishing, and picnicking are popular (Davis, 1959, p. 231).

The following instructions should be given to people who go camping:

- The campfire should be contained in a specially constructed fireplace which should be well away from overhead and surrounding hazardous fuels.
- The campfire should be kept small.
- The campfire should never be left unattended, as a wind could spread the fire into nearby fuels.
- Make sure that the fire is properly extinguished before leaving the site. This can be done by pouring water or sand over the fire and stirring the embers with a stick. By feeling with your hand, check that no burning material remains.

To reduce damage caused by campfires the public should be educated and informed about fire prevention methods. Signs and warning notice boards should be erected and information on how to prepare a safe camp site should be available at all camping sites (Brown and Davis, 1973, p. 273).

3.2.6.3.6 Harvesting and other forest operations

Harvesting and other forest operations often cause wildfires. Careless employees and the use of certain machines, such as power saws, tractors and bulldozers in hazardous areas during the fire danger season can be the cause of fires (Luke and McArthur, 1978, p. 148).

The use of approved spark arrestors in tractors and other power driven equipment is one way to reduce the risk of fire in the forest. Welding operations should be restricted to designated safe areas and some of the more dangerous forestry operations should be restricted by local regulations. While working in the forest, the employees should be trained in the use of, fire suppression equipment, such as fire extinguishers, shovels and wajax pumps. These should be quickly accessible.

3.2.6.3.7 Arsonists (Incendiarism)

Le Roux (1988) found that 4.8% of fires in plantations in the Sabie area were caused by arsonists. Kromhout (1990) found it to be 3%, while this study recorded a figure of 15.5% (refer to Table 3.11).

Motives behind incendiarism are often extremely complex and subtle, and unless they are understood in a particular situation, preventive action may be futile. Brown and Davis (1973. p. 273) provide a classification of incendiary fire motives:

1. Fires set for direct personal economic gain to:
   - Burn property of others to protect owned property
   - Improve grazing, control of stock, or hunting
   - Facilitate harvesting

2. Fires set for indirect economic gain to:
   - Obtain employment
   - Kill timber to make its sale necessary
   - Control pests and diseases, e.g. snakes and ticks

3. Fires set to obtain a goal or personal satisfaction:
   - Spite against management
   - Personal grudges
   - Drunk or disorderly conduct

4. Fires set to conceal a crime:
   - Destroy evidence of timber theft and illegal hunting

5. Fires set by mentally afflicted and immature:
   - Pyromaniacs
   - Incompetent persons
   - Children

In many countries, e.g. the USA and Ghana, the number of wildfires started by arsonists has increased at an alarming pace. It is difficult to prevent this new development and law enforcement is generally regarded as the only deterrent to arson (Heikkilä *et al.,* 1993, p. 57 and Ford, 1995).

3.2.6.3.8 Children

Children playing with matches or with other sources of fire are causing an increasing number of wildfires each year (Brown and Davis, 1973, p. 290 and Folkman, 1972).

Children are often too young to understand what is dangerous playing. Training, relevant education and proper parental supervision are necessary to prevent this cause of wildfires. Le Roux (1988) found that 0.9% of fires were started by children while Kromhout (1990) published a figure of 5% for the Sabie area. According to the information in Table 3.11, children caused 2.1% of the fires in the study area.

3.2.6.3.9 Lightning

Lightning is an energetic electrical discharge caused by the separation of positive and negative charge in clouds leading to voltage differences in the order of 10 - 100 MV (Latham and Williams, 2001 p. 377).

Lightning is one cause of wildfire that is not preventable. Fires started by lightning strikes may smoulder for days before conditions become favourable for the spread of the fires.

Constant detection is required to locate these dormant or sleeping fires. Lightning storms usually follow a definite path across the terrain. A map which shows the fires caused by lightning over a period of ten years will usually show the lightning fire pattern. Prompt detection is the best defence against fires caused by lightning.

Lightning is generally considered the most significant of the natural causes (excluding man) of veld fires in South Africa (Booysen and Tainton, 1984, p. 25). Although accepted as an ignition source, options differ as to the frequency and importance of lightning induced fires in natural ecosystems. Compared with recorded lightning ground flash densities, the number of recorded lightning fires is low. (Booysen and Tainton, 1984, p. 27). However, lightning played a significant role in plantation fires in the study area and caused 21.9% of plantation fires. Both Le Roux (1988) and Kromhout (1990) found that 30% of plantation fires were caused by lightning.

3.2.6.4 Fire causes in the study area

The different causes and the number of fires per cause for the eight KLF plantations in the study area are given in Table 3.11.

Table 3.11: Fire causes and number of fires (1950 – 1999)

Fire cause description	Number of fires	%
Blasting	5	0.6
Brushwood/Slash burning	8	0.9
Chainsaws	6	0.7
Children	17	2.1
Contractors	9	1.1
Cooking fires	1	0.1
Fire breaks	95	11.2
Honey hunters	101	11.9
Lightning	185	21.9
Neighbours	25	2.9
Other/Smokers	150	17.8

Fire cause description	Number of fires	%
Picnickers	21	2.6
Power lines	8	0.9
Power tools	2	0.2
Refuse dumps	3	0.3
Static electricity	1	0.1
Suspected arson	131	15.5
Trace burning	1	0.1
Trains	9	1.1
Unknown	61	7.2
Veld/Grazing	3	0.3
Warming fires	4	0.5
Total	**846**	**100**

From Table 3.11 it can be seen that:

- Lightning fires have the highest incidence: 21.9%
- Smokers and others, account for 17.8% but due to many unknown factors included in “other” it is difficult to manage and to prevent.
- Suspected arson amounts to 15.5%.

As was explained in paragraph 3.2.6.3.2, there are 27 different fire causes identified in the KLF fire report form.

However to make it easier to analyse the data, the 27 causes were grouped in four cause groups as tabled below:

Table 3:12 Fire cause groups

Cause detail	Cause group
Unknown	People
Trains	People
Chainsaws	Work
Power Lines	Work
Power Tools	Work
Blasting	Work
Fire Breaks	Work
Brushwood/Slash	Work
Refuse Dumps	People
Veld/grazing	Work
Trace Burning	Work
Suspected Arson	People
Contractors	Work
Cooking Fires	Work
Warming Fires	Work
Honey Hunters	Honey
Children	People
Picnickers	People
Neighbours	People
Lightning	Lightning
Static Electricity	Work
Other/Smokers	People

The four cause groups are people, work related, honey hunting and lightning. It is important to do this classification as definite management strategies need to be formulated to address each of these groups. Fire causes were analysed in detail and some of the results obtained are as follows:

3.2.6.4.1 Fire causes per plantation

Fire causes per plantation show interesting patterns as indicated in Table 3.13.

Table 3.13: Fires causes per plantation

Planta-tion	Planted area (ha) 99/00	No. of fires: Honey	No. of fires per 1 000 Ha planta-tion	No. of fires: Light-ning	No. of fires per 1 000 Ha planta-tion	No. of fires: People	No. of fires per 1 000 Ha planta-tion	No. of fires: Work	No. of fires per 1 000 Ha planta-tion	Total No. of fires:	No. of fires per 1 000 Ha planta-tion
Bergvliet	5 641	22	3.90	23	4.08	56	9.90	15	2.66	116	20.6
Blyde	4 324	1	0.23	5	1.16	8	1.85	12	2.77	26	6.0
Brooklands	9 505	24	2.52	40	4.21	84	8.84	23	2.42	171	18.0
Frankfort	2 917	7	2.40	8	2.74	12	4.11	8	2.74	35	11.0
Morgenzon	3 129	1	0.32	7	2.24	21	6.71	7	2.24	36	11.5
Spitskop	3 677	5	1.36	1	0.27	27	7.34	10	2.72	43	11.7
Tweefontein	12 859	6	0.47	52	4.04	93	7.23	41	3.19	192	14.9
Wilgeboom	6 864	5	0.73	18	2.62	18	2.62	7	1.02	48	7.0
Total	**48 916**	**71**	**1.45**	**154**	**3.15**	**319**	**6.52**	**123**	**2.51**	**667**	**13.6**

Tweefontein, Brooklands and Bergvliet are consistently amongst the highest for each of the cause categories. Fire management actions should be developed, based on these figures to address honey hunting fires in Bergvliet and Brooklands and work related fires at Tweefontein. People-related fires also showed a high frequency at Bergvliet and Brooklands. Bergvliet showed the highest incidence of fires with 20.6 fires per 1 000 ha plantation compared to Wilgeboom with only 7.0 and Blyde with 6.0 fires per 1 000 ha plantation.

3.2.6.4.2 Fire causes per day of week

Table 3.14: Fire causes per day of week

	Day of the week							Total
	Mon	Tue	Wed	Thurs	Fri	Sat	Sun	
Honey	6	9	10	12	5	15	14	71
Lightning	27	13	24	15	28	24	23	154
People	41	53	33	34	43	63	52	319
Work	31	29	26	22	9	4	2	123
Total	**105**	**104**	**93**	**83**	**85**	**106**	**91**	**667**

The fire causes per day of the week in Table 3.14 confirms that data recorded on fire records corresponds with what would be expected as work related fires occurred during the week, honey hunting fires more during weekends and the people related fires also showed a slight increase over weekends. As would be expected, lightning fires occured throughout the week.

3.2.6.4.3 Fire causes per month

Table 3.15: Frequency of fires per cause and per month

Month	Honey	Lightning	People	Work	Total
January		9	8	2	19
February	1	8	5	1	15
March		8	5	1	14
April		7	1	1	9
May	4	8	20	12	44
June	17	2	42	45	106
July	22		53	36	111
August	15	7	67	7	96
September	9	36	77	7	129
October	1	26	29	5	61
November	1	32	7	5	45
December	1	11	5	1	18
Total	**71**	**154**	**319**	**123**	**667**

Work related fires, such as burning of tracer belts, occurred mainly during May, June and July (Table 3.15). Most people related fires occurred during the drier months of the year, i.e. May to October as the other months are too wet. Lightning fires also show a definite pattern in the early summer when dry thunderstorms are frequent – September, October and November. Wolffsohn (1980, p. 17) also found that lightning fires are usually strongly seasonal in tropical pine forests and that as the weather becomes warmer, lightning fires become more numerous and start earlier in the day.

Lastly, honey hunting fires also happened more during certain months, i.e. June to August. Therefore, management actions are easier to implement.

3.2.6.4.4 Relationship between fire cause and time of day

A day was divided into three periods. Morning from 03h00 to 09h59, day time from 10h00 to 17h59 and night time from 18h00 to 02h59. As expected, the majority of fires occurred in day time (Table 3.16). There were slightly more fires during the night time than in the morning category.

Table 3.16: Frequency of fires per cause and per time of day

Cause group	Day time	Morning	Night	Total
Honey	51	11	9	71
Lightning	112	24	18	154
People	151	69	99	319
Work	96	20	7	123
Total	**410**	**124**	**133**	**667**
% of fire per time of day	**61.5**	**18.6**	**19.9**	**100**

Most lightning fires occurred during daytime probably due to day time thunderstorm developments. As could be expected all other causes like honey hunting, people and work related fires also occurred mainly throughout the daytime hours. People related fires which include arson also showed a remarkable high tendency in the night time category.

From Table 3.16 it can be seen that 410 fires started between 10h00 and 17h59 (61.5%), 124 in the morning (18.6%) and 133 fires during the night between 03h00 and 09h59 (19.9%).

The following contingency table shows the relationship between cause of fire and time of day. The observed frequencies (0) are presented in Table 3.16.

To test if there is a significant relationship between cause of fire and time of day the χ^2 test was used. The hypotheses tested are as follows:

H_o = There is no relationship between the two variables

H_a = There is a relationship between the two variables

$$\text{The test statistic } (X) = \sum_i \frac{(O_i - e_i)^2}{e_1}$$

$$= 62.70$$

Where o_i = observed frequency

e_i = expected frequency

The expected frequencies (e) for cause of fire and time of day are shown in Table 3.17 and is calculated as follows:

$$Expected\ \ frequency: \frac{Row\ total \times Column\ total}{Grand\ total}$$

Table 3.17: Expected frequencies for different fire causes and time of day

	Time of day		
Cause	**Day time**	**Morning**	**Night**
Honey	43.6	13.2	14.2
Lightning	94.7	28.6	30.7
People	196.1	59.3	63.6
Work	75.6	22.9	24.5

The distribution of x is approximately χ^2 with (h-1) x (k-1) degrees of freedom.

Chi – Sq (0.05, 6) = 12.59
Chi – Sq (0.01, 6) = 16.81

Because X = 62.7 > χ^2 = 16.81, the null hypothesis is rejected at 1% level of significance and the conclusion is that there is a relationship between fire cause and time of day.

Comparing the observed and expected frequencies the following can be seen:

- Honey hunters were more often the cause of fire in day time than expected.
- Lightning was more often the cause of fire in day time than expected.
- People cause more fires in the morning and night than expected.
- Work related activities were more often the cause of fire in the morning than expected.

Additional to the number of fires during these time categories, the area burnt and total extinguishing cost were also calculated (Table 3.18).

The approximate 60% of fires that occurred during day time (paragraph 2.3.3) resulted in 69% of the burnt area (6 787 ha) and 81% of the extinguishing cost (R4,3 million). This is an indication that fires during day time are more expensive to control, and burn larger areas. This is due to higher air temperatures during day time and probably lower humidities resulting in more aggressive fire behaviour than during night time.

Table 3.18: Area burnt and fire cost per time of day

Time of day	Number of fires	Area burnt (ha)	Extinguishing cost (R)
Day	517	6 787	4 354 539
Morning	153	2 544	473 781
Night	176	535	522 082
Grand total	**846**	**9 866**	**5 350 403**

The fires in the morning resulted in approximately five times larger burnt area per fire compared to night fires, most probably also due to different climatic conditions.

3.2.7 Extinguishing costs

The actual extinguishing cost for each fire was recorded in the fire report. This cost included labour, materials, transport and equipment cost used in fire fighting. To compare costs over different years, the actual costs have been updated by using a Production Price Index (PPI) (Number P014.1) to obtain a real cost with the year 2001 as base year (Statistics, South Africa, 2001).

The factor used for 1970 is 27.47 while the factor for 2001 is one. The assumption being that all items (materials, equipment and personnel) have all increased equally on this basis.

3.2.7.1 Total extinguishing costs per plantation

Table 3.19 gives the extinguishing costs per plantation. To compare costs to number of fires the number of fires are also given. It is, however, difficult to draw any conclusions from this as extinguishing costs are influenced by many variables, e.g. species, terrain, topography and wind.

Table 3.19: Extinguishing costs per plantation

Plantation	Number of fires	Total extinguishing cost (R)	Average cost per fire (R)
Bergvliet	147	1 870 391	12 723
Blyde	47	170 900	3 636
Brooklands	172	688 713	4 004
Frankfort	50	120 387	2 407
Morgenzon	36	390 349	10 843
Spitskop	70	447 644	6 394
Tweefontein	245	1 571 238	6 413
Wilgeboom	79	90 781	1 149
Total	**846**	**5 350 403**	**6 324**

From Table 3.19 it can be seen that average costs per fire for Bergvliet and Morgenzon are much higher than the cost per fire for the rest of the plantations. According to Kromhout (1990) the average damage per fire for 152 fires in insured plantations in the Sabie area amounted to R395 per fire (or R892 per fire at 2001 costs). The average damage per fire for fires in insured plantations for the whole of South Africa was R5 729 per fire (R12 947 at 2001 costs). The same information for Le Roux (1988) are R111 per fire in the Sabie area (R324 at 2001 costs) and R6 936 per fire for South Africa for 1 675 fires during 1979 to 1985 (R20 253 at 2001 costs). The average cost per fire within KLF is, therefore, much lower than the industry costs, which could be the result of numerous factors such as early detection, quick response and efficient fire fighting.

3.2.7.2 Extinguishing cost per month

From Table 3.20 (number of fires per month) it is clear that the majority of fires occurred during the dry months (winter months in Mpumalanga). It is therefore logic that extinguishing costs will follow the same pattern and this is shown in Table 3.20.

Table 3.20: Extinguishing costs per month

Month	Number of fires	Total extinguishing cost (R)	Average cost per fire (R)
January	22	29 932	1 360
February	18	9 594	533
March	17	13 203	7 766
April	14	8 769	626
May	53	154 374	2 912
June	123	1 121 018	9 113
July	140	1 062 077	7 586
August	128	1 174 711	9 177
September	166	1 068 646	6 437
October	85	524 997	6 176
November	56	168 704	3 012
December	24	14 976	599
Total	**846**	**5 350 403**	**6 324**

The months June, July and August not only have many fires but fires during this period are also expensive to extinguish. This may be as a result of climatic conditions resulting in high fire danger and fire behaviour that is difficult to control.

