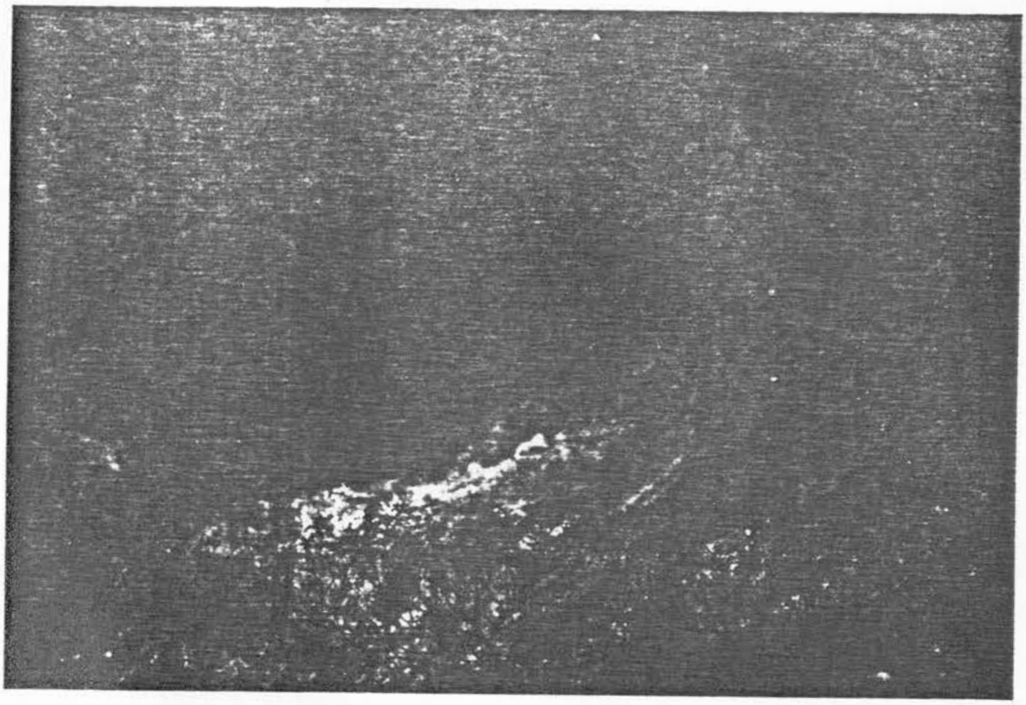
THE DERIVATION OF FIRE HAZARD INDICES AND BURNING PRESCRIPTIONS FROM CLIMATIC AND ECOLOGICAL FEATURES OF THE FYNBOS BIOME

by

BRIAN WILLIAM VAN WILGEN

Thesis submitted in partial fulfilment of the requirements for
the degree of
Doctor of Philosophy
in the Department of Botany, University of Cape Town.

August 1985



FRONTISPIECE

An experimental fire on plot C4 in the Cederberg. The fire had a rate of spread of 0,89 m s^{-1} and an intensity of 16 840 kW m^{-1}.

CONTENTS

rating in the fynbos biome. *South African Forestry Journal* 131,13-17. .... Page 68

Paper 2. Van Wilgen ,B.W., Le Maitre, D.C. and Kruger, F.J. (1985) Fire behaviour in South African fynbos (macchia) vegetation and predictions from Rothermel´s fire model. *Journal of Applied Ecology* 22, 207-216.. Page 74

Paper 3. Van Wilgen, B.W. and Burgan, R.E. (1984). Adaptation of the United States Fire Danger Rating System to fynbos conditions. II Historic fire danger in the fynbos biome. *South African Forestry Journal* 129, 66-78. .... Page 85

Paper 4. Van Wilgen, B.W. Fire danger during large wildfires in fynbos vegetation in the western Cape Province................... Page 99

Paper 5. Van Wilgen,B.W.(1984). Fire climates in the southern and western Cape Province and their potential use in fire control and management. *South African Journal of Science* 80,358-362. .... Page 121

Paper 6. Van Wilgen, B.W., and Viviers, M. (1985). The effect of season of fire on serotinous Proteaceae in the western Cape and the implications for fynbos management. *South African Forestry Journal* 133, 49 - 53.. Page 127

Paper 7. Van Wilgen, B.W. and Richardson, D.M. (1985) Factors influencing burning by prescription in mountain fynbos catchment areas. *South*

ABSTRACT

This study deals with the development of fire behaviour prediction and fire danger rating systems, and their potential use in fynbos catchment areas. Fynbos catchments are managed for sustained water yields and for nature conservation. Wildfires have always been a problem in these areas, and early management consisted almost entirely of attempts to protect the vegetation from fire. More recently a policy of prescribed burning has been introduced.

The analytical fire modelling approach adopted in the United States of America was identified as having potential for use in the management of catchment areas. This study was aimed at testing a number of hypotheses related to the adoption of this system in the management of fynbos areas. It further aimed to combine practical aspects of burning and fire control with conservation goals to provide meaningful burning prescriptions for the biome.

The United States National Fire Danger Rating System (NFDRS) is based on Rothermel´s analytical fire model. Vegetation characteristics are summarised in a fuel model and used in the NFDRS together with weather variables to produce fire danger indices. The physical properties of fynbos fuels were determined and a fuel model was derived. The fuel model was tested in a series of experimental fires where it was found to predict fire behaviour parameters with acceptable accuracy. Climate

data from nine weather stations were used in a preliminary study with the NFDRS to examine the variation in fire danger over the fynbos biome and to establish ranges of danger indices. The NFDRS reflected the expected seasonal trends in fire potential accurately, and indices compared well with actual fire occurrence. Recorded weather conditions during eight large wildfires were used to generate fire danger indices to determine the value of the various indices for reflecting fire danger. The energy release component was shown to be the steadiest indicator of high fire danger. The system shows good potential for use in the formal management of fynbos catchment areas.

The NFDRS was then used in conjunction with the fynbos fuel model and climate data from 40 weather stations to define five distinct fire climate zones within the fynbos biome. The seasonal cycle of fire danger is pronounced in two inland zones, but mean fire danger shows little seasonal fluctuation in three coastal zones. Fires will occur in the coastal zones under occasional suitable conditions. These zones are useful fire management zones.

The response of serotinous Proteaceae to season of fire was examined. Regeneration was best following late summer-early autumn fires, but some geographical variation was noticed. The results were used together with other examples from the fynbos biota to support seasonal constraints on burning operations in conservation areas. Ecologically acceptable burning seasons coincide with periods of high fire danger, which complicates the prescribed burning task. The conditions currently

favoured by managers for burning operations were determined, and used together with the seasonal constraints to define preliminary burning prescriptions. The seasonal occurrence of these prescribed conditions in the different fire climate zones was determined to examine the feasibility of burning in the ecologically acceptable season. While suitable conditions are rare in all seasons, it is concluded that burning could feasibly be carried out in ecologically acceptable seasons if an awareness of the conditions leading to safe fires is fostered among managers.

The effects of invasion of fynbos by alien shrubs on fire hazard and potential fire behaviour were determined by deriving fuel models for invaded fynbos. Invasion increases fuel loads and changes the nature of fuel beds so that fires become difficult to control under extreme weather conditions. This provides a further argument for the eradication of such weeds from catchment areas.

The results of this study can be used to refine fire management policies in fynbos mountain catchment areas. No previous work has quantified the seasonal and absolute variations in the physical fire environment of the fynbos biome, or attempted to combine practical aspects of burning and fire control with conservation goals. The study also presents baseline data on fuels, fire behaviour and burning prescriptions. The results therefore represent a contribution to the understanding of fire as a physical factor in the management of catchment areas in the fynbos biome.

ACKNOWLEDGEMENTS

I thank the Deputy Director-General of the Directorate of Forestry for permission to undertake this study for degree purposes and for financial support. The Directorate also funded a period of study in the United States of America and a study tour of Australia.

This study would not have been possible without the willing help of the staff of the Northern Forest Fire Laboratory, Missoula, Montana. Dr. Frank Albini arranged a working visit there and was most helpful and hospitable. Mr. Bob Burgan spent many hours helping me with programming and his advice on the use of the NFDRS was invaluable. All other members of the staff (and particularly Dick Rothermel, Pat Andrews and Bobbie Hartford) were helpful and friendly at all times.

I am grateful to my supervisor, Prof. Eugene Moll for his advice and encouragement in the preparation of this thesis. I have also benefitted from the comments and advice of my colleagues in the Directorate of Forestry, particularly Mr. Fred Kruger of the South African Forestry Research Institute, Pretoria. Messrs Jan Bosch, Dirk Versfeld, Pat Manders, Dave le Maitre and Dave Richardson of Jonkershoek, Messrs William Bond, Johan Breytenbach and Jeremy Midgley of Saasveld, all provided useful comments and advice at various stages.

Many people assisted me with data collection and processing. Messrs. Dave le Maitre and Ben Durand were responsible for the collection of biomass data that were used in the fire behaviour studies. Mr. Mike Viviers was responsible for field work involved in the survey of Proteaceae regeneration. Mr. Jasper Hoon of Elsenburg helped me obtain weather data from agricultural stations; Mr. Frank Rogers of Jonkershoek helped with the data from forestry weather stations. Lisa Klaussner assisted with data processing. Messrs. Dave le Maitre, Ben Durand, Ross Haynes, Allan Lamb and Gregory Baily assisted with fire behaviour measurements at experimental fires. Gideon Slabbert helped to collect weather data during burning operations.

I am also grateful to my wife Jane for her support in many ways during the writing up of this thesis, and to Ina Eygelaar and Rhoda Vos for help with typing.

PREAMBLE

This study was undertaken as part of a project aimed at the developement of prescribed burning systems in fynbos mountain catchment areas, and forms part of the conservation research programme of the South African Directorate of Forestry. The results are required for inclusion in management programmes and their early dissemination is therefore desireable. The results of post-graduate studies are often never published when theses are prepared in a traditional format, as a thesis is often regarded as a finished product. In order to overcome this, and to facilitate the early dissemination of results, this study is presented in the form of eight research papers. The papers are presented in a section entitled "Research findings", in the form in which they were, or are to be, published. Two sections entitled "Introduction" and "Literature review" are followed by a "Critique" section. In the critique I have attempted to draw the results of the research findings together. The major hypotheses of the study are presented and the rationale behind the research papers is discussed in relation to these hypotheses. The critique contains a concluding section which lists the main results of the study, their implications, and priorities for future research. This form of thesis presentation is currently encouraged by the University of Cape Town, and represents an improvement on the conventional thesis format.