3.2.8 Fire report times

The fire report time is the time when the fire was reported to the forest office or forester on duty by the lookout or on occasion, the neighbour or the public. Figure 3.3 shows that a large percentage of fires are reported between 11h00 and 15h00 (45%). During 1979 – 1985 29,4% of fires occurred between 12h00 and 14h55 in private plantations in the Sabie area (Le Roux, 1990), while Kromhout found that the frequency was 30% for the period 1985 – 1989. Special measures should therefore be put into place during severe climatic conditions to detect fires as quickly as possible, especially between 11h00 and 15h00. Current practice in KLF is to put additional staff in lookouts and high-risk areas when weather conditions are conducive to run away fires.

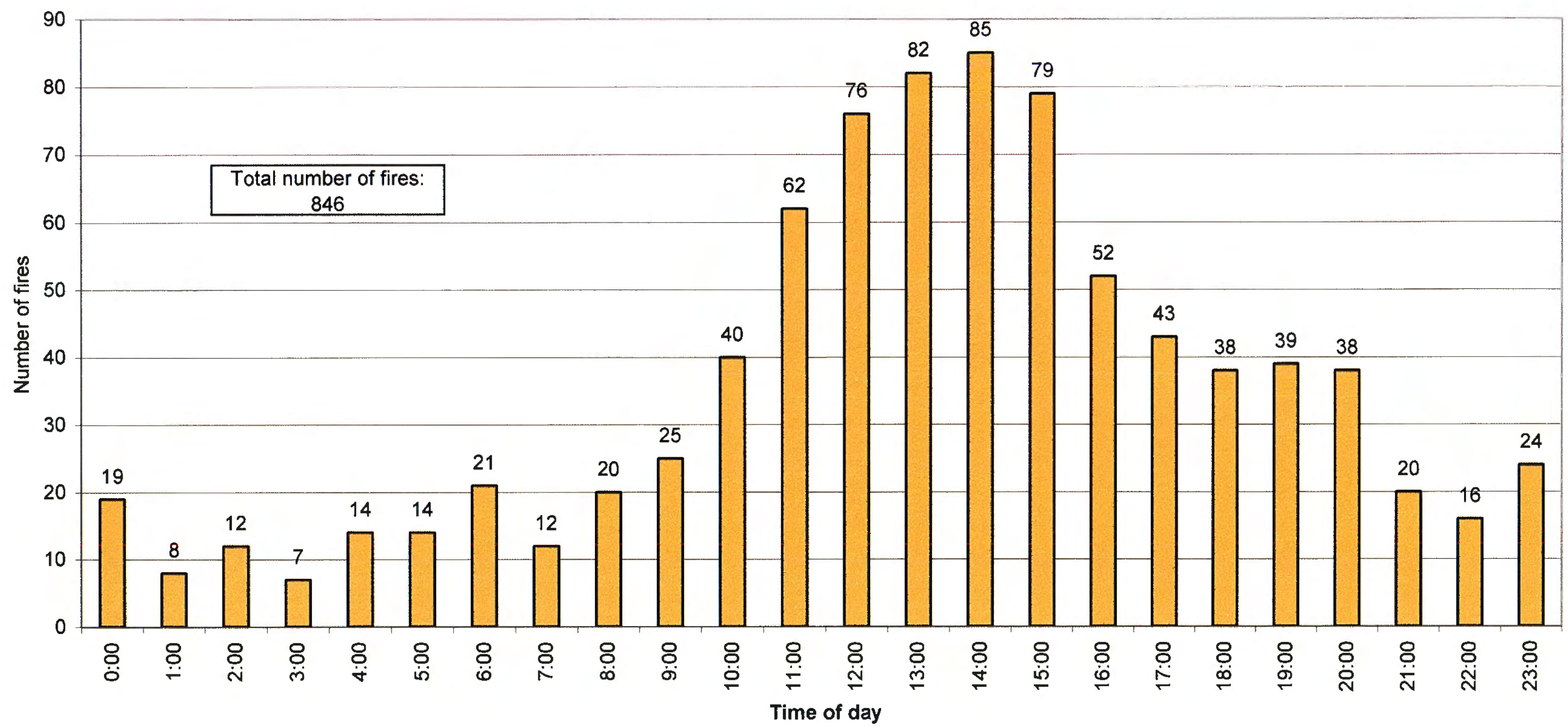

Figure 3.3: Total number of fires reported during a 24 hour period

3.2.9 Arrival times at fires after reporting

The time when the first crew arrived at the fire was recorded for 667 fires (not in the Hilligan data set). The difference between the fire report time and the arrival time is the response time. Response time is important from a management viewpoint as it reflects on operational efficiency. However, it will also be influenced by distance to the fire, road conditions and quality of information received by the lookout on where the fire is located. From Table 3.21 it is clear that there is a wide range in response times although the majority of fires were responded to within 20 minutes after reporting.

Table 3.21: Number of fires related to response time

Time (minutes)	Immediately	0—10	11—20	21—30	31—60	>60	Total
Number of fires	38	246	226	82	48	27	667
%	5.7	36.9	33.9	12.3	7.2	4.0	100

It is a concern that it took longer than 30 minutes to arrive at 75 fires (11.2% of the total number of fires). This might be because of poor communication, labour problems, terrain, road conditions and remoteness.

3.2.10 Fire fighting time

The fire fighting time is the difference between the time the crew arrived at the fire and the time that the fire was under control. This time excludes the period the fire was guarded after controlling it.

Fire fighting time is a function of slope, species, weather conditions and available resources. A summary of fire fighting times is given in Table 3.22.

Table 3.22: Fire fighting time in minutes

Time (minutes)	0-5	6-10	11-15	16-30	31-60	61-120	121-180	>181	Total
Number of fires	93	99	65	120	104	89	33	64	667
%	13.9	14.8	9.8	18.0	15.6	13.3	4.9	9.7	100

From the recorded 667 fires, 56% took not more than 30 minutes to bring under control. Only 9.7% of the fires took longer than 3 hours to extinguish. This is important information for training purposes and incident control system application. Le Roux (1988) and Kromhout (1990) determined that 56% of all fires in the Sabie area took less than 30 minutes to extinguish.

This also underlines the importance of accurate and effective fire detection to ensure quick response times. It is also important to correlate the fire fighting time with the area burnt. Table 3.23 gives the fire fighting time and the area burnt.

Table 3.23: Area burnt and fire fighting time

	Fire fighting time in minutes									
Area burnt (ha)	**0-5**	**6-10**	**11-15**	**16-30**	**31-60**	**61-120**	**121-180**	**>180**	**Total**	**%**
0 – 0.99	91	93	55	100	73	47	15	20	494	74.0
1.0 – 4.99	1	5	10	16	22	25	9	8	96	14.0
5.0 – 9.99	0	0	0	2	1	9	2	7	21	3.0
10 – 49.99	1	1	0	2	1	5	4	9	23	3.0
50 – 99.99	0	0	0	0	2	1	1	5	9	1.5
100 – 299.99	0	0	0	0	3	2	2	8	15	2.0
300 – 499.99	0	0	0	0	3	0	0	3	4	1.25
>500	0	0	0	0	1	0	0	4	5	1.25
Total	**93**	**99**	**65**	**120**	**104**	**89**	**33**	**64**	**667**	100

It is clear from the information in Table 3.23 that 74% of fires were small (<1.0 ha) but took anything from five minutes to over three hours to extinguish.

Only five fires were over 500 hectares in size and one took between 30 minutes and one hour to extinguish, while the other four large fires took longer than three hours to put out. This large fire with the quick extinguishing time occurred on Morgenzon plantation during June 1978. It was a grass fire and was probably contained within existing fire belts.

3.2.11 Climatic information

3.2.11.1 Introduction

For all the fires, except the Hilligan data set, a number of climatic variables were recorded. The variables collected were:

- Wind speed
- Wind direction
- Temperature
- Humidity
- Fire danger index (FDI)

However, a large percentage of this information was not reported, incomplete or wrongly reported on the fire recording forms. This is due to the fact that information like FDI's only became available in recent years and that humidity information is still difficult to collect and therefore rarely occur in fire reports.

To try and support the lack of climate data on the fire reports, weather information was obtained from the South African Weather Bureau for the Mpumalanga area. Unfortunately the Graskop and Bushbuckridge weather stations operated only for a limited period and they, together with the White River weather station, only recorded a limited number of climatic variables such as rainfall and temperature. For this reason no in-depth correlation could be carried out. An attempt to develop a decision support model based on weather failed.

3.2.11.2 Wind speed

Wind speed has a very important influence on fire behaviour and directly influences

FDI. The information available on wind speed in fire reports is of poor quality. It seems that most wind speeds were estimated. It is understandable as accurate instruments were not available to foresters and they had to phone weather stations for information which might also have differed from local conditions.

Table 3.24: Number of fires for different wind velocities

Wind speed (km/h)	Number of fires	%
0	34	5.0
5	159	23.8
10	106	15.9
15	53	7.9
20	17	2.5
30	13	1.9
No records	73	10.9
"Suspect information"	212	32.1
Total	**667**	**100**

Wind speed is not regarded a major factor in the Mpumalanga Escarpment area as 44.7% of the fires occurred during wind speeds of 10 km/h or less (Table 3.24). The poor relationship between wind velocity and area burnt is shown in Figure 3.4. Factors such as effective fire fighting during windy conditions, terrain and humidity can have a major influence on this relationship

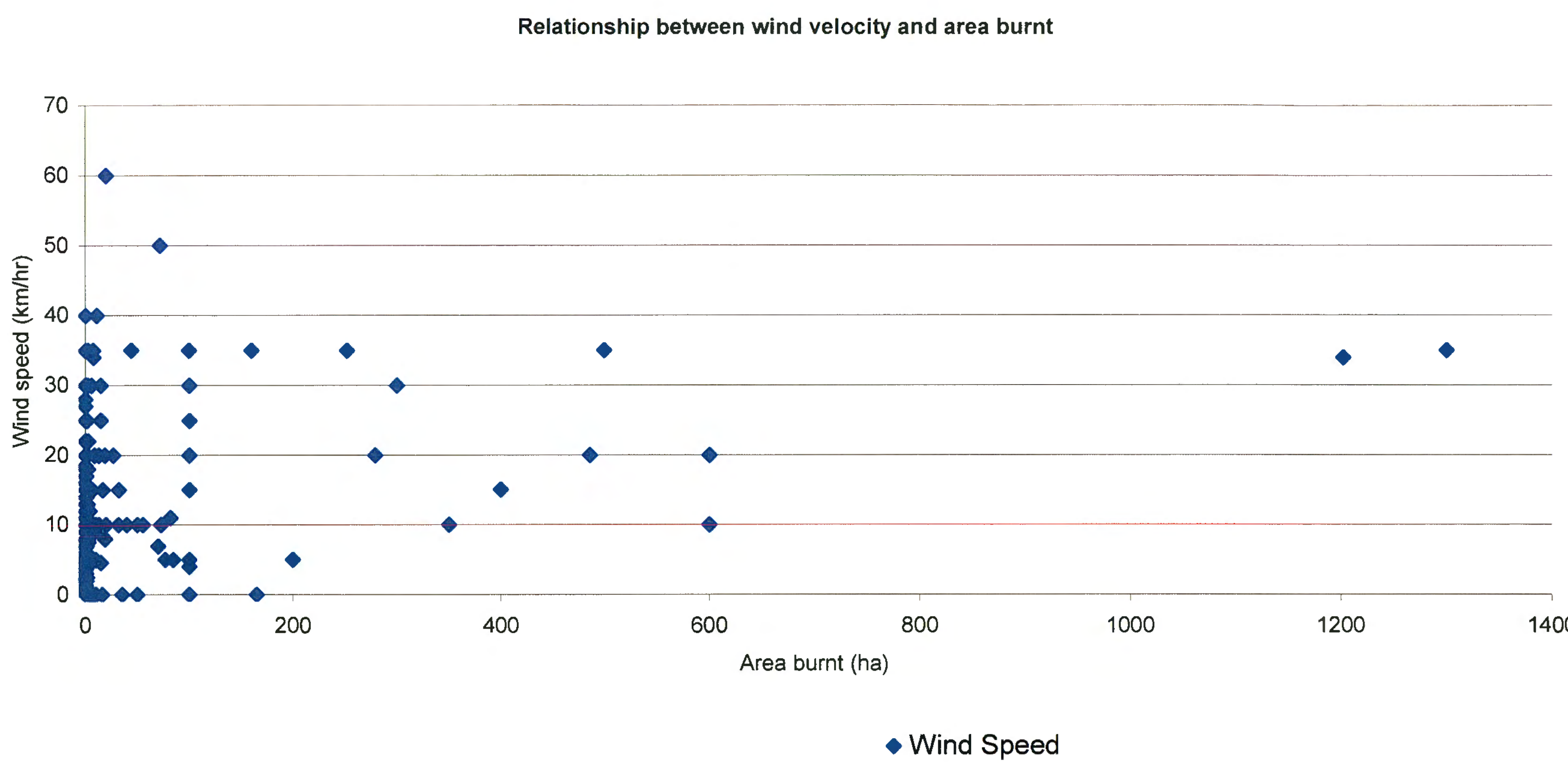

Figure 3.4: Correlation between wind speed and area burnt

3.2.11.3 Wind direction

The following figure shows the number of fires for the major wind directions. Most fires occurred with a NE wind (18.6%), followed by a NW wind (14.8%).

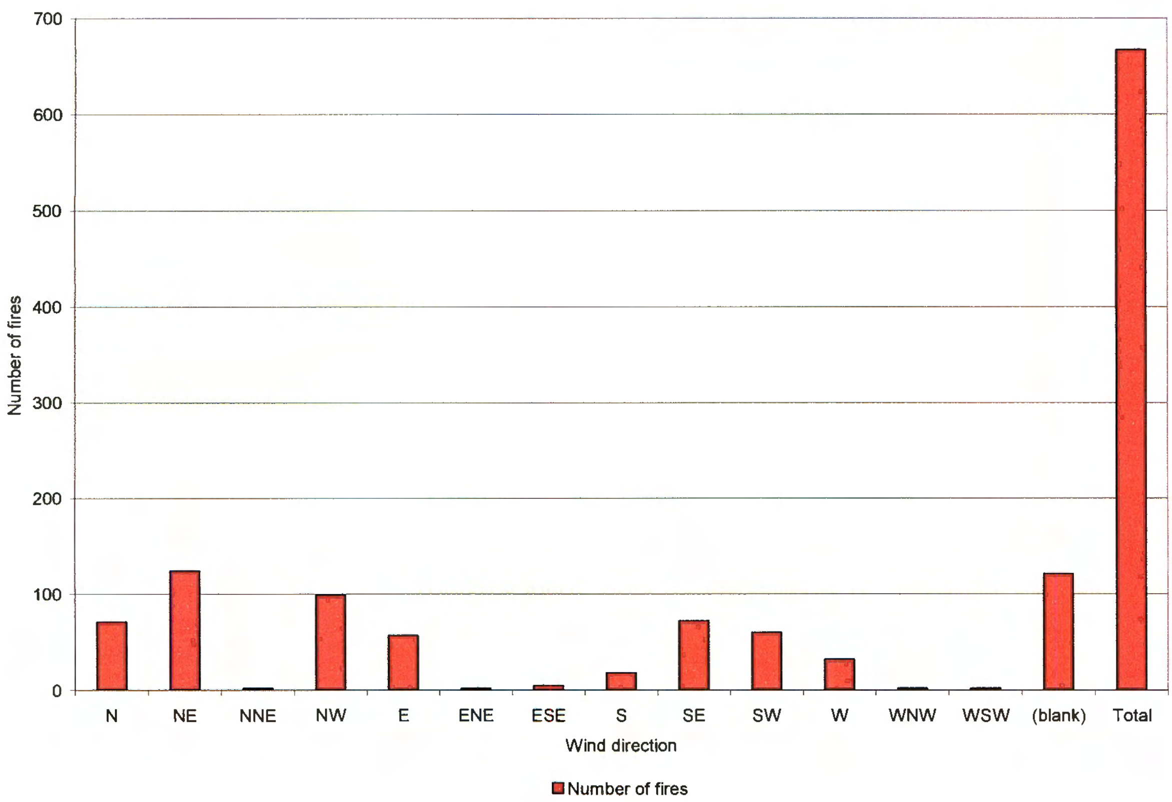

Figure 3.5: Number of fires per wind direction

Unfortunately 121 (18.3%) fire reports provide no wind direction data, which included fires that occurred on days when there was no wind blowing.

Wind directions did not change/differ markedly between the eight plantations for which fire records were kept. Table 3.25 shows that NE winds are dominant on most of the eight plantations. From the climatic information in Chapter 2, paragraph 2.3.8, the north-easterly winds come from the South Indian high pressure system and the anticyclonical circulation causes NE winds to blow over these parts of the Republic of South Africa.

Table 3.25: Number of fires per plantation by wind direction

	Plantation								
Wind direction	Bergvliet	Blyde	Brooklands	Frankfort	Morgenzon	Spitskop	Tweefontein	Wilgeboom	Total
N	18	4	20	1	7	7	10	4	71
NE	26	4	20	7	3	9	46	9	124
NNE	1							1	2
NW	16	8	36	1	7	3	24	4	99
E	12	1	7	5	2	1	25	4	57
ENE			1				1		2
ESE	3						2		5
S	4		10		1		3		18
SE	10	4	18	5	8	2	22	3	72
SW	10		13	4	1	5	25	2	60
W	5	2	10	2	1	2	7	3	32
WNW			1				1		2
WSW			1			1			2
(Blank)	11	3	34	10	6	13	26	18	121
Total	116	26	171	35	36	43	192	48	667

Neither wind direction nor wind speed correlated with fire size (area burnt) or fire cost. This was due to lack of available climatic data and the fact that management is more alert during adverse weather conditions.

3.2.11.4 Rainfall

Although rainfall figures were not recorded in the fire reports, the monthly rainfall figures for Bergvliet Plantation were obtained from the Agricultural Research Council (ARC). This information is listed in the Table 3.26. The rainfall for Bergvliet Plantation was used as it was regarded as representative for the study area.

Table 3.26: Rainfall figures (mm): Bergvliet Plantation

	Month												
Year	Jan	Feb	March	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
1960	121.5	314.0	88.4	188.3	33.6	1.1	6.3	29.0	60.8	19.0	329.0	354.9	1,545.9
1961	167.9	185.9	149.6	130.2	9.0	63.2	30.1	21.4	41.2	87.1	164.0	192.2	1,241.8
1962	125.7	178.2	84.5	76.8	24.6	0.0	0.8	21.4	18.5	69.0	439.8	163.5	1,202.8
1963	91.1	87.7	67.7	65.0	58.5	83.6	31.8	0.4	10.4	95.9	225.4	117.1	934.6
1964	195.4	122.5	34.8	70.7	45.5	17.5	0.0	20.8	19.3	155.0	142.2	331.9	1,155.6
1965	193.1	105.7	48.7	38.4	7.4	0.6	11.0	14.0	41.8	36.4	169.2	115.1	781.4
1966	181.9	264.7	18.5	38.3	12.0	13.0	7.3	15.9	30.5	114.0	123.4	228.0	1,047.5
1967	172.9	409.4	68.9	319.5	8.5	7.0	14.9	14.6	4.3	116.7	144.9	136.1	1,417.7
1968	90.2	76.5	108.0	165.8	43.7	27.8	16.2	18.0	22.5	76.7	197.7	163.1	1,006.2
1969	193.3	220.4	245.2	75.5	80.2	4.0	21.3	0.0	52.4	213.6	133.9	289.4	1,529.2
1970	56.0	90.7	36.6	31.8	31.4	40.0	13.0	50.5	22.8	53.1	152.9	188.8	767.6
1971	331.0	102.4	78.9	61.4	38.3	28.3	14.5	9.5	65.2	103.1	131.7	291.1	1,255.4
1972	374.9	330.1	289.9	93.8	64.0	1.0	3.5	10.7	11.8	123.1	170.6	114.8	1,588.2
1973	172.9	104.8	104.8	155.2	20.0	4.5	26.5	29.0	224.1	100.0	247.4	313.8	1,503.0
1974	376.3	172.0	81.3	165.5	17.2	0.0	41.7	5.0	39.0	62.9	161.5	172.3	1,294.7
1975	307.1	275.5	133.5	55.8	36.0	25.0	0.0	33.0	40.0	69.4	106.3	254.0	1,335.6
1976	394.5	270.5	288.1	72.1	23.5	0.0	0.6	29.5	21.5	14.5	129.1	252.2	1,496.1
1977	159.4	153.1	118.7	53.6	3.0	0.0	0.0	40.6	92.5	36.9	106.5	368.5	1,132.8
1978	205.8	118.7	152.7	36.8	5.5	0.0	7.8	15.0	24.8	94.8	211.0	107.6	980.5
1979	128.6	92.9	75.7	33.0	190.9	7.4	13.7	23.1	45.0	89.2	198.5	117.5	1,015.5
1980	176.9	353.9	133.5	30.4	6.8	0.0	0.0	37.3	81.5	63.1	373.0	233.0	1,489.4
1981	409.9	361.0	143.6	31.9	23.0	0.8	0.0	30.8	65.7	100.9	79.5	110.9	1,358.0
1982	191.6	99.3	294.2	115.9	5.8	0.0	44.0	15.3	23.0	63.4	93.0	84.6	1,030.1
1983	86.1	92.3	176.9	102.8	69.8	6.7	1.8	30.9	28.6	141.4	161.4	193.4	1,092.1
1984	241.7	49.4	123.3	167.0	4.6	12.5	117.6	16.6	89.3	90.1	221.5	145.4	1,279.0
1985	207.1	503.8	62.3	13.8	57.0	8.3	0.1	11.4	53.1	127.5	94.3	275.3	1,414.0
1986	122.9	219.9	96.6	216.6	7.0	9.0	0.8	21.6	75.9	92.7	115.9	145.5	1,124.4
1987	113.3	114.2	315.5	35.4	5.5	11.9	7.1	61.6	147.4	60.7	103.0	295.0	1,270.6
1988	111.4	307.5	140.6	48.1	3.2	29.5	3.9	30.6	73.1	168.9	79.7	145.5	1,142.0
1989	71.7	335.6	42.4	30.1	15.0	1.8	0.0	12.1	10.6	107.5	209.4	202.2	1,038.4
1990	205.6	259.2	126.4	58.7	19.5	0.5	20.9	15.9	11.7	118.5	131.0	255.2	1,223.1
1991	255.5	176.2	194.3	0.0	16.4	56.7	0.1	6.5	44.5	39.9	135.2	129.2	1,054.5
1992	131.0	35.1	107.1	42.0	7.4	2.1	1.4	25.7	25.6	117.1	116.4	162.1	773.0
1993	121.1	154.3	0.0	30.8	0.0	0.0	1.1	30.6	16.4	79.7	0.0	149.9	583.9
1994	69.6	152.9	151.2	1.3	0.0	0.0	0.0	24.1	27.7	115.1	85.4	143.9	771.2
1995	200.1	130.1	0.0	0.0	0.0	0.3	0.4	0.0	10.7	65.5	181.7	316.9	905.7
1996	284.1	755.2	145.6	75.9	85.5	10.3	38.7	42.7	12.8	99.2	112.0	202.3	1,864.3
1997	230.1	166.9	403.9	90.2	33.9	6.5	15.2	7.1	153.6	97.1	120.0	121.8	1,446.3
1998	306.7	81.3	67.7	66.8	0.0	0.0	33.4	4.6	62.5	172.6	99.5	354.6	1,249.7
1999	172.9	270.5	157.2	71.8	27.1	0.0	10.5	15.6	34.5	72.3	177.6	288.9	1,298.9
2000	264.5	688.3	166.2	86.0	5.2	81.2	2.1	0.0	60.1	69.3	219.9	314.3	1,957.1
Average	195.4	219.1	129.8	79.1	27.9	13.7	13.7	20.5	48.7	92.5	160.8	208.3	1,209.7
Total	8,013.3	8,982.6	5,323.0	3,243.0	1,145.5	562.1	560.1	842.4	1,996.7	3,792.9	6,594.4	8,541.8	49,597.8

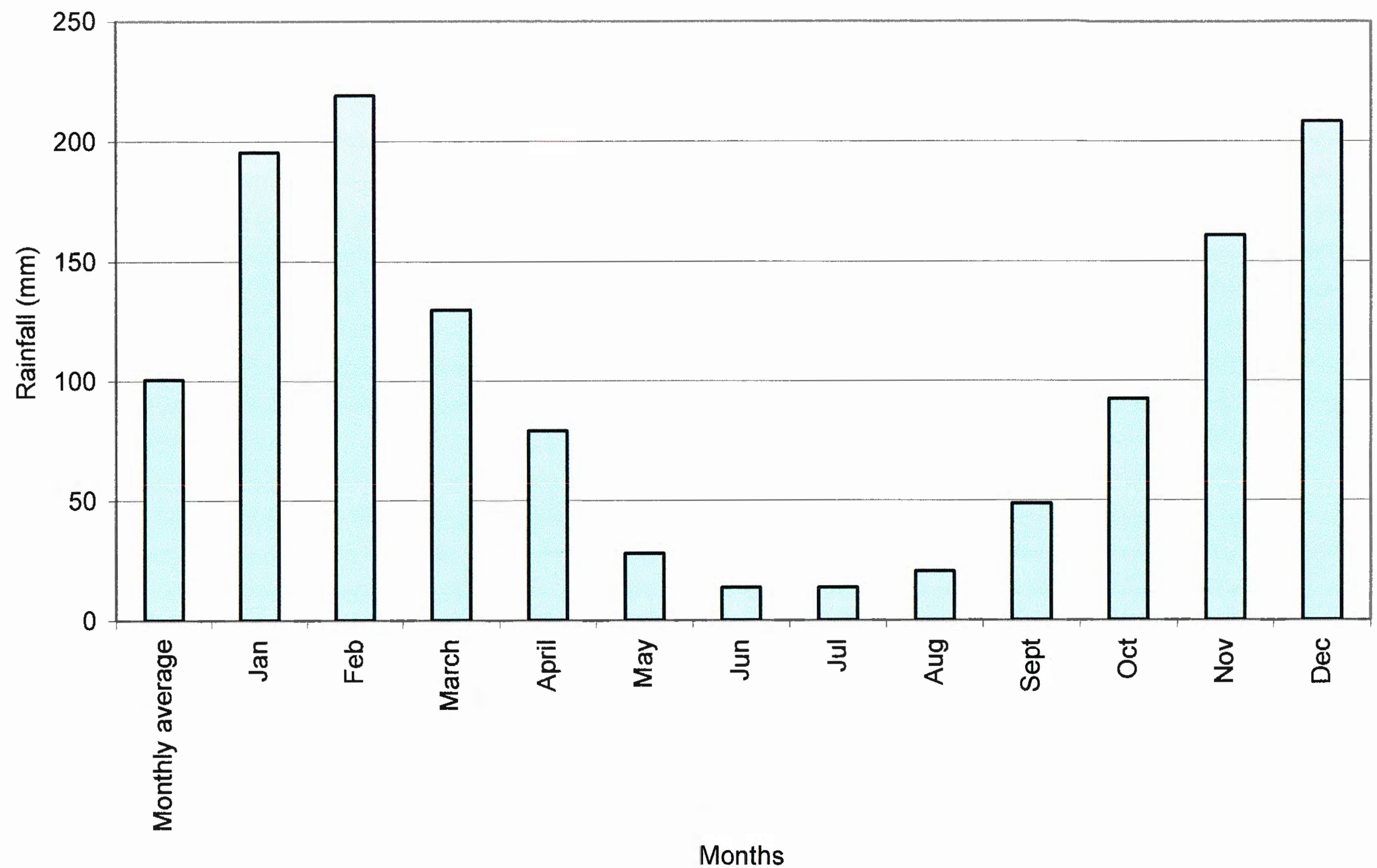

Figure 3.6: Mean monthly rainfall figures for Bergvliet Plantation

The average annual rainfall over 41 years for Bergvliet Plantation is 1 209.7 mm. The results in Table 3.26 show that 1978 experienced a low rainfall (980 mm). During that year an area of 3 040 ha was burnt (Refer to Table 3.5). Severe droughts were experienced during 1992 – 1995, which also resulted in catastrophic fires during 1994.

The rainfall information in Figure 3.6 shows that the winter months, May to August, are the driest with an average rainfall of only 18.9 mm per month.

3.2.11.5 Fire Danger Index (FDI)

The Fire Danger Index (FDI) is calculated and distributed to plantations by the local Fire Fighting Association (FFA) in Nelspruit. Unfortunately this service has only been operational for the past ± 15 years using the Lowveld FDI model. FDI's are calculated for 10h00 and 14h00 each day using temperature, humidity, wind speed and rainfall figures.

The following tables provide the FDI information per month for June to October from 1996 to 2000.

Table 3.27: Nelspruit monthly FDI distribution (1996 – 2000)

	10h00				
	FDI Blue 0 – 20	**FDI Green 21 – 45**	**FDI Yellow 46 – 60**	**FDI Orange 61 – 75**	**FDI Red 76 - 100**
June	35	155	23	0	0
July	38	228	31	1	0
August	57	237	72	2	0
September	82	184	78	6	0
October	100	160	40	0	0
Total	312	964	244	9	0
%	20.4	63.0	16.0	0.6	0
	14h00				
	FDI Blue 0 – 20	**FDI Green 21 – 45**	**FDI Yellow 46 – 60**	**FDI Orange 61 – 75**	**FDI Red 76 - 100**
June	20	106	81	6	0
July	15	147	131	5	0
August	30	152	148	36	2
September	40	130	123	55	2
October	78	114	88	19	1
Total	183	649	571	121	5
%	12.0	42.4	37.3	8.0	0.3

(FFA, 2003)

From the information in the above tables it can be seen that FDIs at 14h00 were higher than the 10h00 FDIs, as more days over the five year period were in the orange and red categories. On average there were only 1 to 2 extreme weather days per year with FDI's > 75 (Red) for the Nelspruit area which included Sabie and Graskop. August and September are dangerous months for wildfires as FDI's at 14h00 more often reach an index of 61 – 75 (Orange).

Forecasting of dangerous fire weather must receive continuous attention and when high FDIs are forecasted special precautionary measures must be implemented. Special management actions during high FDI days may include additional lookouts, stopping of dangerous plantation activities such as using chainsaws and keeping labour at strategic locations together with fire fighting equipment.

3.2.12 Area burnt

The area burnt was recorded on every fire report. The information in Table 3.28 shows that the total area burnt from 1950 to 1999 was 9 866 ha.

3.2.12.1 Areas burnt and number of fires per month and per year (1950 – 1999)

The total hectares burnt for June was 2 765 ha of which the most fires were caused by work related activities (Table 3.28). Although July had more fires than June the area damaged was only 420 ha. The months of August and September had a high fire incidence and the largest area burnt. The high frequency of fires in September were mainly caused by lightning and people (Table 3.28).