PART I INTRODUCTION

Features of the fynbos biome

The fynbos biome corresponds geographically with the Cape Floristic Kingdom, and occupies a small area in the southwest of southern Africa. The biome essentially covers the Cape folded mountain belt described by Wellington (1955). The mountains occur for the most part in sub-parallel ranges with an average elevation of 1 000 - 1 500m, individual peaks reaching over 2 000m. The mountains of the southeastern half of the biome lie south of 33° 00´S latitude, between 19° 30´ and 23° 00´E longitude, and have an east to west trend. The western half of the biome lies south of 32° 00´S latitude, between 18° 00´ and 19° 30´E longitude. In this half of the biome the mountain ranges tend to run from north to south. The biome is bordered to the south by the Indian Ocean, and to the west by the Atlantic Ocean.

The climate of the region is often referred to as a mediterranean type (cf. di Castri & Mooney 1975) although this is not strictly true for the whole of the biome. Rainfall is very variable and ranges from 300 to 2 500 mm or more per annum (Taylor 1978). In the western half of the biome rainfall is concentrated in winter (45-55% in three months), although some rain falls in all months of the year. East of 20° 30´E latitude, rain falls throughout the year (Fuggle 1981). In the winter snow falls regularly on the higher mountains, especially in the interior, but snow cover is of short duration. Temperatures below freezing are rare in lower lying areas.

The flora of the fynbos biome is distinctive and it forms one of the world's six floral kingdoms (Good 1964; Takhtajian 1969). It is also the smallest kingdom, representing less than 1% (67 000 km2) of the total land surface of Southern Africa. Within this region there occur some 8 550 species of vascular plants, of which 73%, or 6 252 species, are endemic. These 8 550 species are in 957 genera, of which 198 genera are endemic. Seven families, namely the Bruniaceae, Penaeaceae, Grubbiaceae, Roridulaceae, Retziaceae, Stilbaceae and Geissolomataceae are also endemic to the Cape Floristic Kingdom (Goldblatt 1978).

Acocks (1953) recognized seven veld types within the fynbos biome. Three of these (Knysna Forest, Karroid Broken Veld and Strandveld) are of minor importance in terms of area. A fourth, Renosterveld, has all but disappeared under cultivation. The remaining three types, termed Coastal Macchia, Macchia and False Macchia by Acocks, constitute the true fynbos vegetation. Fynbos is an indigenous word probably used for the first time in the literature by Bews (1916), and implies both the fine-leaved form of many of the shrubs and the bushy nature of the vegetation (Taylor 1978). The types Macchia and False Macchia are grouped under the term mountain fynbos (Kruger 1979a) and represent 75% of remaining natural vegetation in the biome (Jarman 1982).

Earlier definitions of fynbos vegetation given by Acocks (1953) and Taylor (1972) have been refined by Campbell et al (1981) and Moll et al (1984), and the term fynbos in reality describes a range of structural vegetation types. Generally speaking, fynbos is characterized by three physiognomic elements : restioid, ericoid and proteoid (Taylor 1978). The restioid element comprises the Restionaceae and similar aphyllous grass-like plants up to 1 m tall, while ericoid plants are usually low shrubs with small, narrow and often rolled leaves. Taller shrubs with moderate sized sclerophyllous leaves comprise the proteoid element, which may be absent in certain habitats.

Fynbos vegetation has burned periodically for probably 100 000 years, and possibly since the early Pleistocene (Kruger 1979a). Fynbos vegetation is finely divided and contains considerable amounts of fine dead material, forming an easily combustible fuel bed. Under warm, dry and windy conditions, fires are common in fynbos, and have been a problem since the time of early settlers. Despite the magnitude of this problem, the nature of fire regimes in the fynbos biome cannot be quantified as comprehensive data are lacking (Kruger 1977).

The importance of mountain catchment areas in the fynbos biome

The mountains of the fynbos biome are of particular importance as water catchment areas. Areas identified as catchments (van der Zel 1981) occupy only 8% of the land surface of South Africa, but yield 49% of the country's total water runoff. For the country as a whole, only 9% of rainfall reaches the streams and rivers, whereas the figure is 50% for the mountain catchment areas (Wilson 1984). Thirty percent of the major catchment areas of South Africa fall within the fynbos biome (Van der Zel 1981). Water is the natural resource which will limit agricultural, urban and industrial development in South Africa, and the conservation and wise use of water resources is therefore of the utmost importance.

The biotic communities of mountain catchment areas within the fynbos biome constitute a valuable reservoir of genetic diversity. The high degree of endemism and relatively small distribution ranges of many plant species has resulted in 1 244 species being classified as endangered, vulnerable or rare (Hall _et_ _al_ 1980). In addition, many species of fauna (some of them rare) find refuge in these areas. Besides their scientific and aesthetic value, and their value as a genetic resource, the natural communities of catchment areas form the best and most cost-effective catchment cover (Wicht & Kruger 1973) and should be maintained for this reason.

Recreation in mountain catchment areas is becoming increasingly important. For example, Wilson (1984) reports an increase of 409% (from 4 556 to 18 673) in the number of permits issued for hiking from 1979 to 1981 in the western Cape catchment areas. With increasing urbanization and population growth the need for such recreational opportunities will continue to grow.

The management of catchment areas

Historical overview

At the beginning of the 20th century there was no systematic management of mountain areas, although many such areas were the responsibility of the Forest Department in the old Cape Colony (Wicht & Kruger 1973). With the formation of the Union of South Africa in 1910 the conservation of water catchment areas became the responsibility of the Forestry Department (by virtue of the Forest Act No. 16 of 1913), and large tracts of Crown land in mountain areas were transferred to the Department.

The Forest and Veld Conservation Act (No. 13 of 1941) made better provision for the control of fires, expropriation of land for veld, soil and water conservation, and the proclamation of nature reserves. The Soil Conservation Act (No. 45 of 1946) passed the control of privately owned catchment areas to the Department of Agriculture, but these were in practice controlled in co-operation with the Department of Forestry for the next 30 years (Wicht & Kruger 1973). In 1952 an interdepartmental committee was appointed under the Soil Conservation Act to investigate problems related to the management of mountain catchments, and in 1961 the first comprehensive report on all the major catchments in the country was produced (Ross 1961). The need to bring control of all mountain catchment areas under one department was formally recognized when the Mountain Catchment Areas Act (No. 72 of 1970) was passed. This act transferred control of all mountain catchment areas to the Department of Forestry. It requires that all privately owned land in catchment areas be formally demarcated and proclaimed. The management of these areas is to be governed by the Department of Forestry.

The early management of fynbos mountain catchment areas consisted almost exclusively of attempts to protect them from fire. Botanists in the early 20th century were totally opposed to fire (Levyns 1924, Marloth 1924, Pillans 1924) and the formation of fire protection committees in 1946 effectively brought privately owned land in line with the protected forestry areas (Wicht & Kruger 1973). The policy proved largely unsuccessful, and uncontrolled fires burnt large areas of fynbos vegetation. This, coupled with evidence that fire was a necessary factor in the ecosystem (Wicht 1945, Le Roux 1966, Van der Merwe 1975, Bond 1980) led to the development of a policy of prescribed burning. Prescribed burning was initiated on a large scale in the middle 1970's, and is thus a relatively recent development.

Aims of catchment management

Mountain catchment areas are managed to ensure a sustained yield of the optimum volume of high quality, silt free water through the prevention of degradation of the catchment. This is the primary objective and applies to both privately owned and State owned land. Secondary objectives on State owned land include the maintainance of natural species diversity, the control of wildfires, the preservation of the wilderness character and provision for low intensity outdoor recreation. On privately owned land secondary objectives may differ, but only practices compatable with the primary objective are permissable.

These aims are achieved largely through the use of fire. Fynbos is a fire-adapted vegetation type (Bond 1980; van Wilgen 1982) and fire is thus necessary to maintain species diversity. Prescribed burning plans are aimed at producing a checker board pattern to avoid large catastrophic fires in times of extreme fire hazard. Blocks of old vegetation are interspersed with younger, less flammable vegetation. Another major task of catchment managers involves the control of woody weed species. These consist mainly of Australian shrubs and trees of the genera *Hakea* and *Acacia*, and European and American pine trees (*Pinus* spp.). Their presence is inconsistent with the aims of catchment management as they suppress the natural vegetation, decrease streamflow and increase fire hazard (Kruger 1979b). Weeds are usually controlled through a combination of felling and burning, and weed control programmes are integrated with the prescribed burning programme. Other catchment management tasks include the control of activities such as afforestation, roadbuilding, grazing and any others which could affect streamflow and water quality from catchment areas.

PART II LITERATURE REVIEW

A REVIEW OF FIRE DANGER RATING AND FIRE BEHAVIOUR PREDICTION SYSTEMS

Fire is important to land managers in many parts of the world, both as a destructive phenomenon to be avoided and as a management tool. Foresters in particular wish to protect their timber crops from fire, while land managers in general would like to avoid uncontrolled fires that can destroy property. Fire is often used as a management tool to reduce fuel loads and fire hazard, for land clearing and for vegetation type conversion. For nature conservation purposes, fire plays an important role in ecosystem maintainance and in wildlife management. In this section a brief review of fire danger rating and fire behaviour prediction systems which have been developed in various parts of the world as an aid to land managers is presented. The review is intended as a background to the studies reported later.

Various systems exist for using weather information, sometimes together with fuel information, to obtain estimates of fire behaviour. There are two kinds of fire behaviour predictions and it is important to distinquish between them. A <u>fire danger rating</u> is an estimate of burning coditions anticipated over a large area at a particular time, usually the early afternoon of the following day. A <u>fire behaviour forecast</u> is an estimate of the rates of spread and other fire behaviour characteristics to be expected during a particular wildfire or prescribed fire over some future time period, usually the next planned burning period. A fire danger rating is generalized for fuel type and topography while a fire behaviour forecast is site specific (Chandler *et al* 1983).

Fire danger rating

The day-to-day measurement of fire danger has become a fire management tool in many countries. The techniques originated and were perfected mainly in Australia, North America and the U.S.S.R. In the United States and Canada, forest fire danger rating systems were developed more or less independantly, beginning about 1920. Although the present Canadian and United States systems are similar in some ways, there are fundamental differences between them (Van Wagner 1975). The basis of the United States system is a mathematical fire spread model (Rothermel 1972), which predicts fire behaviour from predetermined relationships between the physical and chemical properties of the fuel, and the weather conditions under which the fuel burns. The Canadian system is based on statistical analyses of large quantities of field data. The United States system gives a range of fire danger indices for a range of different fuel types or fuel models (20 in all, Deeming *et al* 1978), whereas the Canadian system has a single, universal index, which, given the same weather parameters will give the same value regardless of location and fuel type. The concept of fuel models (Deeming and Brown 1975) was developed to overcome the problem of accurately quantifying fuel parameters for input into the fire danger rating system. A fuel model consists of a set of values which quantify a particular vegetation type in terms of its fuel characteristics; these values are then used as constants in the equations of the fire spread model. A schematic representation of the structure of the United States National Fire Danger Rating System (NFDRS) is shown in Fig. 1.