Table 3.28: Summary of areas burnt and number of fires

	Area burnt per month and per year (ha)													
Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total	Bergvliet Rainfall Figures (mm)
1950						14.6		1.0	1.5	2.8			19.9	
1953								0.1	4.1				4.2	-
1954						0.2	0.2		0.4	3.7		0.1	4.6	-
1955							1.9	0.1	0.1	0.1			2.2	-
1956						0.1		0.2	0.2	0.0		0.1	0.6	-
1958									2.4				2.4	-
1959								0.7	0.2				0.9	-
1960	0.1	0.1				0.3	0.1	0.1	1.2				1.8	1545.9
1961								0.1	7.6	1.5			9.2	1241.8
1962				0.4			1.3	0.1	162.5	0.2	4.0		168.5	1202.8
1963			0.1		1.2			1.6	11.3				14.2	934.6
1964						70.4	82.4	2.0	3.5	0.2	0.1		158.7	960.2
1965		0.0			2.4	0.8	0.1	0.6	0.5	74.1	2.8	24.2	105.6	781.4
1966			0.8	0.7	0.3		0.9	0.9	3.0	0.1	0.8	0.1	7.5	1047.5
1967						1.2	0.1	0.5		0.3	0.0		2.2	1417.7
1968	0.0				0.1		2.0	0.9		72.1		0.4	75.5	1006.2
1969						0.2	0.7		1.1				1.9	1529.2
1970			0.1	0.1	3.3			4.8	0.0		0.0		8.3	767.6
1971						13.0		16.2	35.5			50.0	114.7	1255.4
1972							32.4	16.3	487.8				536.4	1588.2
1973	0.0	0.0					1.5	0.1	161.4	0.5			163.5	1503.0
1974				0.1		3.4	3.0	0.8	25.5	30.4			63.2	1294.7
1975	0.0					0.0	2.0	9.4					11.5	1335.6
1976	2.0					0.7	0.0		3.5	0.1	0.9	1.0	8.2	1496.1
1977	0.0				0.0	20.4	0.1	400.1	7.0	1.0	0.1		428.8	1132.8
1978					0.5	1,300.0	3.0	1,379.0	353.2	0.1	5.0		3,040.8	980.5
1979		0.5	0.7	0.5	0.0	47.2	0.7	0.2	0.2		0.2	2.3	52.5	1015.5
1980	0.0	0.0			1.5	2.1	4.5	3.5	2.1	17.0	0.3		31.0	1489.4
1981	0.6	0.0	0.1			0.7	15.3	539.9	658.6	1.4	0.1	0.0	1,216.8	1358.0
1982			0.6	0.4	0.5	4.4	1.9	5.9	610.1	0.0	0.5	0.5	624.9	1030.1
1983	0.1	4.4	0.7	0.1	3.0	10.2	51.3	1.5	40.4	0.1	3.6	0.0	115.5	1092.1
1984		0.2			0.4	1.2	3.5	1.0	0.2		0.1	0.4	7.0	1279.0
1985			2.0			0.1	10.2	0.0	2.3	9.3	0.4	0.0	24.3	1414.0
1986	1.1		0.1	3.3	0.3	2.0	77.5	1.5	0.5	0.8	0.2	0.5	87.7	1124.4
1987	5.6	2.8			0.6	0.4	0.1	352.5	0.2	0.1	0.2		362.4	1270.6
1988	0.5		0.5		1.5	6.1	2.8	0.9	1.0	2.2			15.4	1142.0
1989						0.5	1.3	1.2	2.3	1.0	0.0		6.2	1038.4
1990	0.1		0.0			20.4	18.1	0.1	25.0	84.0			147.7	1223.1
1991					1.5	0.2	1.7	0.2	23.3		8.2		35.1	1054.5
1992	0.3	0.0	0.0		0.0	8.3	2.1	2.0		1.0		0.0	13.8	773.0
1993					2.0	1.1	2.0	14.8	1.2				21.1	583.9
1994						1,231.9	86.6	1.9	192.9	0.5	1.1	0.6	1,515.5	771.2
1995			0.9			0.1	4.1	71.6	200.8	1.1			278.5	905.7
1996	2.1				0.2	0.5	0.7	72.0	0.9	4.6	0.7		81.7	1864.3
1997					0.6	1.0	1.6	0.0	103.9	0.6	73.2		181.0	1446.3
1998			4.0		64.4	1.6	3.1	0.4	2.6	14.7			90.8	1249.7
1999					0.4			1.5	0.4		0.0		2.3	1298.9
Total	**12.6**	**8.0**	**10.6**	**5.6**	**84.7**	**2,765.2**	**420.8**	**2,908.1**	**3,142.2**	**325.8**	**102.6**	**80.2**	**9,866.3**	

	Number of fires per month and per year													
Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total	Bergvliet Rainfall Figures (mm)
1950						2		1	5	2			10	
1953								1	1				2	-
1954						1	1		2	2		1	7	-
1955							5	2	1	1			9	-
1956						1		1	1	2		1	6	-
1958									1				1	-
1959								4	4				8	-
1960	2	2				1	1	1	1				8	1545.9
1961								1	1	2			4	1241.8
1962				1			4	1	3	2	1		12	1202.8
1963			1		1			1	4				7	934.6
1964						6	2	1	3	1	2		15	960.2
1965		1			2	4	3	6	4	5	3	1	29	781.4
1966			1	2	2		1	4	5	1	4	2	22	1047.5
1967						1	2	4		4	1		12	1417.7
1968	1				1		6	2		2		1	13	1006.2
1969						1	4		1				6	1529.2
1970			1	2	3			2	1		1		10	767.6
1971						1		2	1			1	5	1255.4
1972							4	4	3				11	1588.2
1973	1	1					7	1	4	1			15	1503.0
1974				1		6	2	5	4	3			21	1294.7
1975	1					1	6	7					15	1335.6

	Number of fires per month and per year													
Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total	Bergvliet Rainfall Figures (mm)
1976	1					1	1		7	2	3	2	17	1496.1
1977	1				1	5	1	4	5	2	1		20	1132.8
1978					2	2	4	12	5	1	1		27	980.5
1979		2	1	1	1	4	2	3	3		1	3	21	1015.5
1980	2	1			4	6	3	3	3	4	1		27	1489.4
1981	1	1	1			4	7	4	8	5	3	1	35	1358.0
1982			2	1	4	10	6	6	17	1	4	2	53	1030.1
1983	1	4	2	2	11	3	11	1	6	1	1	2	45	1092.1
1984		2			1	4	4	1	2		1	1	16	1279.0
1985			1			2	7	1	1	4	10	1	27	1414.0
1986	3		1	4	3	10	2	3	8	7	3	2	46	1124.4
1987	2	3			5	4	1	5	1	2	1		24	1270.6
1988	1		1		2	7	4	2	4	2			23	1142.0
1989						1	2	3	9	2	1		18	1038.4
1990	1		1			3	5	1	5	4			20	1223.1
1991					1	3	5	3	4		1		17	1054.5
1992	2	1	1		1	3	3	2		1		1	15	773.0
1993					1	1	3	5	1				11	583.9
1994						10	2	4	6	1	2	2	27	771.2
1995			2			1	5	9	4	6			27	905.7
1996	2				1	4	1	2	2	5	4		21	1864.3
1997					1	5	6	1	9	5	4		31	1446.3
1998			1		4	5	7	1	5	2			25	1249.7
1999					1			1	1		2		5	1298.9
Total	**22**	**18**	**17**	**14**	**53**	**123**	**140**	**128**	**166**	**85**	**56**	**24**	**846**	

There is no clear correlation between the number of fires per year and the area burnt although the low rainfall during 1965 and 1978 was conducive to a high frequency in fires and large burnt areas. However, during the severe drought of 1992 – 1995, the number of fires per year were average. It is, however, a good policy to monitor trends especially to evaluate potential impacts of El Niño.

3.2.12.2 Number of fires and total area burnt per fire size group

For this analysis only the 667 fires in subsets 1 and 2 were used. Fire size (area burnt) was grouped and then the number of fires calculated. In the fire size class of 0 – 0.9 hectare there were 494 fires (74%). The total area destroyed due to these 494 fires was only 79 ha (Table 3.29). Both Le Roux (1988) and Kromhout (1990) found that more than 80% of the fires which occurred in the Sabie area damaged less than 1 ha.

Table 3.29 : Number of fires and total area burnt per fire size group

Areas (ha)	0-0.9	1-4.9	5-9	10-49	50-99	100-299	300-499	500-1 500	Total
Number of fires	494	96	21	23	9	15	4	5	667
Total area burnt (ha)	79	176	140	476	614	2 056	1 536	4 202	9 278

The five fires in the large fire class (500 – 1 500 ha) resulted in a total burnt area of 4 202 ha, which supports the notion that extreme fires should be investigated in detail to determine why these few became disaster fires.

3.2.12.3 Correlation between number of fires and distance to plantation office

As the compartment numbers were recorded for fire records in the main database, the distance from the compartment to the plantation office was calculated by using GIS.

The number of fires for each distance (0 – 0.99 km; 1 – 1.99 km, etc.) were calculated to see if any trend could be found up to 15 km from the office (Figure 3.7). The relationship between number of fires and distance to the plantation office was tested with linear regression. The results of the analysis of variance are shown in Table 3.30.

Table 3.30: Analysis of variance for frequency of fires and distance to plantation office

Source	n	R^2	MSE	F	p
Distance to plantation office	15	0.87	55.45	83.9	<0.05

A strong relationship exists between number of fires and distance from the plantation office as is shown by the high R^2 and highly significant F-value. It is noteworthy that relatively few fires start within the first kilometre from the office.

3.2.12.4 Correlation between number of fires and distance to staff village

To further analyse the fire data, the distance from each fire to the nearest staff village was calculated.

The results are shown in Figure 3.8. Although it shows a high tendency of fires close to the staff village, the actual distance (up to 5 km from the staff village) makes it very difficult to put management strategies into place. Possible management strategies could include planting a more fire resistant species, do prescribed burning under the trees to reduce fuel load and to prepare wide internal fire belts around staff villages (Luke and McArthur, 1978, p. 133).

As with the relationship between number of fires and distance to the plantation office a similar test with linear regression was done on the relationship between number of fires and distance to the nearest staff village. The results of the analysis of variance are shown in Table 3.31.

Table 3.31: Analysis of variance for frequency of fires and distance to staff village

Source	n	R^2	MSE	F	p
Distance to plantation office	15	0.78	123.02	48.38	<0.05

A strong relationship also exists between number of fires and distance to the nearest staff village as with distance to plantation office as is shown by the high R^2 value.

As most fires are caused by people, an analysis was done to compare people-related fires and distance to the staff village. The results of the number of people-caused fires and distance to the staff village are in Table 3.32.

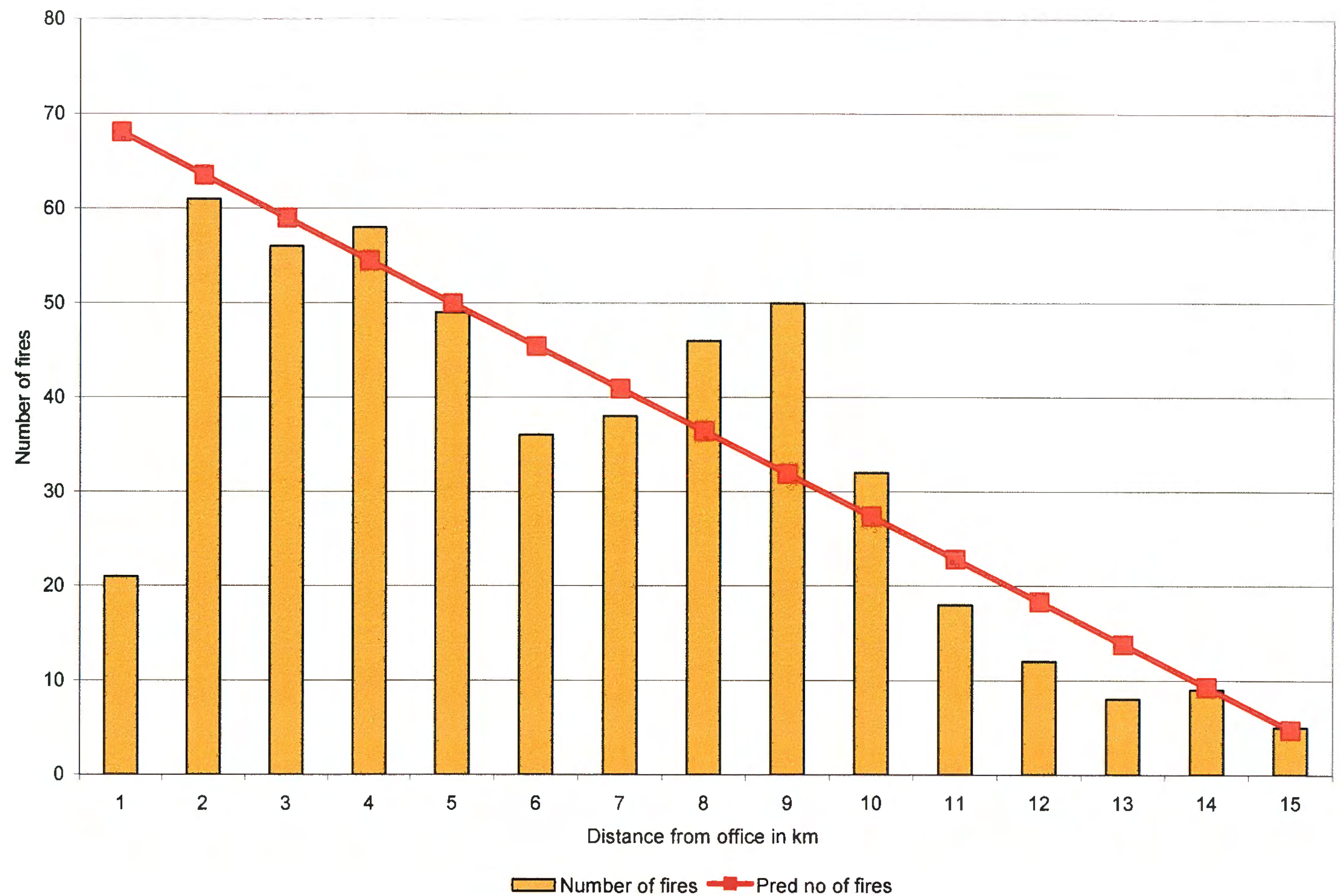

Figure 3.7: Number of fires in relation to distance from office

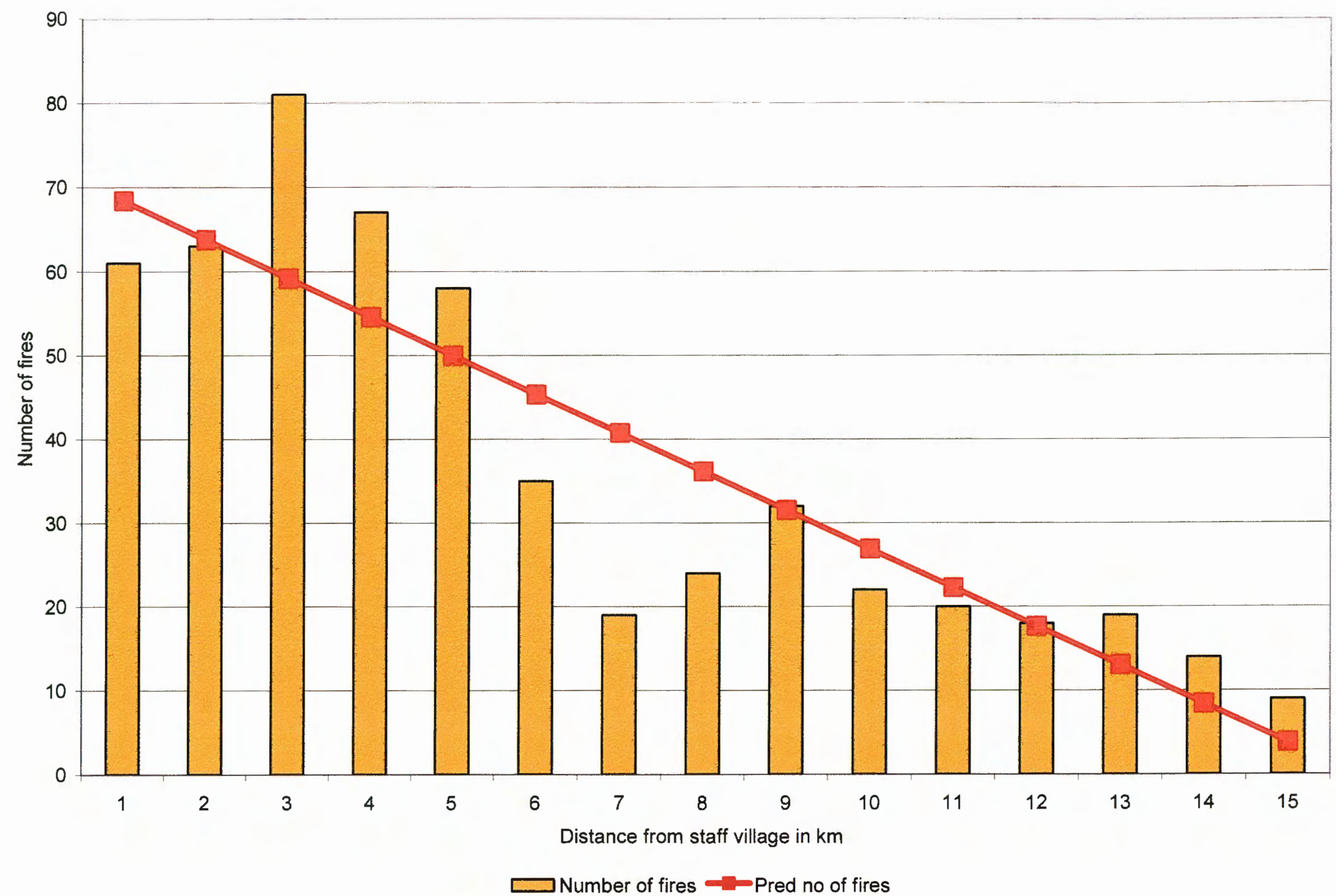

Figure 3.8: Number of fires in relation to distance from staff village

Table 3.32: Correlation between people related fires and distance to staff village

Distance from staff village (km)	Number of fires	%
0 – 0.99	41	15.5
1 – 1.99	42	15.8
2 – 2.99	37	14.0
3 – 3.99	29	10.9
4 – 4.99	22	8.3
5 – 5.99	15	5.7
6 – 6.99	5	1.9
7 – 7.99	10	3.8
8 – 8.99	11	4.1
9 – 9.99	12	4.5
10 +	41	15.5
Total	265	100

The information again shows a higher % fires in the first five kilometres around staff villages. As many of the staff villages are close to towns, and are serviced by public roads, the results are not very valuable from a fire management viewpoint.

3.2.12.5 Areas burnt per fire cause

In order to determine the severity of each cause in terms of areas burnt, the data in all three datasets were analysed. The results are shown in Table 3.33.

Table 3.33: Area burnt and fire frequency per cause

Fire cause	Area burnt (ha)	Number of fires	Area burnt per fire (ha)
Slash burning	77.1	8	9.6
Chainsaws	13.6	6	2.3
Children	293.1	17	17.2
Contractors	3.9	9	0.4
Fire break burning	455.3	95	4.8
Honey hunters	386.9	101	3.8
Neighbours	1 330.1	25	53.2
Smokers	2 628.1	150	17.5
Picnickers	31.9	21	1.5
Suspected arson	738.2	131	5.6
Refuse dumps	1 202.0	3	400.6
Power lines	82.9	8	10.4
Unknown	2 176.2	61	35.7
Other	105.6	26	4.1
Lightning	341.3	185	1.8
Total	**9 866 ha**	**846**	**11.7**

There was one large fire from a sawdust heap next to a sawmill that had a great impact on the "refuse dump" statistics. This specific fire occurred in June 1994 on Brooklands at 13h30 under very unfavourable weather conditions. Other causes that resulted in major fires on average were fires caused by neighbours and fires started by children and smokers. Fires caused by honey hunters and lightning were relatively small on average (3.8 ha and 1.8 ha respectively).

These data were also analysed into cause groups for use in Chapter 4. Areas damaged and fire frequency for each cause group are as follows:

Table 3.34: Area burnt and fire frequency per cause groups

Cause group	Area burnt (ha)	Number of fires
Honey hunters	386.9	101
Lightning	341.3	185
Work related	730.5	143
People related	8 407.5	417
Total	**9 866.2**	**846**

People related fires, e.g. arson, smokers, children, and neighbours are the most common and cause nearly 50% of all plantation fires, and 85% of the total damage. This category is however also the most difficult to manage as it involves psychological behaviour patterns and social and economic influences. Management actions needed are education of the public, regulation of public use and law enforcement measures.

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CHAPTER 4: STRATEGIC FIRE MANAGEMENT PLANNING USING A FIRE PREDICTION MODEL

4.1 INTRODUCTION

The fire reports for 846 fires in KLF plantations during the period 1950 – 1999 were analysed in Chapter 3. During this period these fires resulted in a plantation burnt area of 9 866 ha and extinguishing costs of R5.3 million (calculated at 2001 costs using a PPI index value, refer to paragraph 3.2.7).

The original objective in analysing the KLF fire reports was to develop a fire risk model for the KLF plantations in the Mpumalanga North area. To develop such a risk model, a prediction of the cause of the fire, occurrence and intensity are required. For this purpose various sub-models were required to predict the probability of:

- The cause and frequency of fires
- Such fires spreading and becoming large fires.

A model predicting cause and frequency of fires, based on historic data, could be developed successfully by starting with an initial model and then refining it. However, a model on spread and intensity of fires could not be developed from the existing dataset, largely due to gaps and inconsistencies in climatic data. A literature review was also undertaken to study fire prediction by using Poisson models (Mandallaz and Ye, 1997) and geographic information systems (Backmann and Allguwer, 1998).

The data collected from the fire reports were stored in an Excel spreadsheet. During the development of the model additional data on fire cause were added. A total of 846 fire data records were used, with 742 relating to plantation fires. Some of the data variables had to be grouped into categories for processing with the CATMOD procedure (Categorical data modelling) in SAS® (Statistical Analysis System). The CATMOD procedure is generally used to analyse data that can be represented by a contingency table. It fits linear models to functions of response frequencies and can be used for linear modelling, log-linear modelling, logistic regression and repeated measurement analysis (SAS, 1990). The following categories were adopted:

Veld type:
- Plantation
- Open land

Cause of Fire: The 27 causes were grouped into:
- Lightning
- Honey hunters
- People related
- Work related

Fire season:
- High (July – Oct)
- Low (Nov – Feb)
- Medium (March – June)

Day of the Week:
- Weekday (Mon – Fri)
- Weekend (Sat – Sun)

Time of day:
- Morning (03h00 – 09h59)
- Day (10h00 – 17h59)
- Night (18h00 – 02h59)

Area burnt:
- Small (0 to 0.01 ha)
- Medium (0.01 to 0.1 ha)
- Large (greater than 0.1 ha)

Although an area of 0.1 ha cannot be considered large, the high number of "small" fires forced the inclusion of this classification of areas burnt for analysis purposes.

Graphical, as well as correlation and regression analyses were done to establish major relationships between variables. Many gaps and inconsistencies were identified in the data relating mainly to climatic data, which in many cases were not properly recorded at the time of fire reporting. Substitute data from weather stations further afield did not correlate well with locally recorded data. Climate factors that are important to fire management are temperature, humidity, rainfall and wind speed.

Especially wind speed and humidity were difficult to measure in the past as was explained in paragraph 3.2.11 and was therefore seldom in the fire reports.

The development of a model incorporating weather data and areas burnt was not possible as most of the fires (95%) were very small and quickly extinguished. Their size or intensity did not relate to climatic, physiograhic and management factors and many had missing or substituted values. Dependent variables used were fire size (in many cases 10 m^2 in size) and duration of fire (time difference between arrival at fire and having the fire under control).

Independent variables tested in the model varied from climatic, physiographic (slope, aspect) to management (species, age-class, distance from office, reaction-time). The variables were categorised into classes and run with the CATMOD (SAS®) procedure, but no meaningful model could be developed. Wind speed and wind direction were significant in some of the models but, due to incomplete data, could not be used.

4.2 FIRE PREDICTION MODEL

Analysis of the data from fire reports showed that the data could be used for general fire-cause and frequency prediction, using time and date variables as predictors. Spatial variables such as distance from office or compound did not seem to have significant effects and rather confounded the main effects of time of the year (season), time of the week (weekday or weekend) and time of the day on predicting the fire-cause and frequency. Tests were done to determine the significance of interactions between main effects, but they were all non-significant.

4.2.1 Results from the CATMOD procedure

The results from the CATMOD procedure are summarised in Tables 4.1, 4.2 and 4.5.

The 27 fire causes, as identified on the fire report form used in the South African forestry Industry, was grouped into 4 groups (paragraph 3.2.6.4) and is shown in Table 4.1.

Table 4.1 Cause of fire response variables

Response	Cause of fire
1	Honey hunters
2	Lightning
3	People
4	Work related

Table 4.2 gives the results from the maximum likelihood analysis of variance. The χ^2-test statistic indicates that time-of-day, fire season and time-of-week are highly significant.

Table 4.2 Maximum likelihood analysis of variance

Source	DF	Chi-Square	Pr > ChiSq
Intercept	3	114.23	<.0001
TIME_OF_DAY	6	55.50	<.0001
FIRE_SEASON	6	105.32	<.0001
TIME_OF_WEEK	3	32.78	<.0001
Likelihood Ratio	36	42.38	0.2151

4.2.2 Goodness of fit analysis

The likelihood ratio in Table 4.2, being non-significant (P = 0.2151),indicates that the model is independent and fits well. Figure 4.1 shows that the variation between residual and predicted probabilities are decreasing slightly with increasing value of predicted probability. This indicates some heteroscedasticity in the data. Table 4.3 gives the probabilities and Table 4.4 the predicted frequencies for the different combinations of time of day, fire season, time of week and different fire causes.

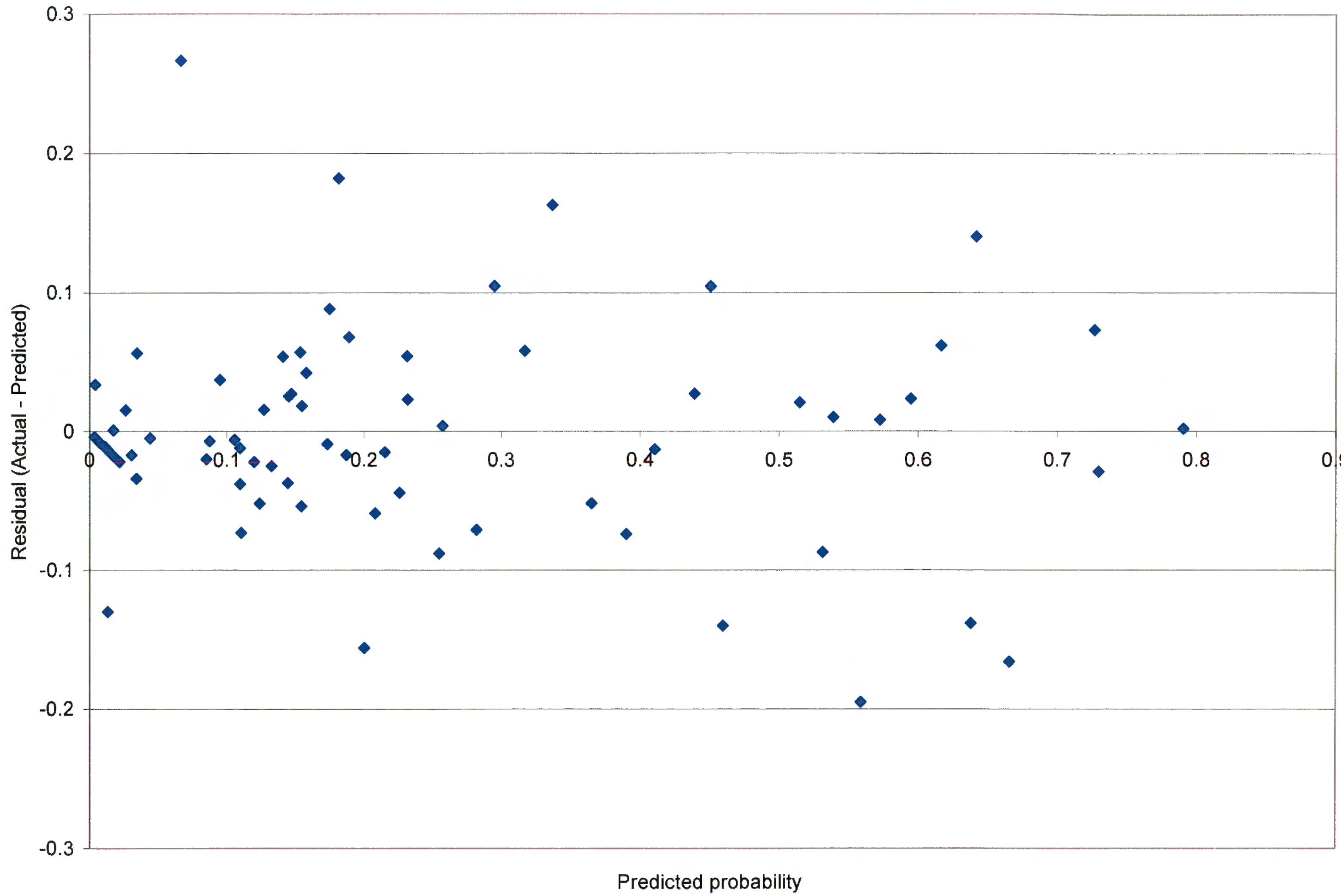

Figure 4.1: Relationship between residual and predicted fire probabilities

Table 4.3 Maximum likelihood predicted values for probabilities

TIME_ OF_DAY	FIRE_ SEASON	TIME_ OF_WEEK	CAUSE_ OF_FIRE	Observed Probability	Standard Error	Predicted Probability	Standard Error	Residual
DAY	HIGH	WEEK	HONEY HUNTERS	0.1705	0.0283	0.145	0.0226	0.0254
			LIGHTNING	0.1705	0.0283	0.187	0.0246	-0.017
			PEOPLE	0.3977	0.0369	0.4107	0.0316	-0.013
			WORK RELATED	0.2614	0.0331	0.2572	0.0308	0.0041
DAY	HIGH	WEEKEND	HONEY HUNTERS	0.1486	0.0414	0.208	0.0364	-0.059
			LIGHTNING	0.2568	0.0508	0.1888	0.0319	0.0679
			PEOPLE	0.5811	0.0574	0.5726	0.0418	0.0085
			WORK RELATED	0.0135	0.0134	0.0306	0.013	-0.017
DAY	LOW	WEEK	HONEY HUNTERS	0.0182	0.018	0.0173	0.0123	0.0009
			LIGHTNING	0.6182	0.0655	0.5947	0.0528	0.0235
			PEOPLE	0.2	0.0539	0.2149	0.04	-0.015
			WORK RELATED	0.1636	0.0499	0.1731	0.0473	-0.009
DAY	LOW	WEEKEND	HONEY HUNTERS	0.0417	0.0408	0.0262	0.0187	0.0154
			LIGHTNING	0.5833	0.1006	0.6351	0.0595	-0.052
			PEOPLE	0.375	0.0988	0.3169	0.0566	0.0581
			WORK RELATED	0	0	0.0218	0.0113	-0.022
DAY	MEDIUM	WEEK	HONEY HUNTERS	0.1071	0.0337	0.1443	0.0294	-0.037
			LIGHTNING	0.0714	0.0281	0.1097	0.0246	-0.038
			PEOPLE	0.2857	0.0493	0.2313	0.0344	0.0545
			WORK RELATED	0.5357	0.0544	0.5147	0.0491	0.021
DAY	MEDIUM	WEEKEND	HONEY HUNTERS	0.4	0.098	0.2951	0.0569	0.1049
			LIGHTNING	0.2	0.08	0.1579	0.0381	0.0421
			PEOPLE	0.32	0.0933	0.4597	0.0568	-0.14
			WORK RELATED	0.08	0.0543	0.0873	0.0352	-0.007
EVENING	HIGH	WEEK	HONEY HUNTERS	0.0649	0.0281	0.0852	0.022	-0.02
			LIGHTNING	0.1948	0.0451	0.1408	0.0277	0.054
			PEOPLE	0.7013	0.0522	0.7299	0.036	-0.029
			WORK RELATED	0.039	0.0221	0.0441	0.0164	-0.005
EVENING	HIGH	WEEKEND	HONEY HUNTERS	0.1321	0.0465	0.0949	0.0261	0.0372
			LIGHTNING	0.0377	0.0262	0.1104	0.0255	-0.073
			PEOPLE	0.7925	0.0557	0.7906	0.0352	0.0019
			WORK RELATED	0.0377	0.0262	0.0041	0.0023	0.0337
EVENING	LOW	WEEK	HONEY HUNTERS	0	0	0.0117	0.0089	-0.012
			LIGHTNING	0.5333	0.1288	0.5149	0.0701	0.0185
			PEOPLE	0.4667	0.1288	0.4393	0.0688	0.0274
			WORK RELATED	0	0	0.0341	0.0165	-0.034
EVENING	LOW	WEEKEND	HONEY HUNTERS	0	0	0.0145	0.0111	-0.015
			LIGHTNING	0.5556	0.1656	0.4508	0.0756	0.1047
			PEOPLE	0.4444	0.1656	0.5311	0.0754	-0.087
			WORK RELATED	0	0	0.0035	0.0023	-0.004
EVENING	MEDIUM	WEEK	HONEY HUNTERS	0.1429	0.0661	0.1272	0.0361	0.0157
			LIGHTNING	0.0714	0.0487	0.1239	0.0329	-0.052
			PEOPLE	0.6786	0.0883	0.6165	0.0558	0.0621
			WORK RELATED	0.1071	0.0585	0.1325	0.045	-0.025
EVENING	MEDIUM	WEEKEND	HONEY HUNTERS	0.1	0.0949	0.1542	0.0452	-0.054
			LIGHTNING	0.1	0.0949	0.1057	0.0311	-0.006
			PEOPLE	0.8	0.1265	0.7267	0.0526	0.0733
			WORK RELATED	0	0	0.0133	0.0074	-0.013
MORNING	HIGH	WEEK	HONEY HUNTERS	0.098	0.0416	0.1198	0.0323	-0.022
			LIGHTNING	0.2549	0.061	0.2317	0.0442	0.0232
			PEOPLE	0.549	0.0697	0.5388	0.0519	0.0102
			WORK RELATED	0.098	0.0416	0.1096	0.0329	-0.012
MORNING	HIGH	WEEKEND	HONEY HUNTERS	0.1739	0.079	0.1469	0.0412	0.027
			LIGHTNING	0.0435	0.0425	0.2	0.0452	-0.156
			PEOPLE	0.7826	0.086	0.642	0.0553	0.1406
			WORK RELATED	0	0	0.0111	0.0058	-0.011
MORNING	LOW	WEEK	HONEY HUNTERS	0	0	0.0129	0.01	-0.013
			LIGHTNING	0.5	0.2041	0.6657	0.0705	-0.166
			PEOPLE	0.1667	0.1521	0.2547	0.0614	-0.088
			WORK RELATED	0.3333	0.1925	0.0666	0.0297	0.2667
MORNING	LOW	WEEKEND	HONEY HUNTERS	0	0	0.0176	0.0137	-0.018
			LIGHTNING	0.5	0.3536	0.6379	0.0809	-0.138
			PEOPLE	0.5	0.3536	0.337	0.0785	0.163
			WORK RELATED	0	0	0.0075	0.0047	-0.008
MORNING	MEDIUM	WEEK	HONEY HUNTERS	0.2105	0.0935	0.1533	0.0441	0.0572
			LIGHTNING	0.2632	0.101	0.1747	0.045	0.0885
			PEOPLE	0.3158	0.1066	0.39	0.061	-0.074
			WORK RELATED	0.2105	0.0935	0.282	0.0703	-0.071
MORNING	MEDIUM	WEEKEND	HONEY HUNTERS	0.1818	0.1163	0.2258	0.0627	-0.044
			LIGHTNING	0.3636	0.145	0.1812	0.0503	0.1824
			PEOPLE	0.3636	0.145	0.5585	0.0689	-0.195
			WORK RELATED	0.0909	0.0867	0.0345	0.0176	0.0565