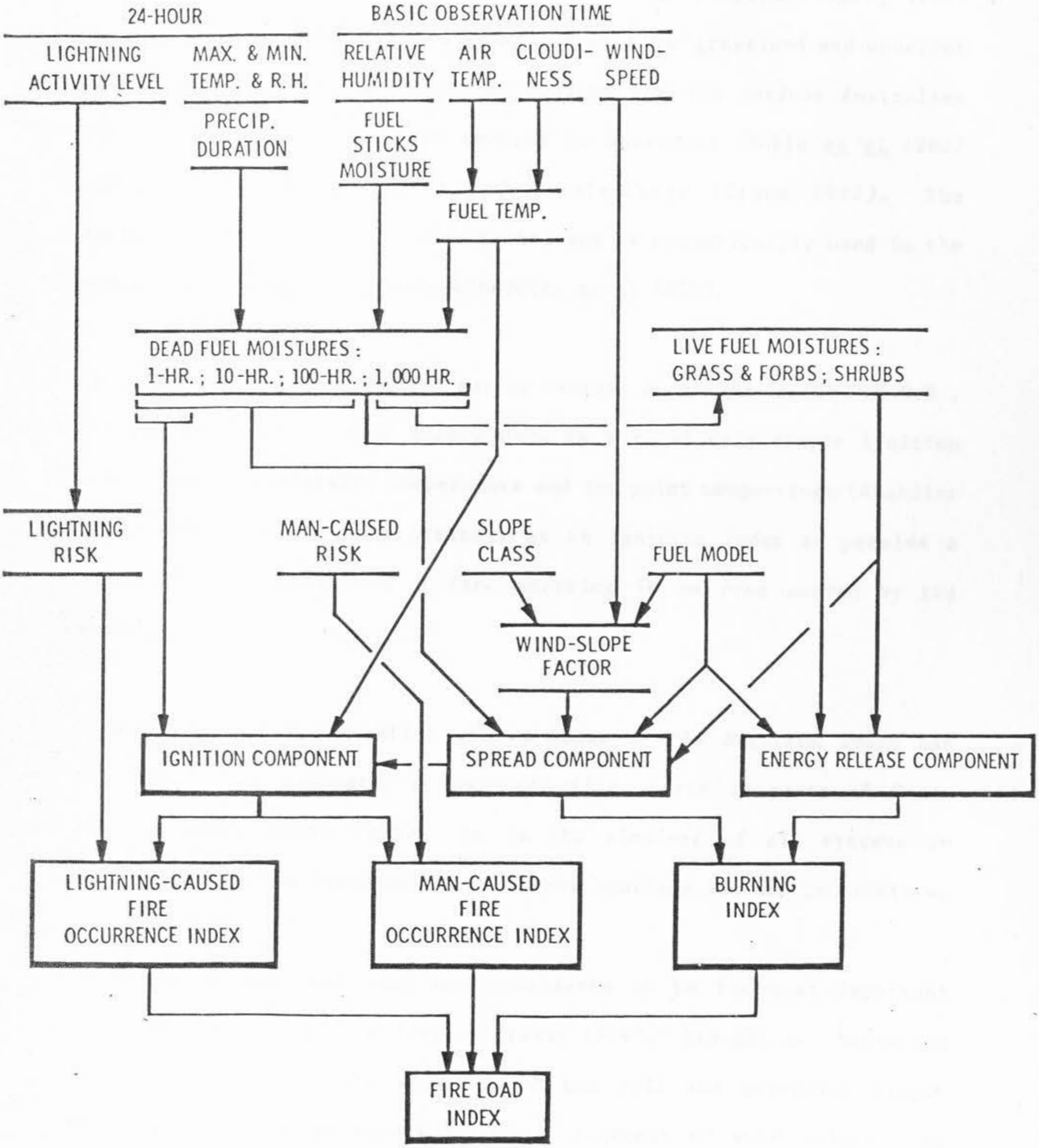


Fig. 1. Structure of the United States National Fire Danger Rating System (after Deeming *et al*. 1978).

The development of Australian fire danger rating systems was, like the Canadian system, done on an empirical basis. McArthur (1966, 1967) designed a meter based on fire behaviour data for grassland and eucalypt forest ecosystems. The tabulated indices for the various Australian fire danger meters have been reduced to equations (Noble et al 1980) and programmed for use on a pocket calculator (Crane 1982). The Australian system has also been tested and is operationally used in the mediterranean region of Spain (Chandler et al 1983).

There have been several danger rating systems developed in the U.S.S.R., but the one that is most widely used is a relatively simple ignition index, based on rainfall, temperature and dew point temperature (Chandler et al 1983). It is used strictly as an ignition index to provide a measure of the chance of a fire starting in an area served by the weather station.

A Swedish fire danger rating system known as the Angstrom Index has been used as an indicator of expected fire starts in parts of Scandinavia (Riefsnyder 1978). It is the simplest of all systems in current use, and is based only on relative humidity and air temperature.

In France drought and wind are considered to be the most important variables for rating fire danger (Orieux 1974). Drought is determined from the available water capacity of the soil and potential evapotranspiration, and is combined with a forecast of wind velocity to determine the level of fire danger.

The New Zealand Forest Service uses a fire danger rating system which appears to be based on a system formerly used in the south-eastern United States (Reifsnyder 1978). It uses fuel moisture sticks to estimate fine fuel moisture, a drought index based on precipitation and temperature to keep track of heavy fuel moisture content, relative humidity, air temperature and wind speed. The ratings correspond closely to the energy release component of the United States National Fire Danger Rating System.

Baumgartner et al (1967) developed an ignition index which is used in Bavaria. It is based on a balance between precipitation and evaporation and was developed through a statistical analysis of past fire records. It is apparently the only system currently in use in any part of the West German states (Reifsnyder 1978).

In Finland, a system based on forest fire statistics for the years 1959-67 and corresponding weather observations from 28 stations throughout Finland were used to construct a multiple regression equation that would estimate an ignition index (Reifsnyder 1978). The regression uses rainfall, temperature, humidity, cloud amount and pressure for different regions and seasons.

Some of the systems described above have been adapted for use in other countries, such as the Australian meter used in Spain. A modified

Canadian system has been used in parts of Spain, in Mexico, Venezuela, Chile and Argentina to some extent. The Swedish Angstrom Index is used in Protugal and several former Portuguese possessions (Chandler et al 1983).

Reifsnyder (1978) reports that "few, if any, countries in Africa have utilized any kind of fire danger rating system". The lack of fire behaviour data and formal hazard rating systems in Africa is further reflected in recent reviews of the state of knowledge on fire ecology and management in various regions of the world (Mooney and Conrad 1977, Gill et al 1981, Wright and Bailey 1982, Wein and MacLean 1983, Booysen and Tainton 1984). For example, Gill´s chapter on post-settlement fire history in Australia (in Gill et al 1981) reviews the development of fire danger rating systems. Wright and Bailey (1982) give detailed prescriptions for burning in various vegetation types. In contrast, Bands´ review of prescribed burning in the Cape fynbos (Mooney and Conrad 1977) makes no mention of any systems to rate fire hazard, as they did not exist. Edwards´ chapter in Booysen and Tainton (1984) on fire regimes on the biomes of South Africa states that "unfortunately, little work has been undertaken on the relationships of fire to the kind and amount of functional biomass and the amount of dead material. At present, therefore, available biomass and yield data serve to indicate the potential, type and quantities of fuel available". Trollope (in Booysen and Tainton 1984) reviews available information on fire behaviour in South Africa and concludes that "there is a serious lack of quantitative data on the effect of various factors on the behaviour of fire in South Africa". He contrasts this situation with that in the United States of America and Australia where the study of fire behaviour is at "an advanced and very sophisticated level".

Fire behaviour prediction

As stated earlier, fire behaviour predictions are site specific. Such predictions can be useful to managers, particularly for prescribed burning purposes. For example, desired rates of spread can be specified so that the burning job is completed within a certain time. A desired fire intensity, for example that required to stimulate germination of soil-stored seed or to kill the seedlings of weed species, can also be specified. If the relationships between fuel, weather and fire behaviour are known, then meaningful fire management can be achieved through setting such goals. Chandler et al (1983) give fire behaviour rules of thumb, where the effect of fuel loading, fuel moisture, wind and slope on fire behaviour are approximated. While such rules of thumb would be useful where no other information exists, recent developments in fire behaviour prediction technology give managers better options, provided that the relationships between fuel, weather and fire behaviour have been established for the region. The system designed in the United States of America to rate fire danger is finding increasing use as a guide to the prescription of management fires in conservation areas (Gill and Groves 1981). Albini (1976) states that "because specific effects are sought and specific sites are burned under preselected conditions to achieve them, in many cases prescribed burning poses the most stringent requirements for fire behaviour prediction models. The use of pre-established fuel bed descriptions (such as the fuel models used in the NFDRS) may be inappropriate for accurate prediction as the specific site being burned may differ substantially from the assumed fuel bed. But such stylized models may be useful in establishing roughly what the fire behaviour will be before the first burn, or for estimating what the sense and magnitude of changes in fire behaviour will be as the burning conditons vary". The technology described by Albini (1976) has advanced significantly over the past few years, and the use of site-specific fuel models, rather than stylized models of a more general nature, is advocated by Burgan and Rothermel (1984). These authors describe a set of interactive computer programmes (the BEHAVE system) for estimating wildland fire potential under various fuels, weather and topographic situations. Their document outlines field procedures and programmes which enable field managers to construct site specific fuel models and to test their fire behaviour characteristics under a variety of simulated environmental conditions. Andrews (in prep) describes programs which use these fuel models together with state-of-the-art fire prediction techniques for predicting fire behaviour for operational use.

FIRE AND ITS EFFECTS ON NATURAL ECOSYSTEMS

Except for Antartica, practically no region of the world is entirely free from fires (Luke and McArthur 1978), though fires are unlikely in rainforests (where high, evenly distributed rainfall usually prevents them) or in deserts (where there is usually no fuel). Probably the most hazardous zones are those with either mediterranean or continental climates, where high temperatures co-incide with periods of low rainfall.

Fire dependant ecosystems

An ecosystem may be said to be fire dependant when its continued existence depends on the periodic occurrence of fires. This concept is put forward by Chandler et al (1983), who maintain that if fires occur with sufficient regularity, as they do in many parts of the world, these ecosystems may remain stable for millennia. The species in such vegetation types are adapted to survive fire; the various adaptive responses are reviewed in the next section. Post-fire environments are favourable for the establishment of many species. The favourable factors include increased nutrient availability in ashbeds and decreased competition for various resources. Where species are adapted to take advantage of such conditions, it is also advantageous for the species to ensure that a fire does occur during its lifetime, so that the reproductive advantage can be realized. Consequently, fire dependant ecosystems tend to be highly flammable and their flammability tends to increase over time (Chandler et al 1983). This has been taken a step further with the formal proposal of a hypothesis (Mutch 1970) that fire-dependant plant communities burn more readily than non-fire dependant communities because natural selection has favoured characteristics that make them more flammable. Mutch´s hypothesis has been widely cited in the ecological literature, not always favourably (see

Snyder´s (1984) article entitled "The role of fire : Mutch ado about nothing?"). Whatever the case, the fact remains that fire protection in a fire dependant ecosystem results in longer fire-free intervals and a buildup of fuels and flammability in the ecosystem. When they do occur, fires in such protected areas are usually far more intense than they would normally have been. In many parts of the world management has changed from unsuccessful attempts at fire exclusion to policies that emphasize hazard reduction and ecosystem maintainance through the judicious use of fire (Chandler et al 1983, Luke and McArthur 1978, Bands, in Mooney and Conrad 1977).