Table 4.4: Maximum likelihood predicted values for frequencies

TIME_ OF_DAY	FIRE_ SEASON	TIME_ OF_WEEK	CAUSE_ OF_FIRE	Observed Frequency	Standard Error	Predicted Frequency	Standard Error	Residual
DAY	HIGH	WEEK	HONEY HUNTERS	30	4.988623	25.52689	3.982559	4.473114
			LIGHTNING	30	4.988623	32.91506	4.324401	-2.91506
			PEOPLE	70	6.493003	72.2838	5.564321	-2.2838
			WORK RELATED	46	5.829003	45.27425	5.426116	0.725746
DAY	HIGH	WEEKEND	HONEY HUNTERS	11	3.060207	15.39145	2.690773	-4.39145
			LIGHTNING	19	3.757875	13.97371	2.361496	5.026285
			PEOPLE	43	4.244233	42.3709	3.094391	0.629104
			WORK RELATED	1	0.99322	2.263939	0.958992	-1.26394
DAY	LOW	WEEK	HONEY HUNTERS	1	0.990867	0.95151	0.676477	0.04849
			LIGHTNING	34	3.603029	32.70804	2.902472	1.291964
			PEOPLE	11	2.966479	11.82166	2.201029	-0.82166
			WORK RELATED	9	2.743588	9.518792	2.600638	-0.51879
DAY	LOW	WEEKEND	HONEY HUNTERS	1	0.978945	0.629731	0.4494	0.370269
			LIGHTNING	14	2.415229	15.24165	1.426851	-1.24165
			PEOPLE	9	2.371708	7.606161	1.358595	1.393839
			WORK RELATED	0	0	0.522463	0.271452	-0.52246
DAY	MEDIUM	WEEK	HONEY HUNTERS	9	2.834734	12.12293	2.466645	-3.12293
			LIGHTNING	6	2.360387	9.213631	2.065659	-3.21363
			PEOPLE	24	4.140393	19.42512	2.890265	4.574882
			WORK RELATED	45	4.570871	43.23832	4.126775	1.761682
DAY	MEDIUM	WEEKEND	HONEY HUNTERS	10	2.44949	7.377489	1.421666	2.622511
			LIGHTNING	5	2	3.947909	0.953637	1.052091
			PEOPLE	8	2.332381	11.49237	1.419632	-3.49237
			WORK RELATED	2	1.356466	2.182234	0.88072	-0.18223
EVENING	HIGH	WEEK	HONEY HUNTERS	5	2.16225	6.56023	1.697691	-1.56023
			LIGHTNING	15	3.47533	10.84053	2.13247	4.15947
			PEOPLE	54	4.016201	56.20135	2.771897	-2.20135
			WORK RELATED	3	1.697974	3.397895	1.261046	-0.39789
EVENING	HIGH	WEEKEND	HONEY HUNTERS	7	2.464847	5.030816	1.383742	1.969184
			LIGHTNING	2	1.387274	5.853362	1.350955	-3.85336
			PEOPLE	42	2.952453	41.89972	1.867873	0.100281
			WORK RELATED	2	1.387274	0.216103	0.122788	1.783897
EVENING	LOW	WEEK	HONEY HUNTERS	0	0	0.17531	0.132779	-0.17531
			LIGHTNING	8	1.932184	7.722948	1.0518	0.277052
			PEOPLE	7	1.932184	6.589572	1.032504	0.410428
			WORK RELATED	0	0	0.512169	0.248147	-0.51217
EVENING	LOW	WEEKEND	HONEY HUNTERS	0	0	0.130809	0.099655	-0.13081
			LIGHTNING	5	1.490712	4.057426	0.680693	0.942574
			PEOPLE	4	1.490712	4.78007	0.678682	-0.78007
			WORK RELATED	0	0	0.031694	0.02066	-0.03169
EVENING	MEDIUM	WEEK	HONEY HUNTERS	4	1.85164	3.560826	1.012009	0.439174
			LIGHTNING	2	1.36277	3.468234	0.921631	-1.46823
			PEOPLE	19	2.471263	17.262	1.563285	1.737995
			WORK RELATED	3	1.636634	3.708935	1.25874	-0.70894
EVENING	MEDIUM	WEEKEND	HONEY HUNTERS	1	0.948683	1.542009	0.452144	-0.54201
			LIGHTNING	1	0.948683	1.057499	0.310604	-0.0575
			PEOPLE	8	1.264911	7.267288	0.526359	0.732712
			WORK RELATED	0	0	0.133204	0.074203	-0.1332
MORNING	HIGH	WEEK	HONEY HUNTERS	5	2.12363	6.112169	1.64885	-1.11217
			LIGHTNING	13	3.112278	11.81795	2.251999	1.182054
			PEOPLE	28	3.553512	27.4784	2.647755	0.521604
			WORK RELATED	5	2.12363	5.59149	1.677413	-0.59149
MORNING	HIGH	WEEKEND	HONEY HUNTERS	4	1.817787	3.378449	0.94794	0.621551
			LIGHTNING	1	0.978019	4.599382	1.039111	-3.59938
			PEOPLE	18	1.978141	14.76585	1.271259	3.234151
			WORK RELATED	0	0	0.256319	0.134527	-0.25632
MORNING	LOW	WEEK	HONEY HUNTERS	0	0 0	.077489	0.060032	-0.07749
			LIGHTNING	3	1.224745	3.994201	0.422968	-0.9942
			PEOPLE	1	0.912871	1.528471	0.36867	-0.52847
			WORK RELATED	2	1.154701	0.39984	0.178405	1.60016
MORNING	LOW	WEEKEND	HONEY HUNTERS	0	0	0.035151	0.027366	-0.03515
			LIGHTNING	1	0.707107	1.275744	0.161813	-0.27574
			PEOPLE	1	0.707107	0.674063	0.15693	0.325937
			WORK RELATED	0	0	0.015042	0.009452	-0.01504
MORNING	MEDIUM	WEEK	HONEY HUNTERS	4	1.777047	2.912648	0.837453	1.087352
			LIGHTNING	5	1.91943	3.319409	0.855814	1.680591
			PEOPLE	6	2.026145	7.409635	1.159682	-1.40963
			WORK RELATED	4	1.777047	5.358308	1.335048	-1.35831
MORNING	MEDIUM	WEEKEND	HONEY HUNTERS	2	1.279204	2.484095	0.689163	-0.48409
			LIGHTNING	4	1.595448	1.993318	0.553139	2.006682
			PEOPLE	4	1.595448	6.143587	0.758281	-2.14359
			WORK RELATED	1	0.953463	0.379	0.193643	0.621

The conclusion is that the model fits the data adequately, which is indicated by the log-likelihood ratio being non-significant (Table 4.2) and also by the distribution of residuals as indicated in Figure 4.1.

4.2.3 Interpretation of the fire model parameters

The response is multinomial and is regarded as being nominal rather than ordinal. That is, we assumed that there is no inherent order in the values of CAUSE OF FIRE. As there was no significant interaction between the predictor variables, the interpretation of the model is greatly simplified. One merely needs to interpret the parameter effects one by one to understand the impacts of the different levels of the variables on CAUSE OF FIRE. The parameter estimate table is presented below and some (not all) parameter estimates are interpreted.

Table 4.5: Analysis of maximum likelihood estimates

Parameter		Function Number	Estimate	Standard Error	Chi-Square	Pr > ChiSq
Intercept		1 honey	0.4933	0.3704	1.77	0.1829
		2 lightning	1.7080	0.2863	35.58	<.0001
		3 people	2.3463	0.2763	72.12	<.0001
Time_Of_Day	DAY	1	-0.6310	0.2262	7.78	.0053
	DAY	2	-0.8487	0.2095	16.42	<.0001
	DAY	3	-1.1541	0.1899	36.92	<.0001
	EVENING	1	0.5999	0.3235	3.44	0.0636
	EVENING	2	0.6302	0.3012	4.38	0.0364
	EVENING	3	1.1839	0.2757	18.44	<.0001
Fire_Season	HIGH	1	0.8095	0.2979	7.38	0.0066
	HIGH	2	-0.1086	0.1845	0.35	0.5559
	HIGH	3	0.5064	0.1742	8.45	0.0036
	LOW	1	-0.9204	0.5266	3.05	0.0805
	LOW	2	1.4445	0.2489	33.69	<.0001
	LOW	3	0.2552	0.2598	0.97	0.3259
Time_Of_Week	WEEK	1	-1.2449	0.2360	27.82	<.0001
	WEEK	2	-1.0694	0.2311	21.41	<.0001
	WEEK	3	-1.2307	0.2209	31.05	<.0001

There are always three “Function Numbers” displayed (or rather, one less than the number of categories of the dependent variable. CAUSE_OF_FIRE in Table 4.1 has four categories, therefore three function numbers’ are displayed. The first function number 1 relates to “Honey Hunters” , function number “2” relates to “Lightning” and function number “3” relates to “People”. The fourth function number (not shown) relates to “Work Related”, which is used as the reference variable by the model.

The value of this parameter, which can easily be calculated as the sum of all four parameters must be equal to zero. For instance, for TIME_OF_DAY being "Day" the parameter estimate of "Work Related" is 2.6338 (as the estimates of the first three functions –0.6310, -0.8487, -1.1541 add up to –2.6338) (Table 4.5).

Now, odds ratios are usually used to quantify the effects of significant independent variables on the dependent ones. Since we have no interaction effects, the odds ratios are just the natural exponent of the estimate, i.e. [exp(estimate)].

For instance, at TIME_OF_DAY='DAY', FIRE_SEASON='HIGH' and TIME_OF_WEEK='WEEK' the estimated logits (or the natural log of the odds) are:

Log[prob(Honey Hunters) / prob(Work Related)] = 0.4933 + (-0.6310) + 0.8095 + (-1.2449) = -0.5731.

The odds ratio of this logit is exp(-0.5731) = 0.5638 meaning that the odds of a fire being caused by honey hunters during the DAY time in the HIGH fire season during the week is 0.5638 times that of the one being caused by Work Related phenomena.

Log[prob(Lightning) / prob(Work Related)] = 1.7080 + (-0.8487) + (-0.1086) + (-1.0694) = -0.3187 with the odds ratio = exp(-0.3187) = 0.7271. That is, the odds of a fire caused by lightning during the DAY time in the HIGH fire season during the WEEK is 0.7271 times that of the one being caused by Work Related fires. If one takes the inverse of the odds ratio, for example the inverse of 0.7271 is 1 / 0.7271 = 1.375, then the interpretation is that Work Related Fires cause 1.375 times more fires than Lightning in the DAY time, HIGH fire season during the WEEK.

This way one can continue to scrutinise the entire table. Note, though, that the parameter estimates can all be calculated by keeping in mind that the sum of the parameter values add up to zero (as has been demonstrated above). The calculation of the estimates not shown by CATMOD is shown below in Table 4.6.

Table 4.6: Calculation of estimates

Time of week	Honey Hunters	Lightning	People	Work Related	Sum
Week	-1.2449	-1.0694	-1.2307	3.545	0
Weekend	1.2449	1.0694	1.2307	-3.545	0
Sum	0	0	0	0	0

Fire Season	Honey Hunters	Lightning	People	Work Related	Sum
High	0.8095	-0.1086	0.5064	-1.2073	0
Low	-0.9204	1.4445	0.2552	-0.7793	0
Medium	0.1109	-1.3359	-0.7616	1.9866	0
Sum	0	0	0	0	0

The parameters relating to Weekend were not supplied by SAS® at all, but can be calculated as they must add up to zero. The same can be done with all combinations of the CAUSE_OF_FIRE variable, as well as the independent variables.

By themselves, the parameter estimates are even easier to interpret. For instance, the value of the estimate for DAY Function Number 1 is –0.6310 (Table 4.5). Note that this estimate relates to the Honey Hunters category of the CAUSE_OF_FIRE variable. Taking the exponent of this value, we obtain the odds ratio of exp(-0.6310) = 0.5321. In other words, when it is DAY time, the odds of a fire being caused by Honey Hunters is 0.5321 of that being caused by work related fire causes (Table 4.5).

The odds of a fire being caused by Honey Hunters in the HIGH Fire Season is 2.2467 times that of a fire being caused by Work Related causes, as Work Related causes is the reference category (exp (0.8095) = 2.2467).

Calculating probabilities with equations:

The probability of a fire caused by honey hunters in day time, in high fire season and in a week day, is calculated as follows:

Time of Day = Day; Fire season = High; Time of Week = Week;

p1_p4 = 0.4933 +(-0.6310) +0.8095 +(-1.2449) = -0.5731; *honey_work

p2_p4 = 1.708 + (-0.8487) + (-0.1086) +(-1.0694) = -0.3187 *lightning_work

p3_p4 = 2.3463 +(-1.1541) + 0.5064 +(-1.2307) = 0.4679 *people_work

then:

p1=exp(p1_p4)/(1+exp(p1_p4)+exp(p2_p4)+exp(p3_p4));

p1 = 0.14502 (see Table 4.3 first line under Predicted probability)

Table 4.4 gives the predicted frequencies of all combinations for the system. These frequencies reflect the historic occurrences of fires by cause over time. To relate them to some form of dimensionless probability (or percentage), their sum can be determined and then each individual frequency divided by this total. The predicted frequency for the different combinations of time of day, fire season, day of week and fire cause divided by the total number of fires (742) gives the model probability (x 100) as is shown in Table 4.7. These values can then be used as scores representing the probability (likelihood) of any combination of variables occurring by fire cause. An example is to take the relevant sample size of 176, of sample 1 (day time; high fire season and week day) in Table 4.4. The probability of 0.14502 as calculated before, times the relevant sample size (176) gives the predicted frequency of 25.52689 (as in Table 4.4).