Plant adaptations to fire

Plant responses to fire fall into two broad categories: those that survive fires by sprouting from rootstocks, bulbs, epicormic buds and the like (the sprouters), and those that are killed by fire and regenerate from seed afterwards (the non-sprouters). These two broad categories have been much used by fire ecologists (Gill, in Gill et al 1981), but the scheme is simple, being based on the response of single species to a single fire. For example, variations in the developmental stage of an individual plant or variations in fire intensity may produce different responses from the same species. It is therefore first necessary to consider the various adaptations that plants show to fire (unless otherwise stated, from Gill, in Gill et al 1981).

Sprouting

i) Soil protection of buried buds is an effective mechanism of surviving fire, but the extent of survival may vary according to the vitality of the plant and the severity of the fire.

ii) Bark protection of aerial buds occurs in many species, for example Eucalyptus species in Australia. An example from the fynbos is Protea nitida.

iii) Sprouting is induced by the removal of the inhibiting effects of the crown. This may occur through fire, drought, grazing or insect damage, all of which evoke the same response. Sprouting may thus be considered as an adaptation to stress, one of these stresses being fire.

Flowering

i) Many species flower profusely immediately after fire but rarely between fires. Such flowering may enhance reproduction in the favourable post-fire environment, for example through seed predator satiations, as was shown to occur in Watsonia pyramidata (Le Maitre 1984) in the fynbos.

Reproducing from seed

i) Some plants do effectively the same thing as flowering profusely after a fire by flowering at a relatively low level in the interfire period, but retaining seed on the plant until its release is triggered by fire. A good example of this strategy is provided by Protea and Leucadendron in the fynbos (Bond 1985) and by invasive Australian Hakea species in the fynbos.

ii) Seed storage in the soil: Gill refers to hardseededness, such as is seen in Acacia species in Australia. Seeds with hard coats can resist predation and survive in the soil until stimulated to germinate by fire. Another example is provided by the many genera in the fynbos (for example Mimetes, Leucospermum and Serruria) where an ant-seed relationship (myrmecochory) has developed and seeds are buried by ants (Bond and Slingsby 1983).

Avoiding fire

i) Avoidance in space: Examples of this strategy are provided by plants which occupy sites in fire-prone ecosystems that nevertheless seldom, if ever, burn (Frost, in Booysen and Tainton 1984). In fynbos species escape fires by being restricted to rocky areas (eg. the small trees Maytenus oleoides, Heeria argentia and Olea europaea ssp. africana) or permanently wet sites (eg. Disa uniflora).

ii) Escape in time: Many species, usually sprouters such as geophytes and grasses are totally dormant at the time when fires are most likely, and in this way escape the harmful effects of fire.

Using a knowledge of adaptations

Noble and Slatyer (1980) have proposed a scheme whereby the "vital attributes" of plant species are determined and used to predict successional changes in plant communities subject to disturbances such as fire. Three main groups of vital attributes are recognized. These relate (i) to the method of persistance of a species during a disturbance and to its subsequent arrival; (ii) to its ability to establish and grow to maturity following disturbance, and (iii) for the time taken for it to reach critical stages in its life history. The scheme is used to simulate the interaction between various species and to yield a replacement sequence which depicts the major shifts in composition and dominance which occur after disturbance. If ecosystems managers know how the species in their area are adapted to survive fires, the scheme provides a useful framework for assessing the effects of fire on natural communities. It is important that plant species responses to fire are interpreted in terms of the life cycle of the species concerned (Noble and Slatyer´s critical stages in the life history) and also in terms of the fire regime : the season, frequency and intensity of fires (Gill, in Gill et al 1981).

The fire regime

Fire frequency

This refers to the return period of fires and varies considerably in different ecosystems of the world. It is determined largely by the rate of accumulation of fuel. Chandler et al (1983) show that fire frequencies can range from once every 1 000+ years in Alpine tundra, to annual fires in some grasslands. Other factors influencing fire frequency include availability of sources of ignition and the incidence of suitable weather conditions. Fire frequency and intensity are related in that one could have a situation of frequent, low intensity fires (due to low fuel loads) or infrequent, high intensity fires (due to a buildup of fuel between fires) on the same site. Fire frequency in fynbos probably varied at random between 6 and 40 years under a natural regime (Kruger and Bigalke, in Booysen and Tainton 1984). Changes in fire frequency have marked effects on fynbos, particularly on seed-regenerating species, since frequent fires do not allow such species to mature and set seed between fires so they disappear from the community (van Wilgen 1982). On the other hand, long intervals between fires result in senescence, a depletion of seed pools and poor regeneration following fire (Bond 1980). Moderate frequencies of between 12 and 25 years appear necessary to maintain species diversity.

Fire intensity

The degree of fire intensity will determine the degree to which fire sensitive species are affected, and thus the species composition of a community. Fire intensity was defined by Byram (1959) as the product of rate of fire spread, mass of fuel consumed and heat yield of the fuel. Fire intensity in natural vegetation can vary from 20 to over 60 000 kW m-1 (Luke and McArthur 1978). Kruger, in Mooney and Conrad (1977) states that "though fires in fynbos are fairly intense (fires of intensity greater than 2 500 kW m-1 appear to be regular) they are apparently not as intense as those in mature chaparral since fuel particles > 6 mm diameter are usually not burned and ash beds are rare or small". Kruger and Bigalke, in Booysen and Tainton (1984) say that "fynbos fires are not exceptionally intense" and quote observed values from unpublished results of between 5 000 and 10 000 kW m-1. This compares with values of between 380 and 35 000 kW m-1 for chaparral

(Rothermel and Philpot 1972).

Fire season

Fires at different times of the year will produce different results depending on the phenological stage of the plant being burnt and on weather conditions which follow the fire. Kruger's review (in Booysen and Tainton 1984) of fire regimes in South Africa states that "in any given biome fires tend to occur during the season when vegetation is driest and thus very often dormant, and when climatic variables favour fire". Plants survive fire best if burnt when dormant. Seasonality has interacted with environmental factors as a selective force to determine species composition in any given biome, and the vegetation is usually highly stable under such a "natural" seasonality (Kruger, in Booysen and Tainton 1984). Variability in the incidence of fire within the favourable fire season would contribute to the continued co-existence of species by allowing fluctuations around the mean composition. If the season of fire changes beyond the adaptive capacity of plants, the effect on vegetation structure may be marked. In fynbos, little information on the effects of fire season are available, but Bond et al (1984) show that the recruitment of dominant Proteaceous shrubs varies significantly with fire season.

CURRENT PROBLEMS ASSOCIATED WITH FYNBOS CATCHMENT MANAGEMENT

Fire related problems

The major problems which face the catchment manager in fynbos are related to rotation (frequency) of burning, season of burn, size of burn and the selection of the optimum conditions under which to burn.

Current data show that fynbos is fire adapted and that fire at intervals exceeding 40 years results in senescence and poor regeneration after fire (Bond 1980; Van Wilgen 1982). Fire at intervals of less than eight years is detrimental on the other hand, as many obligate reseeding shrubs cannot mature and produce seed between fires (Van Wilgen & Kruger 1981; van Wilgen 1982). Fires conducted in fynbos catchment areas by the government Forestry Branch are currently planned at 12-15 year intervals, but areas are assessed before burning to determine whether the vegetation has matured and set sufficient seed for adequate regeneration (Kruger & Lamb 1978). Carefully determined working plans are often upset by unplanned fires, or by the inability to predict the correct fire frequency for an area.

When the government Forestry Branch´s policy of prescribed burning was first introduced in fynbos areas, late summer was proposed as the correct season to burn, as most plant species had produced seed and were dormant by then. However, previous protection meant that the vegetation was old and dense, and it would be risky to burn such vegetation in summer. A Forestry Branch policy statement was therefore issued in 1970, <u>preliminarily</u> restricting burning to late autumn or early spring until such old veld had burnt at least once. In many areas the prescribed burning programme has passed through the first cycle, and summer burning should soon be initiated. Practical experience in the southwest Cape shows that most catchment managers are understandably reluctant to burn in summer. Evidence of the detrimental effects of spring and late autumn burning has accumulated steadily (Jordaan 1949, 1962, 1981; Bond 1980, 1984; Bond, Vlok & Viviers 1984) and this problem urgently needs to be resolved.

In fynbos areas managed by the government Forestry Branch, prescribed burns are carried out on management units called compartments. Compartments must be small enough to allow for completion of a burn in a day, and large enough to keep costs low and to allow for an effective checker board of vegetation age for fire control. Compartment size is also dictated to some degree by the extent of invasion by alien vegetation which has to be cleared. Ecological considerations centre mainly on the effects of compartment size on seed predators (Kruger 1981), which require shelter (unburnt vegetation) and can have marked effects on regeneration (Bond 1984). Compartment sizes currently range from 500-2 000 ha depending on vegetation density, accessibility and natural fire barriers. However, a predictive knowledge of the conditions which will lead to successful fires that can be completed within a predetermined time needs to be developed to determine optimum compartment sizes.

The selection of suitable days for burning is a major problem facing catchment managers. The old policy of fire exclusion did not necessitate formal decision-making; fires were simply excluded or suppressed when they accidentally occurred. This <u>fire control</u> contrasts with the concept of fire management, where decisions must be taken on actually initiating fires. The manager's level of expertise is reflected in the tendency to burn under conservatively safe conditions . As such conditions are rare in the correct season (ie summer) prescribed burning programmes tend to fall behind, or are carried out at unsuitable times (spring or late autumn). The ability to predict fire behaviour in order to burn safely in the correct season needs to be developed if the aims of catchment management are to be achieved.

Other problems

Scientific catchment management in the fynbos biome is a relatively new field and data on the effects of various activities on the ecosystems are lacking. While fire is the major management tool, other problems face the catchment manager. The integration of weed control operations with the fire programme needs to be investigated and developed to achieve optimum control. Permissable levels of afforestation, grazing and other agricultural activities need to be determined. Nevertheless, it is likely that the majority of catchments will remain under natural vegetation and that fire will remain the major management tool.