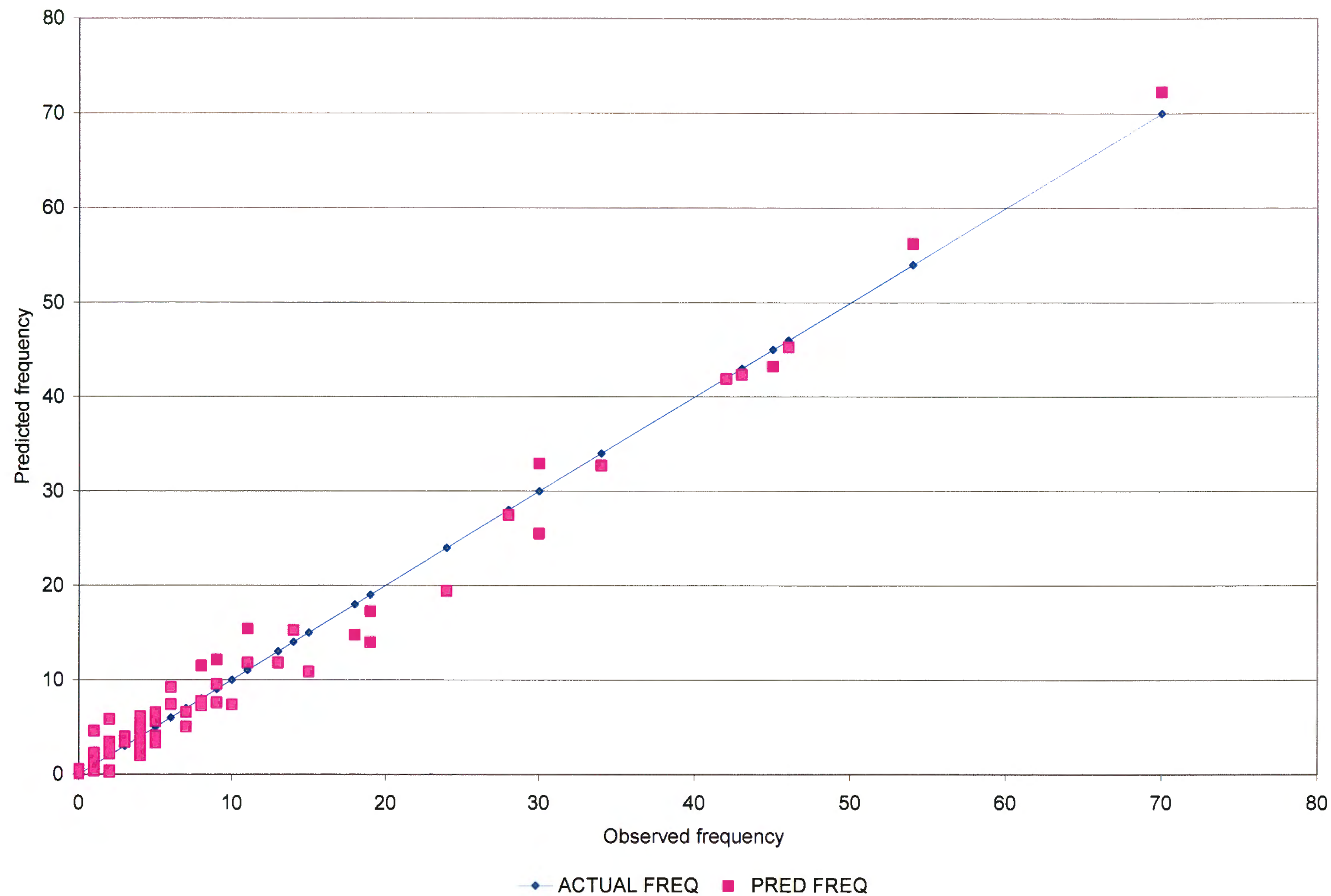

Figure 4.2: Predictive ability of the fire prediction model

4.2.4 Predictive ability of the fire prediction model

Based on the predicted frequency information in Table 4.4 for all combinations of cells, the predictive ability was evaluated to determine how well the model works. The results are shown in Figure 4.2.

The criteria mean bias ($\overline{B}$) and standard deviation of differences (S_D) were used to evaluate the predictive ability of the model. The standard deviation of differences measures the precision of prediction. High accuracy is obtained by low mean bias and high precision.

$$\overline{B} = mean\ bias,\ defined\ as: \frac{1}{n}\sum_{i=1}^{n} (y_{i-}\hat{y}_i)^2$$

y_i = observed value of parameter of interest

$\hat{y}_i$ = estimated value of parameter of interest

S_D = standard deviation of the difference defined as:

$$\sqrt{\frac{1}{n-1}\left[\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 - \frac{\left(\sum_{i=1}^{n}(y_i - \hat{y}_i\right)^2}{n}\right]}$$

The values for mean bias and standard deviation are:

Mean bias ($\overline{B}$) = 3.61 E – 07

Standard deviation (S_D) = 4.23 E – 08

As both these values are very low a high accuracy is obtained for the model.

4.2.5 Application of the model

4.2.5.1 Introduction

As was discussed in detail in paragraph 4.2.3 the model probabilities for the different combinations of time of day, fire season, day of week and fire causes are derived from the predicted frequencies and relevant sample sizes.

These model probabilities (Table 4.7) can be used as scores representing the likelihood of any combination of variables occurring by fire cause. From the probabilities calculated in Table 4.7 it is possible to select and add probabilities e.g. for honey hunters, lightning, people related fires, work related fires or a combination of all the causes. Summaries of these probabilities can be used in the development of guidelines for fire management planning. Table 4.8 shows an example of a table with the probabilities for various combinations of the predictor variables for all fire causes combined (CAUSE = All). These probabilities in Table 4.8 are expressed as % value.

Table 4.7: Summary of fire probabilities by day, fire season and cause

Time of day	Fire season	Weekday/ Weekends	Fire cause	Actual frequency	Actual frequency %	Predicted frequency %	Model % probability
Day	High	Week	Honey hunters	30	4.04	25.5	3.44
Day	High	Week	Lightning	30	4.04	32.9	4.43
Day	High	Week	People	70	9.43	72.2	9.74
Day	High	Week	Work related	46	6.10	45.3	6.10
Day	High	Weekend	Honey hunters	11	1.48	15.4	2.07
Day	High	Weekend	Lightning	19	2.50	14.0	1.88
Day	High	Weekend	People	43	5.70	42.3	5.71
Day	High	Weekend	Work related	1	0.13	2.2	0.30
Day	Low	Week	Honey hunters	1	0.13	0.9	0.12
Day	Low	Week	Lightning	34	4.50	32.7	4.40
Day	Low	Week	People	11	1.48	11.8	1.59
Day	Low	Week	Work related	9	1.20	9.5	1.28
Day	Low	Weekend	Honey hunters	1	0.13	0.6	0.08
Day	Low	Weekend	Lightning	14	1.88	15.2	2.05
Day	Low	Weekend	People	9	1.20	7.6	1.02
Day	Low	Weekend	Work related	0	0	0.5	0.07
Day	Medium	Week	Honey hunters	9	1.21	12.1	1.63
Day	Medium	Week	Lightning	6	0.81	9.2	1.24

Time of day	Fire season	Weekday/ Weekends	Fire cause	Actual frequency	Actual frequency %	Predicted frequency %	Model % probability
Day	Medium	Week	People	24	3.13	19.4	2.61
Day	Medium	Week	Work related	45	6.00	43.2	5.82
Day	Medium	Weekend	Honey hunters	10	1.30	7.3	0.99
Day	Medium	Weekend	Lightning	5	0.67	3.9	0.53
Day	Medium	Weekend	People	8	1.08	11.4	1.54
Day	Medium	Weekend	Work related	2	0.26	2.1	0.29
Evening	High	Week	Honey hunters	5	0.67	6.5	0.88
Evening	High	Week	Lightning	15	2.00	10.8	1.46
Evening	High	Week	People	54	7.27	56.2	7.57
Evening	High	Week	Work related	3	0.40	3.3	0.45
Evening	High	Weekend	Honey hunters	7	0.94	5.0	0.67
Evening	High	Weekend	Lightning	2	0.26	5.8	0.78
Evening	High	Weekend	People	42	5.66	41.8	5.64
Evening	High	Weekend	Work related	2	0.26	0.2	0.02
Evening	Low	Week	Honey hunters	0	0	0.1	0.02
Evening	Low	Week	Lightning	8	1.08	7.7	1.04
Evening	Low	Week	People	7	0.94	6.5	0.88
Evening	Low	Week	Work related	0	0	0.5	0.06
Evening	Low	Weekend	Honey hunters	0	0	0.1	0.01
Evening	Low	Weekend	Lightning	5	0.67	4.0	0.54
Evening	Low	Weekend	People	4	0.54	4.7	0.64
Evening	Low	Weekend	Work related	0	0	0	0.00
Evening	Medium	Week	Honey hunters	4	0.54	3.5	0.48
Evening	Medium	Week	Lightning	2	0.27	3.4	0.46
Evening	Medium	Week	People	19	2.50	17.2	2.32
Evening	Medium	Week	Work related	3	0.40	3.7	0.50
Evening	Medium	Weekend	Honey hunters	1	0.13	1.5	0.20
Evening	Medium	Weekend	Lightning	1	0.13	1.0	0.14
Evening	Medium	Weekend	People	8	1.08	7.2	0.97
Evening	Medium	Weekend	Work related	0	0	0.1	0.01
Morning	High	Week	Honey hunters	5	0.67	6.1	0.82
Morning	High	Week	Lightning	13	1.73	11.8	1.59
Morning	High	Week	People	28	3.70	27.4	3.70
Morning	High	Week	Work related	5	0.67	5.5	0.75
Morning	High	Weekend	Honey hunters	4	0.54	3.3	0.45
Morning	High	Weekend	Lightning	1	0.13	4.5	0.62
Morning	High	Weekend	People	18	2.40	14.7	1.99
Morning	High	Weekend	Work related	0	0	0.2	0.03
Morning	Low	Week	Honey hunters	0	0	0	0.01
Morning	Low	Week	Lightning	3	0.40	3.9	0.53
Morning	Low	Week	People	1	0.13	1.5	0.20
Morning	Low	Week	Work related	2	0.27	0.3	0.05
Morning	Low	Weekend	Honey hunters	0	0	0	0.00
Morning	Low	Weekend	Lightning	1	.013	1.2	0.17
Morning	Low	Weekend	People	1	0.13	0.6	0.09
Morning	Low	Weekend	Work related	0	0	0	0.00
Morning	Medium	Week	Honey hunters	4	0.54	2.9	0.39
Morning	Medium	Week	Lightning	5	0.67	3.3	0.44
Morning	Medium	Week	People	6	0.81	7.4	0.99
Morning	Medium	Week	Work related	4	0.54	5.3	0.72

Time of day	Fire season	Weekday/ Weekends	Fire cause	Actual frequency	Actual frequency %	Predicted frequency %	Model % probability
Morning	Medium	Weekend	Honey hunters	2	0.27	2.4	0.33
Morning	Medium	Weekend	Lightning	4	0.54	1.9	0.26
Morning	Medium	Weekend	People	4	0.54	6.1	0.82
Morning	Medium	Weekend	Work related	1	0.13	0.3	0.05
Total number of fires				**742**	**100.00**		**100.00**

Table 4.8: Fire probabilities expressed as % values for all fire causes

Fire cause	All

Sum of % probability		Time of day			
Fire season	Weekday / Weekend	Day	Night	Morning	Total
Low	Week	7.41	2.02	0.80	10.24
	Weekend	3.23	1.21	0.26	4.71
Low total		10.64	3.23	1.07	14.95
Medium	Week	11.32	3.77	2.56	17.65
	Weekend	3.36	1.34	1.48	6.19
Medium total		14.69	5.12	4.04	23.85
High	Week	23.71	10.37	6.87	40.97
	Weekend	9.97	7.14	3.09	20.21
High total		33.69	17.52	9.97	61.18
Total		59.02	25.87	15.09	100.00

The information in Table 4.8 represents the probability by fire cause under various seasonal and time conditions, but does not give an indication of the number of fires. If the dataset had contained records of all the fires that occurred over the period of investigation, the frequency model of the number of fires per annum would have been:

Annual number of fires = (Total number of fires in dataset/Number of years of fire records kept)

This could, however, not be done with the present dataset as not all fires that occurred have been included. A dataset containing all fire occurrences for the study area for a specific time period, must be compiled and the above calculation made. Use the probabilities in Table 4.8 to determine the expected frequency of fires for the year by cause, season and time of day.

The statistical analysis in Chapter 3 showed that the eight plantations experienced several disastrous fires over the 47 years, resulting in large plantation areas burnt (1952 – 1999). The aim of this study was to put all these statistics in a format for use as guidelines in fire management planning.

The average number of fires per year over the 47 year period was18 fires. If only the last 20 years are considered, the average number of fires per year rised to 25. For planning purposes the figure of 25 fires per year will be used as it is likely that the more recent fire statistics are more complete, because some of the old fire files could be missing.

The average area lost as a result of wildfires over the 47 years was 209.9 ha per year. Once again, for data of the last 20 years, the average increased to 242.9 ha burnt per year. This figure will be used in fire management planning.

The above frequencies are based on the data of the original 667 fires. The causes of wildfires in the Mpumalanga North area are: people: 48%; work related: 16.5%; lightning: 22% and honey hunters: 13.5%.

Frequencies of fires must also be linked to area burnt per cause. As was discussed in paragraph 3.2.12.5, the areas burnt per fire cause are shown in Table 4.9 below:

Table 4.9: Area burnt per fire cause

Fire cause	Area burnt (ha)	%
Honey hunters	386.9	3.9
Lightning	341.3	3.5
People related	8 407.5	85.2
Work related	730.5	7.4
Total	**9 866.2**	**100**

If area burnt figures and fire frequency per fire cause are compared, it shows that lightning caused 22% of the plantation fires but is only responsible for 3.5% of plantation fire damage. According to Le Roux (1988) lightning accounts for 12.6% of plantation fires in South Africa, burn 12.16% of total plantation area and is only responsible for 1.09% of damage caused. The worst cause is people (49%), which contributes 85% of the damage (Table 4.10).

Table 4.10: Comparison between area burnt and fire frequency per fire cause

Fire cause	% of total area burnt	% of total number of fires
Honey hunters	3.9	12.0
Lightning	3.5	22.0
People related	85.2	49.0
Work related	7.4	17.0
Total	**100**	**100**

From a management viewpoint it is best to focus on fire causes that are responsible for most damage. Based on the fire statistics of the past 47 years, it is definitely people related fires which include: Unknown, suspected arson, smokers, picnickers, children and fires from neighbours. Each of the main causes of plantation fires is discussed below in more detail.

4.2.5.2 People related fires

Table 4.11: Probability table predicting likelihood of "people" caused fires

Fire cause	**People**

Sum of % Probability		**Time of day**			
Fire season	**Weekday/ weekend**	**Day (10h00 – 17h59)**	**Night (18h00 – 02h59)**	**Morning (03h00 – 09h59)**	**Total**
Low	Week	1.59	0.88	0.20	2.68
	Weekend	1.02	0.64	0.09	1.76
Low total		2.61	1.53	0.29	4.44
Medium	Week	2.61	2.32	0.99	5.94
	Weekend	1.54	0.97	0.82	3.35
Medium total		4.16	3.30	1.82	9.29
High	Week	9.74	7.57	3.70	21.01
	Weekend	5.71	5.64	1.99	13.34
High total		15.45	13.22	5.69	34.36
Total		22.23	18.05	7.816	48.11

A total of 319 fires were caused by people. These represented 49% of the total number of fires, and included fires started by arson, contractors, cooking or warming fires, children, picnickers and by neighbours. As this category caused almost half of all the wildfires it is an extremely important category to manage. From the information in Table 4.11 the following can be seen:

- Approximately 83% of people-related fires occurred during the "day" or night. Few people-caused fires occurred between 03h00 and 09h59 in the morning.
- Approximately 71% of people caused fires occurred in the high fire season, probably due to the ease of ignition during the dry months (May to October).

It is obvious that movement of people must be restricted within plantations during the high fire season. Continuous communication of Fire Danger Index (FDI), impacts of wildfires and fire safety must be maintained with local communities, schools, contractors and visitors to the plantation (CSIR, 2000 and Holmes, 1995).

4.2.5.3 Work related fires

Table 4.12: Probability table predicting likelihood of "work " related fires

Fire cause	**Work related**

Sum of % probability		Time of day			
Fire season	**Weekday/ Weekends**	**Day (10h00 – 17h59)**	**Night (18h00 – 02h59)**	**Morning (03h00 – 09h59)**	**Total**
Low	Week	1.28	0.06	0.05	1.40
	Weekend	0.07	0.00	0.00	0.07
Low total		1.35	0.07	0.05	1.48
Medium	Week	5.82	0.49	0.72	7.04
	Weekend	0.29	0.01	0.05	0.36
Medium total		6.12	0.51	0.77	7.41
High	Week	6.10	0.45	0.75	7.31
	Weekend	0.30	0.02	0.03	0.36
High total		6.40	0.48	0.78	7.68
Total		13.88	1.07	1.61	16.57

Work activities resulted in 123 fires and included causes such as own burning, welding, chainsaws and power lines. Seventeen percent of all fires in the past were as a result of operational activities within the plantation (Table 4.12). More than 75%

of all work related fires occurred during May, June and July (Table 3.15). Furthermore, most fires (approximately 84%), started during day time, which is understandable if it is caused by own employees working in the plantation. With proper control methods in place and continuous communication with staff about fire hazards, this specific cause could be drastically reduced.

All teams working in the plantation specifically from May to August should be given regular fire talks, have fire fighting equipment with them and be in constant radio contact with the plantation office. During periods of high fire danger they should be withdrawn from normal plantation activities and be utilized in fire protection activities. These can include clearing of water points and airstrips in the plantation, and maintenance of fire equipment (ITTO, 1997).