PART III CRITIQUE

AIMS OF THIS STUDY

General

The development of fire danger rating models as a means to predict fire behaviour (sic) was identified as an urgent research requirement for the management of fynbos mountain catchment areas (Kruger 1981). The adoption of an existing system, rather than developing a new one for each region of the world, has a number of advantages (Reifsnyder 1978). Firstly, developing separate systems is wasteful of scientific and technical talent. It would also delay other tasks of higher priority. A single system for rating fire danger and fire climate would also permit the inter-continental comparison of fire hazards on a world-wide basis. Systems based on physical laws, such as Rothermel´s fire model, would feasibly be more easily adapted to new areas than empirically based models. Establishing the feasibility of incorporating systems based on Rothermel´s model into the management of fynbos areas was the major aim of this study. A fuel model for the United States chaparral shrublands exists, and this would be the closest approximation to South African fynbos. Fuel data had to be collected to establish whether the existing chaparral fuel model would suffice in fynbos, and fire behaviour data under varying weather conditions had to be collected to test the model´s predictions. Features of the fire climate of the fynbos biome had to be established as an aid to managers. Lastly, practical aspects of burning and fire control had to be combined with conservation goals, based on ecological features, to provide the basis for a management policy for catchment areas in the fynbos biome. In order to achieve these aims, studies were designed to test hypotheses listed in the next section.

Hypotheses

H1. The chaparral fuel model will not apply to fynbos vegetation due to structural differences between the two vegetation types.

H2. Rothermel´s fire model will predict fire behaviour in South African fynbos shrublands, given an appropriate fuel model.

H3. The magnitude and seasonality of fire danger will vary between different areas within the fynbos biome due to climatic differences. These variations can be established using Rothermel´s fire model.

H4. The biota in the fynbos biome are adapted to survive fire in those seasons when fire danger is highest. This will indicate the season to burn to achieve the aims of conservation.

H5. Enough suitable burning days will occur in the season of high fire danger to allow for prescribed burning programmes to be completed, thus making fire a feasible management tool for the conservation management of fynbos areas.

H6. Invasions of alien shrubs increases fuel loads and fire hazard in the fynbos biome. Changes in potential fire behaviour brought about by invasion can be simulated using Rothermel's model.

RATIONALE AND RESULTS OF THE STUDY

In order to test the hypothesis that the existing chaparral fuel model will not apply to fynbos due to structural differences between the two vegetation types, I determined the fuel properties of fynbos vegetation and used these to define a fynbos fuel model. The description of this work is given in Paper 1. The development of a fuel model was a necessary first step that had to be taken before the second hypothesis, namely that Rothermel's model will predict fire behaviour in South African fynbos shrublands, could be tested. The fuel model was used later for testing the third hypothesis that the magnitude and seasonality of fire danger will vary between different areas within the fynbos biome. It was also used for comparison with simulated fire hazard in alien invaded vegetation to test the sixth hypothesis that invasions of alien shrubs increases fire hazard. The fuel model was derived from biomass data for fuel load, and from measurements of surface area to volume ratios, energy contents and fuel bed depth for the other constants needed in a fuel model. The fuel model given in Paper 1 describes the vegetation at sites where experimental fires were to be conducted to test the model predictions. The results in Paper 1 support the hypothesis that fynbos is structurally different from chaparral. Mature chaparral has higher fuel loads, a greater fuel bed depth, relatively coarse dead fuels and a lack of herbaceous vegetation, when compared to the fynbos described in Paper 1. The fuel model is intended for fire danger rating. It is assumed to be equivalent to fynbos tall open shrublands (Campbell et al 1981), a common structural formation in the fynbos biome, and as such should yield "estimates of burning conditions anticipated over a large area" that are "generalized for a fuel type and topography". The words in quotation marks are taken from the definition of a fire danger rating (see page 15).

Paper 2 represents a direct test of the second hypothesis, namely that Rothermel´s fire model will predict fire behaviour in South African fynbos shrublands. The behaviour of 14 experimental fires, burnt under a range of weather conditions, is described and observed parameters are compared to predictions from Rothermel´s fire model. Fire behaviour predictions using the fuel model described in the first paper gave underestimates of all parameters, which indicated that some adjustment to the fuel model was necessary. Burgan and Rothermel (1984) discuss general techniques for adjusting fuel models. Increasing the fuel bed depth estimate has the effect of decreasing the fuel packing ratios and thus increasing rate of spread and intensity estimates. The fuel bed depth should be about 70 % of the maximum vegetation height (Burgan and Rothermel 1984). The maximum vegetation height was about 2 m in the areas where experimental burns were conducted. By changing the fuel bed depth estimate from 0.9 to 1.4 m (this was done in steps of 0.1 m), estimates of fire behaviour best approximated observed values. Significant relationships exist between observed and predicted parameters (Figure 2) which supports the hypothesis that Rothermel´s model will predict fire behaviour in fynbos.

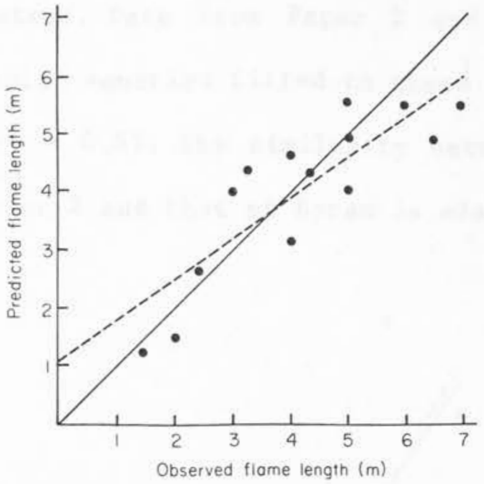


FIG. 2. Observed flame lengths versus predictions from Rothermel's fire model for fourteen fynbos fires (●). The solid line (——) is the line of perfect agreement. The dotted line (– – –) is the linear regression ($y = 0{\cdot}71\,x + 1{\cdot}01$, where y is predicted and x is observed flame length; $r^2 = 0{\cdot}739$, $P < 0{\cdot}01$).

The results are compared to fire behaviour in other shrubland ecosystems in Paper 2. Rates of spread and fire intensity are greater in fynbos than in Scottish heathland, despite similarities in biomass, and this is attributed to differences in vegetation structure. The intensities are equivalent to those reported for Californian chaparral, and this is contrary to earlier assumptions (Kruger, in Mooney and Conrad 1977) that fynbos fires are not as intense as chaparral fires. The data are a contribution towards rectifying the "serious lack of quantitative data on the effect of various factors on the behaviour of fire in South Africa" (Trollop, in Booysen and Tainton, 1984). For example, the data can be applied in research and management to estimate fire intensity from flame length. Fire intensity is directly related to flame length (Chandler et al 1983). Byram (quoted by Chandler et al 1983) determined an empirical relationship between flame length and fire intensity as:

$I = 273\ (h)^{2.17}$, where I is the intensity in kW m^{-1}, and h is the flame length in meters. Data from Paper 2 are shown graphically in Figure 3. A regression equation fitted to these data gave: $I = 402\ (h)^{1.95}$, $r^2 = 0.87$. The similarity between the model derived from the data in Paper 2 and that of Byram is also shown in Figure 3.

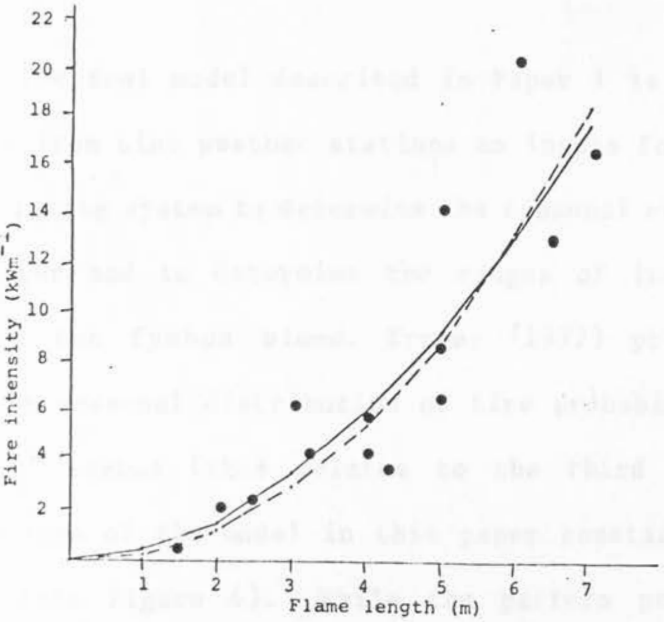


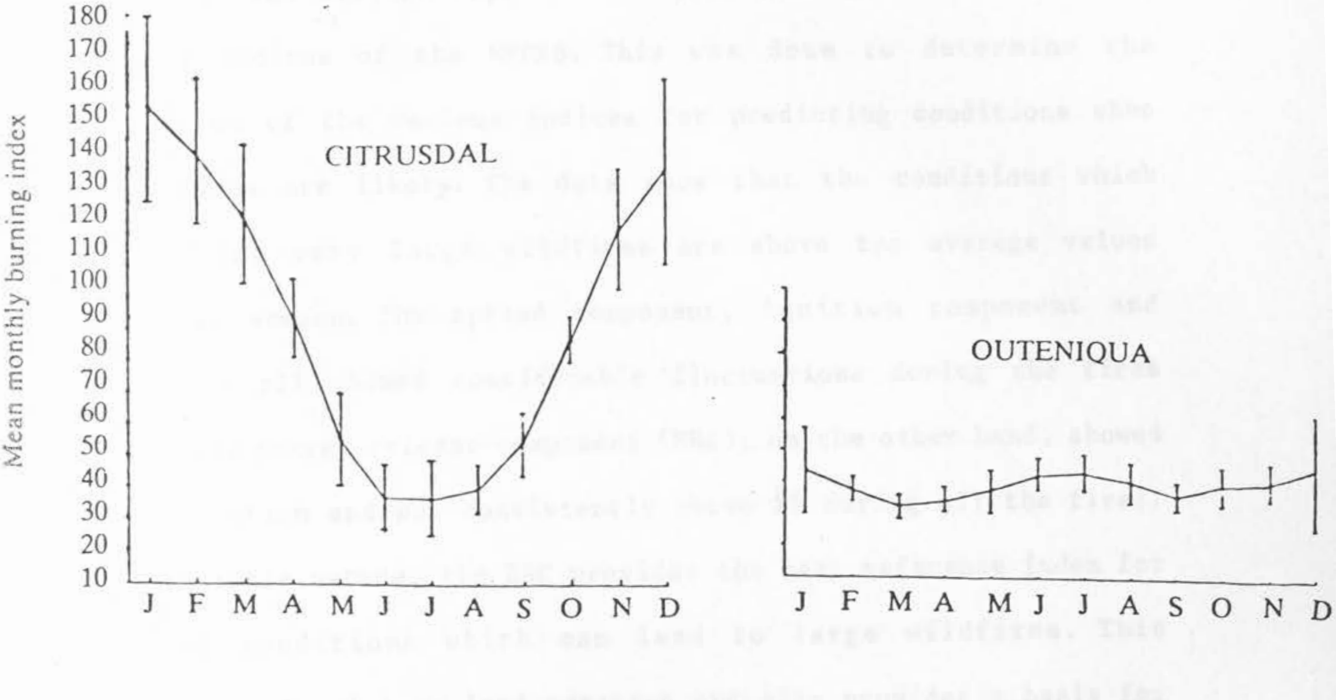
Figure 3 - The empirical relationship between flame length and fire intensity determined in two separate studies. The lines are: (——) $I = 402h^{1.95}$ (this study) and (---) $I = 273h^{2.17}$ (Byram, in Chandler et al 1983), where I is the fire intensity in kWm^{-1} and h the flame length in meters.

Fire intensity estimates should be included in reports on the effects of fire. Fire intensity in fynbos vegetation can vary up to three orders of magnitude, and estimates of intensity from flame length will produce useful "ballpark" figures. The data presented here show that, for fynbos at least, the relationships between flame length and fire intensity are very similar to those estimated by Byram. Chandler <u>et al</u> (1983) suggest the formula $I = 3(10h)^2$ for field use, as it comes to within +/- 20% accuracy within the intensity range of interest. They point out that it is difficult to estimate flame length to better than

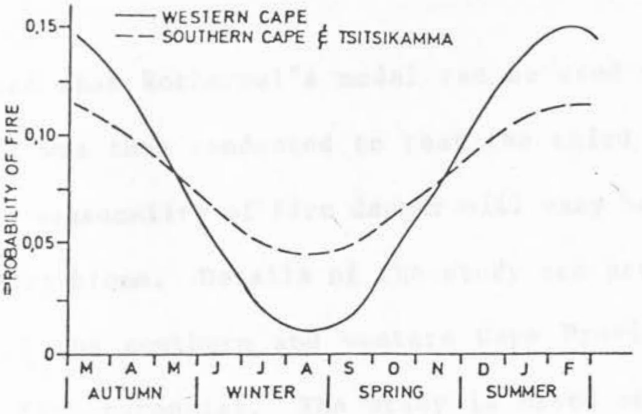
20% accuracy anyway, and the simple formula is usually adequate. Where better estimates are not possible, researchers should use the above relationships which can then be included in reports on the effects of fire on fynbos.

In Paper 3 the fuel model described in Paper 1 is used together with climate data from nine weather stations as inputs for the United States fire danger rating system to determine the seasonal and secular incidence of fire danger and to determine the ranges of indices which can be expected in the fynbos biome. Kruger (1977) proposed hypothetical curves of the seasonal distribution of fire probabilities in "western" and "eastern" fynbos (this relates to the third hypothesis of this study). The runs of the model in this paper constitute a test of this hypothesis (see Figure 4). While the pattern proposed for western fynbos fits Kruger´s hypothetical curve well, a biomodal pattern of fire danger, with peaks of high fire danger in midsummer and midwinter is evident in the eastern stations. This differs from Kruger´s proposed curve for a "eastern" fire regime.

The mean fire hazard at the coastal station at Outeniqua is low, but occasional peaks of high fire danger occur and these indicate the most likely time for fires. The fire hazard indices correlate well with the occurrence of known fires. These data also support the hypothesis that the fire danger rating system will reflect expected fire danger conditions in South African fynbos. The paper also tabulates ranges of burning index which are intended merely as a useful reference for managers who wish to adopt the system.



- 54 -



Hypothetical seasonal fire frequencies for the Fynbos Biome. Solid line represents a "western" fire regime, and broken line, an "eastern" fire regime.

Fig. 4. Mean monthly fire danger at two stations in the fynbos biome (paper 3) compared to hypothetical seasonal fire frequencies for the fynbos biome (Kruger 1977). Citrusdal is a "western" station and Outeniqua is an "eastern" station.

In Paper 4 the conditions prevalent during the eight largest wildfires on record for the western Cape are analysed and examined in terms of fire danger indices of the NFDRS. This was done to determine the relative value of the various indices for predicting conditions when large wildfires are likely. The data show that the conditions which prevail during very large wildfires are above the average values for the fire season. The spread component, ignition component and burning index all showed considerable fluctuations during the fires concerned. The energy release component (ERC), on the other hand, showed little fluctuation and was consistently above 25 during all the fires. Due to its stable nature, the ERC provides the best reference index for recognizing conditions which can lead to large wildfires. This information is of value to land managers and also provides a basis for assessing fire climates in the region (see below).

Having established that Rothermel´s model can be used with acceptable accuracy, a study was then conducted to test the third hypothesis that the magnitude and seasonality of fire danger will vary between different areas in the fynbos biome. Details of the study are presented in Paper 5. The climate of the southern and western Cape Province is examined with respect to fire potential. The study is based on the fuel model for fire danger rating presented in Paper 1, and on climate data from 40 weather stations in the fynbos biome. These stations represent the total number where all the parameters necessary as input for the fire danger rating system were available. The energy release component of the NFDRS was chosen to represent potential fire danger. Any system of defining fire climates should be based on the effects of weather variables on fuel moisture (Fosberg and Furman, 1973; Finklin, 1982). Secondly, while windspeed is important in any point evaluation of fire behaviour, natural variability of windspeed both spatially and temporally is so great that statistically it is almost useless for spatial analysis of fire climates (Fosberg and Furman, 1973). The ERC is also the steadiest indicator of high fire danger (Paper 4). The ERC is thus ideal for the analysis of fire climates, as it simulates moisture content of the fuels in the fuel model but ignores the wind component; it is related to the available energy per unit area within the flaming front at the head of a fire. For the purpose of the exercise the fire season was defined as the three month period with the highest mean ERC. This should not be construed to mean that the fire season is only three months long in all areas (see below); it is merely intended to form a basis for comparison of fire potential at that time when it is at its highest level. The results of this study support the hypothesis that the magnitude and seasonality vary between different areas. Two major distinctions are made between coastal and inland areas. The coastal and inland division differs from Kruger´s hypothesis of a western and eastern division (see Fig 4). Coastal areas have low mean ERC values in the "fire season" and seasonal fluctuations are not marked. Inland areas have high mean ERC values in the "fire season" and marked seasonal fluctuations. The biome was split into three coastal and two inland zones, as these will form more meaningful units in terms of size and current weather conditions (see Figure 5).

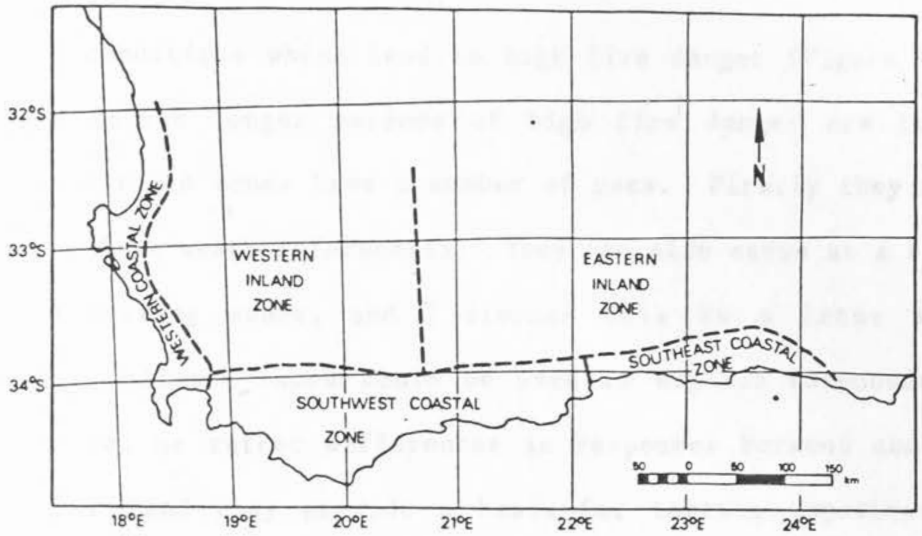


Fig. 5 Fire climate zones based on fire potential during the fire season.

In Appendix 1, the seasonal mean fire danger indices for the 40 weather stations analysed are listed as these will be useful to fire managers. The data presented in Appendix 1 can be used to determine the length of the fire season at each station. Figure 6 in Paper 3 shows that when the burning index (BI) exceeds 70, large fires are reported. BI values exceeding 70 thus indicate periods of high and extreme fire danger, and the number of months at a given station with mean BI values in excess of 70 could be assumed to be the fire season. Examination of the data in Appendix 1 on this basis shows that the mean duration of the fire season at 14 coastal stations was 2.5 months (range 0-7 months; standard deviation 2.35) while at 26 inland stations the mean duration of the fire season was 5.35 months (range 0-12 months; standard deviation 2.19). These differences are significant ($P<0.05$, t test). Similar results are obtained using mean ERC values of >15 to define a fire season. This means, in effect, that the fire season is longer inland then coastally. In coastal areas fire managers must watch for those rare conditions which lead to high fire danger (Figure 4, Paper 3), while inland longer periods of high fire danger are the rule. These fire climate zones have a number of uses. Firstly they serve as a basis for fire weather forecasts. They can also serve as a basis for prescribed burning zones, and I discuss this in a later section. Lastly, fire climate zones could be used to explain responses of the biota to fire, or rather differences in responses between coastal and inland areas, and they provide a basis for testing hypotheses along these lines. The single fuel model used does not account for all the variation in fynbos structure. Nevertheless the climatic trends are the same if different fuel models are used, although the magnitude of indices will differ. In early simulations I used the chaparral fuel model which showed the same trends as those derived by using the fynbos model.