4.2.5.4 Fires caused by lightning

Table 4.13: Probability table predicting likelihood of lightning caused fires

Fire cause	Lightning

Sum of % probability		Time of day			
Fire season	**Weekday/ Weekends**	**Day (10h00 – 17h59)**	**Night (18h00 – 02h59)**	**Morning (03h00 – 09h59)**	**Total**
Low	Week	4.40	1.04	0.53	5.98
	Weekend	2.05	0.54	0.17	2.77
Low total		6.46	1.58	0.71	8.76
Medium	Week	1.24	0.46	0.44	2.15
	Weekend	0.53	0.14	0.26	0.94
Medium total		1.77	0.60	0.71	3.09
High	Week	4.43	1.46	1.59	7.48
	Weekend	1.88	0.78	0.61	3.29
High total		6.31	2.24	2.21	10.78
Total		14.55	4.44	3.63	22.64

Lightning caused 22% of all fires in the Mpumalanga North Region (154 fires). Table 3.27 indicates that lightning fires occurred mainly during the months September to November and are therefore relatively easy to manage. More than half of these fires occurred during day-time and were therefore more convenient to attend to (Table 4.13).

From a management viewpoint, lookout guards and staff must be made aware of the probabilities of lightning fires during the early spring and summer months when lightning and thunderstorms occur frequently.

4.2.5.5 Fires caused by honey hunters

Table 4.14: Probability table predicting likelihood of fires caused by honey hunters

Fire cause	Honey hunters

Sum of % probability		Time of day			
Fire season	**Weekday/ Weekends**	**Day (10h00 – 17h59)**	**Night (18h00 – 02h59)**	**Morning (03h00 – 09h59)**	**Total**
Low	Week	0.12	0.02	0.01	0.16
	Weekend	0.08	0.01	0.00	0.10
Low total		0.21	0.04	0.01	0.26
Medium	Week	1.63	0.47	0.39	2.50
	Weekend	0.99	0.20	0.33	1.53
Medium total		2.62	0.68	0.72	4.04
High	Week	3.44	0.88	0.82	5.14
	Weekend	2.07	0.67	0.45	3.20
High total		5.51	1.56	1.27	8.35
Total		8.35	2.29	2.02	12.66

Only 71 of the 667 (12%) fires were reported to have been started by honey hunters (Table 4.10). June, July and August were the worst months when 76% of fires in this category occurred and special management actions should be implemented to address this issue. Most honey hunting fires started in day time (Table 4.14) as it is then easy to find beehives and to move through the plantation. Ease of detection of fires during day time must contribute to the fact that fires from honey hunters only cause 3.9% of the total plantation area burnt in the study area (Table 4.9).

Special precautions are needed to either assist staff to collect honey in the plantation or to destroy wild beehives. Bees can also be collected by professional beekeepers. A proper reward system for information on wild beehives in the plantation should be introduced as standard practice (SAFCOL, 2000).

With adequate control and reward systems in place, together with fire awareness and fire safety campaigns, the incidence of fires by honey hunters could be reduced drastically.

4.2.6 Recommendations

The following are strategic fire management guidelines proposed for the KLF plantations in the Mpumalanga North area:

- A system of external belts must be maintained as it is a basic requirement for the Veld and Forest Fire Act 101 of 1998. However, placement of buffer zones needs urgent attention to reduce the risk of large fires. For this purpose riparian zones, indigenous forests, provincial roads and fuel reduction zones within the plantation must be used in combination and in an integrated manner. Judging from the fire records Northern and Western boundaries are the most dangerous, as most winds during fires are from the north-west and north-east (Table 3.25).

- Performance criteria must be put in place, for example:
    - Fire control measures – burnt area and time required to control
    - Fire prevention measures – number of ignitions per cause
    - Organisational efficiency measures – response times, areas burnt. Effectiveness of lookouts in detecting fires needs monitoring (De Ronde, 1992 and De Ronde, 1994).

Table 4.15: Number of fires per plantation (1950 – 1999)

Plantation	Plantation area (ha)	Area % of total plantation area	Number of fires	Number of fires per 1 000 ha
Bergvliet	5 585	11.5	147	26.3
Blyde	4 283	8.8	47	10.0
Brooklands	9 370	19.3	172	18.3
Frankfort	2 811	5.8	50	17.8
Morgenzon	3 374	6.9	36	10.7
Spitskop	3 606	7.4	70	19.4
Tweefontein	12 742	26.4	245	19.2
Wilgeboom	6 721	13.9	79	11.7
Total	48 492	100	846	Average: 16.7

Bergvliet performed rather poorly with 26 fires per 1 000 ha of plantation, compared to the average of 16.7. At Blyde there were only 10.9 fires per 1 000 ha. Even if Bergvliet is compared to Wilgeboom, which has the same problems with weeds and people, it performed badly. From the statistics on fire causes per plantation (paragraph 3.3.1.1), honey hunters, people and work-related fires occur more than twice as frequently at Bergvliet as at Wilgeboom, even though its plantation area is smaller than Brooklands, Tweefontein and Wilgeboom (Table 4.15).

- Focus needs to be on the urban interface as the study area experiences increasing population pressures. More and more people infringe on the natural and plantation environment and therefore special measures are needed at some plantations, e.g. Tweefontein, Wilgeboom and Morgenzon. These measures will have to include special buffer zones and advanced fire suppression planning (De Ronde, 1997 and Calvin, 2000).

- Weed control programmes on a regional level must be implemented and maintained to address factors such as biomass accumulation (and subsequent fire hazard). Continuous assessment of veldfire conditions is needed, as well as proper fuel management. Fuel management in the study area should include activities like slash burning, clearfell-waste management, riparian zone management and special precautions around thinning and pruning debris. Selective use of prescribed burning should also be an important activity used in fuel management.

- Each plantation must carry sufficient fire fighting equipment to be able to cope adequately when fires occur in its area. The region must arrange for major support equipment to be available on strategic locations. The region must set levels and ensure availability of resources throughout the year in accordance with variations in the existing and predicted seasonal trends in weather and fuel characteristics.

- Readiness of resources at plantation level must be based on day to day FDI ratings and existing resource commitments. The most important factors in determining first attack effectiveness are early detection and quick response times.

- Personnel standards must be set by the region. The number and location of special fire fighting teams, as well as appropriate levels of own staff, must be determined and implemented.

- The region and each plantation must maintain a strategic road network for fire protection purposes. Plantations must also ensure that all those roads are maintained and accessible before the onset of the fire season, especially the roads in the vicinity of the plantation office and staff village.

- Plantations managers must construct and maintain strategically located properly signposted water points. They should be of a standard that would ensure the quick and safe operation of firefighting vehicles and pumps.

- The region and each plantation must have a clearly defined strategy on aircraft support. A greater emphasis must be put on dedicated fire fighting teams than on aircraft, due to travel times from Nelspruit airport and the cost factor of aerial support.

- Special management actions must be put in place to remove wild beehives, to collect honey from these beehives under safe conditions and to reward staff for information on the location of wild beehives. This will reduce the number of fires caused by honey hunters.

- Seventy five percent of all fires included in this study were small, as they destroyed only between 0 and 0.9 ha of plantation area. This indicates that fire detection and initial attack are generally very effective. Quick response is always critical and staff and equipment must be capable of achieving quick response times. Bakkie-sakkies (LDV with water tank) remain a good option and should be used by strike teams. Large, expensive, dedicated fire tankers are also needed but the number and utilisation should be reconsidered. An alternative is the use of slip-on watertanks on existing personnel carriers.

- Fire fighting time is an important aspect to consider as it impacts on organisation structures, training levels and incident command centres. It took less than an hour to extinguish 76% of fires, and only 9.7% of all fires took longer than three hours to extinguish (Table 3.6). This emphasises the importance of early detection and quick response times. This also means that there is no need for large quantities of back-up equipment and food in plantation stores.

- Time of day plays an important role in fire occurrence and also fire behaviour. More than half (56%) of total fire ignitions occurred between 10h00 and 16h00.

Due to the warmer day-time temperatures and lower humidities, these fires are more expensive to control, and tend to destroy larger areas. Forest managers must be aware of these factors and ensure that all resources are on full alert to control these fires as quickly as possible.

- The statistics show that on average approximately 240 ha or 0.5% of the total plantation area per annum were lost due to fires. According to KLF figures the weighted average loss based on full salvage recovery amounted to R6 623/ha (2002 costs). The total loss was therefore on average close to R1.6 million per annum. It is a strategic decision by the owner to determine if external insurance is required or not. This study provided useful data regarding fire damage and frequency, and the factors affecting the latter, which could be used by forest owners to assist in such decisions.

- Adopt a month to month focus on fire management, as risks differ according to fuel, climate and people behaviour patterns. The most critical months for fire risk are June and July followed by the months of May, September and October.

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CHAPTER 5: CONCLUSION AND FUTURE PERSPECTIVES ON FIRE MANAGEMENT IN MPUMALANGA NORTH

5.1 EVALUATION OF STUDY GOALS

In this chapter the original study goals, as defined in paragraph 1.3, will be evaluated to determine to what extent they were achieved. Secondly, a few perspectives on possible future fire management decisions will be given, as the forestry industry is currently facing some major changes. These changes are due to new stakeholders, different management structures and pressures from Government regarding labour, environmental and legal aspects.

In Chapter 1 the following study goals were identified:

- Establish a theoretical basis on fire management to form a framework for evaluating fire management in Komatiland Forests (KLF).
- Review the extent to which fire management is performing, based on fire records.
- Analyse fire report data to determine trends and patterns in fire occurrence, behaviour, cause, size and damage caused.
- Develop a model based on the fire data to assist in future fire management decision making.
- Recommend possible guidelines to improve fire management in the Komatiland Forests plantations in Mpumalanga North.

In Chapter 2 a theoretical overview on fire management was given. Aspects covered were fire weather, fuels, fire behaviour and fire effects. Some concepts regarding integrated fire management, such as fire breaks and fuel reduction, were also discussed.

The analysis of historic fire data, based on 47 years of fire reports, was done in Chapter 3. Analyses included reports on fire cause, size and frequency of fires per day, month, year and time of day. The areas burnt per plantation, per cause were analysed in detail to determine correlations, to be used in developing decision making models.

A fire cause and frequency prediction model was developed in Chapter 4, together with a presentation of some possible guidelines to improve fire management in the study area. Aspects which have to be focussed on are the following:

- Corporate issues such as strategic fire management planning and the implementation of an organisation structure supporting efficient and effective fire management.
- At a lower hierarchical level, strategies regarding quick response times, early detection mechanisms and strategies regarding the control and prevention of the different fire causes (Wolffsohn, 1980, p. 79).
- Optimum fuel-load management and the application of a proper fire information system have been identified at a functional level as being critical in the management of plantation fires (Martell in Johnson and Miyanishi, 2001, p. 527).
- On an operational level, performance measures were mentioned such as response times, area burnt or restriction of number of ignitions per fire cause.

5.2 FUTURE PERSPECTIVES

A few perspectives on what might happen in future regarding fire management conclude this study. The disastrous plantation fires in 2003 illustrate how vulnerable plantations are under extreme weather conditions. El Niño and global warming will result in more extreme weather in the future.

5.2.1 Outsourcing of fire management functions

Given the government's intention to privatise state assets, the following are possible scenarios:

- Komatiland Forests will be privatised and get a new shareholder or shareholders, which will change current management strategies and practices.
- Global markets, the utilisation of Maputo harbour and new afforestation in Mozambique will force major rationalisation, especially between major forestry companies such as Mondi, Global Forest Products and KLF in order to improve resource utilisation. This will enhance the concept of integrated fire management between the partners (DNFFB, 2002).
- Privatisation and rationalisation cause some uncertainty and often a lack of motivation and even antagonism from staff. Great care must be taken to have adequate measures in place to address current fire problems.

KLF, as well as the other major forestry companies, have implemented a policy of outsourcing its non-core functions. As fire suppression is seen as a specialised function, done by trained, dedicated teams of fire fighters, it is most often outsourced. The integration of fire detection systems, e.g. the electronic camera systems currently in use, with prevention and suppression resources is foreseen. The establishment of Fire Protection Associations (FPA's), as prescribed in the Veld and Forest Fire Act 101, 1998 will also promote the use of outsourced, specialised fire fighting teams, probably strategically positioned throughout the FPA area and working across traditional company boundaries.

5.2.2 Human resource management

For easy integration of staff as well as efficient large-fire organisations, standardised training in Incident Command Systems (ICS) is needed (Chandler *et al.*, 1983, p. 182 and Teie, 1997, p.329). ICS will ensure:

- Common terminology and integrated communication
- A modular organisation with unity of command
- Designated incident facilities

- Comprehensive resource management

Training of forestry staff should only be done by accredited training bodies (DWAF, 2000). The South Africa Qualification Authority (SAQA) is the highest body governing education and training in the country and also registers different Sector Education and Training Authorities (SETA).

SETA maintain training plans, accredit education providers, register assessors and disburse national training funds. All current and new employees must receive fire management training to the standard required by the forestry SETA-FIETA (Forest Industry Education and Training Authority) and the agricultural SETA-PAETA (Primary Agriculture Education and Training Authority). The KLF Platorand Training Centre in Mpumalanga North must ensure continuous accreditation with these authorities.

Refresher courses are essential to update staff on new trends in fire management, and the Veld and Forest Fire Act. Staff must be made aware of fuel management, buffer zones and the impacts of fuel on fire behaviour.

5.2.3 Environmental pressures

Due to global climate changes and the negative effects of smoke pollution, it will become more difficult to obtain permission to burn slash and to execute prescribed burning in plantations (De Bano, Neary and Ffolliott, 1998, p. 253 – 263). Education of the public towards a more realistic view on impacts of fires, and especially wildfires, is critical to ensure the future use of fire as a management tool.

Furthermore, forest managers must realise the wide ranging adverse ecological, economic and social impacts of wild fires. These include:

- Degradation of catchment areas
- Loss of carbon sink resources and increase in percentage of CO_2 in the atmosphere

- Soil erosion negatively affecting site productivity
- Loss of livelihood

Sustainable forest management, including the adequate protection against wild fires are requirements for forest certification. The Forest Stewardship Council (FSC) requires proof of fire suppression action plans, fuel management and protection plans for each plantation.

5.2.4 Strategic fire prevention planning

A fairly new approach to fire protection of industrial plantations has been the development of strategic fire prevention plans that provides a dynamic buffer zoning system, which reduces wildfire hazards significantly and simultaneously provides an effective basis for fuel management (De Ronde, 1997). The integration of riparian zones and nature conservation programmes into existing fire protection systems results in multi-purpose buffer zones. Strategic fire prevention plans start with the mapping of fire hazard at regional level and then placement of buffer zones to address high risk areas. The extreme weather conditions warrant a re-evaluation of fuel management in particular. This includes the use of slash burning after clearfelling and prescribed burning under the trees. The Swaziland Highveld fire management programme integrates fuel modelling, fuel classification and fire hazard rating. The ineffective internal and external fire breaks were replaced by integrated buffer zoning (De Ronde and Masson, 1998).

Fuel management solutions in and around commercial plantations need further investigation and implementation on a broader scale. Fuel management activities to consider are:

- Burning of slash after clearfelling
- Mechanical means of reducing fuel loads
- Development of markets for waste plantation material
- Prescribed burning in compartments on a selective basis
- Management of thinning and pruning waste

- Weed management

5.2.5 Centralised fire fighting teams

Duplication of expensive resources, difficulty in sharing equipment, high training costs and inconsistent knowledge and policy applications are some of the deficiencies in fire management.

Highly specialised, centralised fire fighting organisations are an alternative that is investigated as it monitors the current and predicted fire and resource situations and allocate crew and equipment in anticipation of near-future requirements. Several dedicated fire fighting teams are employed by KLF for the duration of the fire season and they are more efficient and dedicated than own silviculture teams previously used in fighting fires. These centralised fire fighting teams work across plantation boundaries and supply a service to all the forestry companies in a geographic area.

According to Kourtz (1995) advantages of centralised fire fighting teams are:

- Less expensive
- Provides a higher level of professionalism
- Leads to a significantly improved fire control

In order to utilise dedicated fire fighting teams throughout the year, national and international co-operation is needed. Greenlee (1994) identified the following barriers to co-operation:

- Availability and cost of fire fighting equipment
- Incompatibility of fire fighting equipment
- Bureaucracies
- Logistical difficulties

Through national and international fire management networks local fire fighting teams will get greater exposure and will become even more professional and dedicated.

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