Very few data are available to test the fourth hypothesis that the biota in the fynbos biome are adapted to survive fire in those seasons when fire danger is highest. Bond (1984) and Bond _et_ _al_ (1984) provide data to show that seedling recruitment varies significantly with season of burn in the inland ranges of the southern Cape. Paper 6 is an attempt to collect similar data for the western Cape. The data show that patterns of seedling recruitment are similar in the western Cape and southern Cape. Strong seasonal trends in fire hazard exist in inland regions of the fynbos biome (Paper 5). Figure 6 compares the seasonal cycles of flowering in fynbos plants and breeding in fynbos birds and the seasonal differences in fire survival in the genus _Protea_

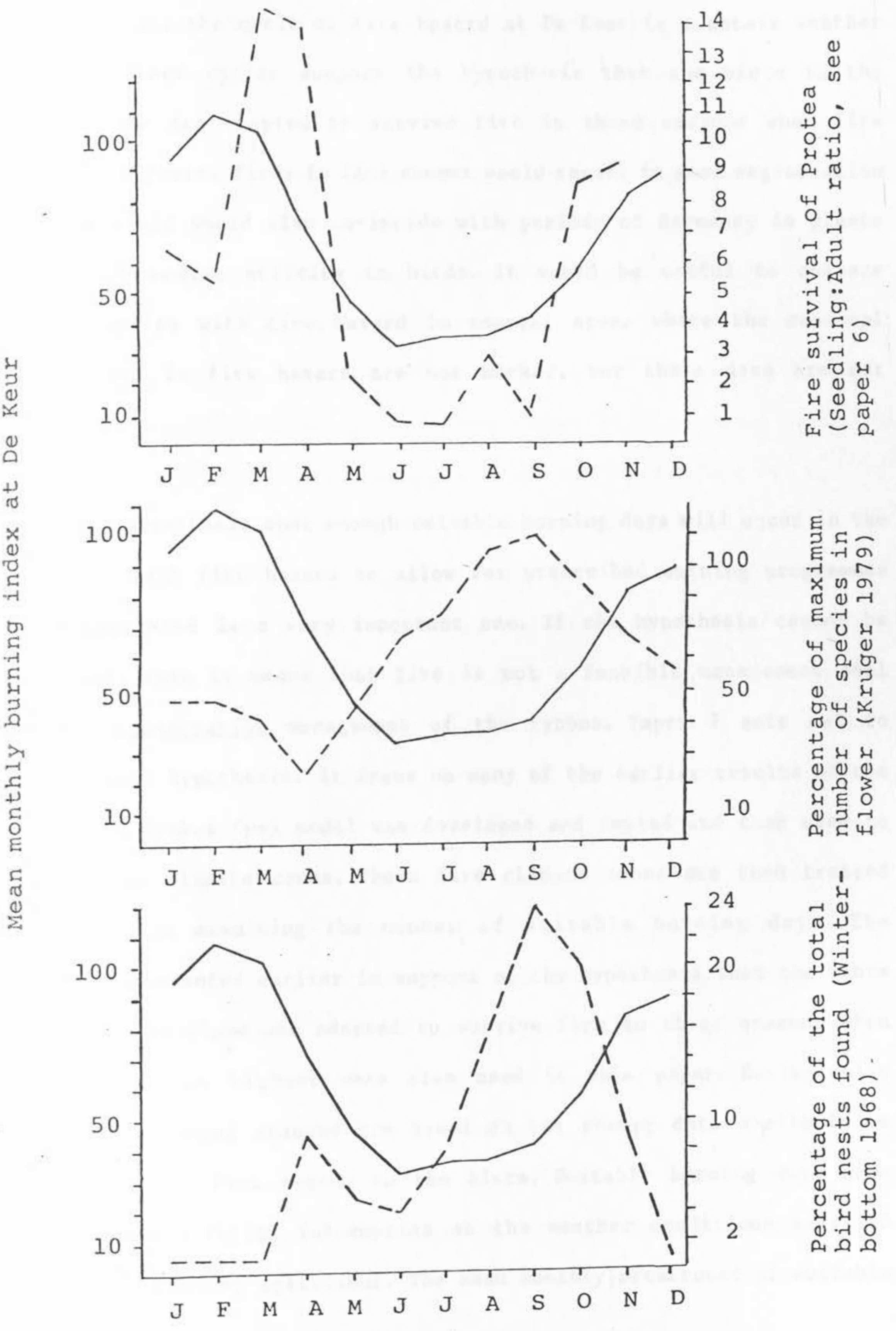


FIGURE 6: Seasonal cycles (dotted lines) in the Fynbos Biome in relation to fire hazard (solid lines).

(Paper 6) with the cycle of fire hazard at De Keur (a mountain weather station). These cycles support the hypothesis that the biota in the fynbos biome are adapted to survive fire in those seasons when fire danger is highest. Fires in late summer would result in good regeneration of proteas and would also co-incide with periods of dormancy in plants and low breeding activity in birds. It would be useful to compare similar cycles with fire hazard in coastal areas where the seasonal differences in fire hazard are not marked, but these data are not available.

The fifth hypothesis that enough suitable burning days will occur in the season of high fire hazard to allow for prescribed burning programmes to be completed is a very important one. If the hypothesis cannot be supported, then it means that fire is not a feasible management tool for the conservation management of the fynbos. Paper 7 sets out to examine this hypothesis. It draws on many of the earlier results of the study. The fynbos fuel model was developed and tested and then used to define fire climate zones. These fire climate zones are then treated separately in examining the number of suitable burning days. The arguments presented earlier in support of the hypothesis that the biota in the fynbos biome are adapted to survive fire in those seasons when fire danger is highest were also used in this paper. Ecologically desireable burning seasons are based on the scanty data available on the effects of fire season on the biota. Suitable burning days were defined by collecting information on the weather conditions selected during past burning operations. The mean monthly occurrence of suitable burning days was then examined in each of the fire climate zones. The paper concludes that suitable burning days are rare in the fynbos biome. Although the analysis shows that enough suitable burning days do occur, the major problem lies in scheduling management activities so that these days can be utilized. Thus while the hypothesis is tentatively supported, managers need to gear themselves for fire management so that rare suitable days can be utilized.

Paper 8 sets out to test the sixth hypothesis that invasions of alien shrub species increase fire hazard through increasing fuel loads. It also represents a test of the second hypothesis. Changes in biomass, size and distribution of plant parts as fuel, and plant moisture and energy contents were determined at two fynbos sites invaded by Hakea sericea and Acacia saligna. The data were used to define fuel models and to simulate fire behaviour using Rothermel's fire model. These simulations were compared to simulations using the fynbos fuel model, as modified to predict fire behaviour (Paper 2). Invasion by H. sericea resulted in a 60% increase in fuel loads and lowered the moisture content of live foliage from 155 to 110%. Simulated rates of fire spread and intensity were nonetheless lower than in fynbos due to a densely packed fuel bed. Invasion by A. saligna resulted in a 50% increase in fuel loads. The high moisture content of foliage of this shrub (about 270%) effectively reduces the fuel loads and the fuel bed depth, resulting in low rates of fire spread and intensity in the simulation. Thus, while it is shown that fuel loads are increased by invasion, the simulations failed to reflect increases in fire behaviour parameters. However, under extreme weather conditions, fire behaviour in invaded stands of fynbos is known from experienced firefighters to be "worse" than in pristine fynbos. Albini (1984) discusses the problem of simulating fire in live shrub foliage, and points out that "a large number of wildland fire phenomena elude theoretical description". The major stumbling block here appears to be the inability of Rothermel's model to accurately simulate the behaviour of fires in live foliage. While dead fuels apparently do not support fires when their moisture content exceeds 15-30%, fires still occur in live foliage with moisture contents in excess of 100% (Albini, 1984). Fires burning under extreme conditions burn the increased biomass of invaded stands of fynbos with great vigour, and under these circumstances fire hazard will be increased by invasion. This conclusion does not necessarily mean that Rothermel's model does not function <u>equally</u> well under South African conditions; it merely provides evidence that underlines a known shortcoming in the model.

GENERAL CONCLUSIONS

Main results of the study

The main results of the study are summarized in point form below.

i) Features of fynbos vegetation as a fuel bed are determined and presented as a fuel model. The fuel properties of fynbos were previously poorly known.

ii) The relationship between environmental parameters, fuel and fire behaviour are determined and shown to be well simulated using Rothermel's model. This is a significant step towards characterizing fires in fynbos.

iii) Data on fire behaviour in fynbos are presented. Such data have not been previously available.

iv) Ranges of expected fire hazard indices are determined and assessed using the data available from large wildfires. These are a contribution to the fire management effort in fynbos.

v) The features of the fire climates of the biome are analysed and shown to differ from earlier presumed patterns. These features provide a framework for analysing responses of the biota and for fire management.

vi) The response of Proteaceae to fire season in the western Cape is shown to be similar to observed responses in the southern Cape.

vii) The feasibility of burning in the summer season is determined and presented. Such data are a contribution to planning fire management in the biome.

viii) The fuel properties of invaded fynbos sites were determined and presented as fuel models.

Hypotheses

The conclusions of this study should also be considered in terms of the hypotheses set on pages 33 - 34 of this thesis.

The first hypothesis, that fynbos vegetation is structurally different to chaparral, is supported. Chaparral differs from fynbos in having higher fuel loads, a greater fuel bed depth, relatively coarse dead fuels and a lack of herbaceous vegetation. It is particularly the herbaceous vegetation which will make fynbos fuel beds differ from vegetation lacking a herbaceous component (see Paper 8 for a discussion of this). A new fuel model for fynbos was therefore used.

The second hypothesis, that Rothermel´s fire model will predict fire behaviour in South African shrublands, is supported by the results of this study. The model did predict the behaviour of fires in fynbos vegetation with acceptable accuracy (Paper 2). The model failed to reflect expected increases in fire behaviour parameters following invasions by alien shrubs (Paper 8). This is attributed to known shortcomings in the model and it does not mean that the model does not perform equally well under South African conditions.

The third hypothesis, that the magnitude and seasonality of fire danger will vary between different areas in the fynbos biome, is supported by the study. In Paper 3 it is shown that western and eastern regimes are different, and that they differ somewhat from those proposed by Kruger (see Figure 4). A more detailed analysis (Paper 5) shows that the major division of fire regions is into inland and coastal, rather than into western and eastern regions. Further analysis of data in Appendix 1 (discussed above) shows that the fire season is much longer inland than coastally (5.4 months vs. 2.5 months). This should influence both the adaptive responses of the biota and the practical application of prescribed burning.

The fourth hypothesis, that fynbos biota are adapted to survive fires at that time of the year when fire danger is highest, is supported by the data given in Paper 6 and in further discussion above. Cowling (1982) maintains that "we must restrain ourselves from concentrating our efforts on the more conspicuous components of the (fynbos) vegetation: the current practice of prescribing burning programmes which are geared towards the maintainance of Proteaceae should be re-evaluated". He indicates two options open to researchers who wish to acquire a predictive knowledge of fynbos dynamics in relation to fire. These are experiments where various fire regimes are tested with controls (van Wilgen & Kruger 1981), or studies on the regeneration niches (Grubb, 1977) or vital attributes (Noble & Slayter 1980) of individual species. Both have drawbacks. The results of experiments only become available after long periods, and their extrapolation to other areas is not always valid. On the other hand the collection of vital attributes of 8 550 fynbos species (Goldblatt, 1978) and all their genotypic variants is a formidable task. The fynbos has evolved with fire as a common pertubation and the biota have adapted accordingly. It is reasonable to assume that co-existing species should be adapted to the same fire regime. Although changes in the fire regime will favour certain species at the expense of others, any change in the fire regime which results in the local extinction of any element of the flora, Proteas or otherwise, is surely not the correct one to apply. Natural communities of species adapted to local environments stabilize under favourable fire seasonalities, which are indicated by seasons of high fire probability. Sympatric species differ in their responses to fire season because of asynchronous phenologies and differences in reproductive biology. Variability in the incidence of fire within the favourable fire season would contribute to the continued co-existence of species by allowing fluctuations around the mean composition (Kruger, in Booysen and Tainton 1984). Shifts in fire season to outside the favourable time can result in the virtual collapse of populations, as has happened with *Protea* species burnt in spring. Proteas are selected because they are relatively easy to study. To be pragmatic, we simply cannot wait for information on all species to become available, as the fynbos requires management now. The approach of relying on "indicator species" is not ideal, but must suffice for the present. Studies on reproductive guilds other than serotinous Proteaceae and their responses to changes in the fire regime are urgently needed to improve knowledge and management. In the meantime, fynbos should be burnt within the prescribed months as given in Paper 7. Prescribed fires in May and September are common (Paper 7), but this could lead to the local extinction of Proteaceae (Paper 6). Fires in these months should therefore be discouraged.

The fifth hypothesis, namely that enough suitable days will occur in the season of high fire danger to allow prescribed burning programmes to be completed, can be tentatively supported by data presented in Paper 7. The important point is to get most of the burning done in the appropriate season. The possibility exists (see above) that species of the region are adapted to a range of different fire seasons and intensities (probably with the most frequent burns being of a high intensity in late summer to autumn). Some species will be favoured over others as a result of shifts in the fire regime. If this is true then the rigorous implementation of prescribed months given in Paper 7 could be detrimental to some species. However, given the rarity of suitable burning days in the fynbos biome, it is unlikely that such a rigorous implementation of burning in the suggested seasons will take place. If management can conduct most of their burning in the suggested seasons (and this is easier said than done), then more than enough burning will be done outside the preferred seasons to take care of any species requiring such burns.

The sixth hypothesis, that invasion of fynbos vegetation by alien shrubs will increase fuel loads and fire hazard is partially supported by this study (Paper 8). Invasion does increase fuel loads, but potential fire behaviour is less serious under moderate weather conditions in invaded stands (particularly those invaded by Acacia saligna). Under extreme weather conditions, however, potential fire behaviour is worse in invaded stands as fires burn in the crowns of invaded shrubs and consume the increased fuel loads vigorously.

Implications for fire management

The adoption of systems based on Rothermel´s fire model into the formal management of fynbos catchment areas is strongly recommended. Two major changes should be made to current management. Firstly the NFDRS should be adopted for wildfire control (Paper 4). Secondly, fire records should contain fire behaviour parameters based on predictions from Rothermel´s model (Paper 2). Weather conditions, fire danger indices and fire behaviour parameters based on a suitable fuel model will serve as a good record of the type of fire that was involved. Such records will be useful when assessing the response of the biota to a given fire.

The fire climate zones presented in Paper 5 should be treated as fire management zones in the fynbos. Separate policies on fire frequency, season and intensity need to be formulated for each zone. The exact boundaries of zones need to be refined by means of an expanded network of weather stations in the mountains.

The recommendations in Paper 7 call for accurate measurements of weather before prescribed fires are attempted. This approach should replace the current practice of subjectively selecting days for burning. Burning by prescription will mean that a more "aware" approach to to fire management will have to be adopted. Methods and channels of obtaining fire weather forecasts need to be investigated. A good knowledge of local conditions is necessary to apply forecasts effectively. Other management activities will have to be scheduled so that burning can have prioity when conditions are within prescription. The prescriptions given in Paper 7 are preliminary and should be continually updated.

When planning the fire-related management of a specific area, the weather record for that area should be examined (for example as was done in Papers 3 and 7) to determine the incidence of fire hazard indices and feasible limits for burning prescriptions. If no weather data are available for an area, then a climate station should be established as a matter of priority. A knowledge of previous weather expressed in terms of indices of the NFDRS will enhance the fire management of an area.

Priorities for future research

Fire danger rating in the fynbos biome can be done initially using the single fuel model described in Paper 1. This is strongly recommended as it has a number of advantages. Firstly, a single fuel model lends simplicity to the system and makes it´s initial adoption easier. Secondly, the fire danger indices produced using one fuel model can be meaningfully interpreted by managers in terms of relative fire hazard, especially if the ranges of various indices in the area are known (see Papers 3 and 5 and Appendix 1). For fire behaviour prediction, site specific fuel models can be developed using the BEHAVE system (Burgan and Rothermel 1984). The BEHAVE system will assign values to fuel models based on the known ranges of variables such as fuel loads, surface area to volume ratios, fuel bed depths and heat contents. Research on the ranges of these variables in South African ecosystems need to be determined to verify or replace the values currently used in the BEHAVE system as these are based on examples from the United States of America.

The question of estimation of fuel moisture in the field was not addressed during this study. While the NFDRS simulates fuel moisture, it is not known how accurately this is done. Accurate estimates of fuel moisture using simple techniques will greatly improve fire danger rating and fire behaviour predictions, and should be investigated.

The effects of the fire regime (fire frequency, season and intensity) on fynbos are still poorly understood. This is especially true of fire season and intensity, and research on these two aspects is urgently required. Fynbos is a species-rich assemblage, and it is important to understand the effects of fire regime on species co-existance. Fire studies should always attempt to quantify fire intensity, as was done in Paper 2 or by using simple relationships such as those that exist between flame length and intensity, to assist in explaining the response of the vegetation.

Finally, fire should not be viewed in isolation. Other disturbance factors such as grazing, large scale flower picking and weed clearing must have significant effects on fynbos ecology, but have received little attention. The ultimate aim of the Fynbos Biome Project (Kruger,

1978) is sound conservation management. To achieve this, we must understand the effects of all disturbance factors. Management should take the form of rational decisions, based on the systematic evaluation of available information (von Gadow, 1981). The study of other disturbance factors and the incorporation of results into formal management structures is urgently required.

REFERENCES

Acocks, J.P.H. (1953). Veld types of South Africa. Mem. Bot. Surv. of S. Afr., 28, Government Printer, Pretoria.

Albini, F.A., (1976). Estimating wildfire behaviour and effects. USDA, For. Serv., Gen. Tech. Rep. INT - 30.

Albini, F.A. (1984). Wildland fires. American Scientist 72, 590-597.

Andrews, P.L. (in prep). BEHAVE: fire behaviour and fuel modeling system - BURN subsystem USDA, For. Serv. Gen. Tech. Rep. (draft).

Baumgartner, A., Klemmer, L., Raschke, E. AND Waldmann, G. (1967). Waldbrände in Bayern 1950 bis 1959. Mitteiiungen aus der Staatsforestvenvaltung Bayerns, 36, 1-2 3. München.

Bews, J.W., (1916). An account of the chief types of vegetation in South Africa, with notes on the plant succession. J. Ecol. 4, 129-159.

Bond, W.J., (1980). Fire and senescent fynbos in the Swartberg. S. Afr. For. J. 114, 68-71.

Bond, W., (1984). Fire survival of Cape Proteaceae - influence of fire season and seed predators. Vegetatio 56, 65-74.

Bond,W.J. (1985). Canopy stored seed reserves (serotiny) in Cape Proteaceae. S. Afr. J. Bot. 51, 181-186.

Bond, W.J. and Slingsby, P. (1983). Seed dispersal by ants in shrublands of the Cape Province and its evolutionary implications. S. Afr. J. Sci. 79, 231-233.

Bond, W., Vlok, J. & Viviers, M., (1984). Variation in seedling recruitment of Cape Proteaceae after fire. J. Ecol. 72, 209-221.

Booysen, P. De V. and Tainton, N.M. (1984). Ecological effects of fire in South African Ecosystems. Springer, Berlin.

Burgan, R.E. and Rothermel, R.C. (1984). BEHAVE ; Fire behaviour prediction and Fuel modeling system - FUEL sub-system. USDA, For. Serv. Gen. Tech. Rep. INT- 167.

Byram, G.M. (1959). Combustion of forest fuels. Forest fire : control and use. (Ed. by K.P. Davis pp 155-182). McGraw-Hill, New York.

Campbell, B.M., Cowling, R.M., Bond, J. & Kruger, F.J. Structural characterization of vegetation in the Fynbos Biome. South African National Scientific Programmes Report 52. CSIR, Pretoria.

Chandler, C., Cheney, P, Thomas, P., Trabaud, L. and Williams, C., (1983). Fire in Forestry Vol. I. Forest Fire Behaviour and Effects. Wiley, New York.

Crane, W.J.B. (1982). Computing grassland and forest fire behaviour, relative humidity and drought index by pocket calculator. Aust. For. 45, 89-97.

Cowling, R.M. (1982). Vegetation studies in the Humansdorp region of the Fynbos Biome. Ph.D. thesis, University of Cape Town.

Deeming, J.E., Burgan, R.E. & Cohen, J.D., (1978). The National Fire Danger Rating System - 1978. USDA (For. Serv.), Gen. Tech. Rep. INT - 39.

Deeming, J.E., & Brown, J.K., (1975). Fuel models in the National Fire Danger Rating System. J. For. 73, 347-350.

Di Castri, F., & Mooney, H.A. (1975). Mediterranean type ecosystems. Chapman & Hall, London.

Finklin, A.I. (1982). Fire climates of coastal Alaska. USDA For. Serv. Gen. Tech. Rep. INT-128.

Fosberg,M.A. and Furman, R. (1973). Fire climates in the southwest. Agric Meteorol. 12, 27-31.

Fuggle, R.F., (1981). Macro-climatic patterns within the Fynbos Biome. Unpublished report, Fynbos Biome Project, CSIR.

Gill, A.M. & Groves, R.H., (1981). Fire regimes in heathlands and their plant-ecological effects. Heathlands and related shrublands of the world Vol. 9 B. Analytical studies (Ed. by R.L. Specht), pp 61-84. Elsevier, Amsterdam.

Gill, A.M., Groves, R.H. and Noble, I.R. (1981). Fire and the Australian Biota. Australian Academy of Science, Canberra.

Goldblatt, P., (1978). An analysis of the flora of Southern Africa: its characteristics, relationships and origins. Annals of the Missouri Botanical Gardens, 65, 369-436.

Good, R., (1964). The geography of flowering plants. Longmans and Green, London.

Grubb, P.J. (1977). The maintenance of species richness in plant communities : the importance of the regeneration niche. Biological Review 52; 107-145.

Hall, A.V., de Winter, M., de Winter, B. & van Oosterhout, S.A.M., (1980). Threatened plants of southern Africa. South African National Scientific Programmes Report 45, CSIR, Pretoria.

Jarman, M., (1982). A look at the littlest floral kingdom. Scientae 23, 9-19.

Jordaan, P.G., (1949). Aantekeninge oor die voortplanting en brand periodes van Protea mellifera Thunb. Jl S. Afr. Bot. 15, 121-125.

Jordaan, P.G., (1965). Die invloed van ′n winterbrand op die voortplanting van vier soorte van Proteaceae. Tydskr. Natuurw. 5, 27-31.

Jordaan, P.G., (1982). The influence of a fire in April on the reproduction of three species of the Proteaceae. Jl S. Afr. Bot. 44, 1-4.

Kruger, F.J., (1977). Fire. Fynbos ecology : a preliminary synthesis. (Ed. by J. Day, W.R. Siegfried, G.N. Louw & M.L. Jarman). South African National Scientific Programmes Report 40, CSIR, Pretoria, pp. 43-57.

Kruger, F.J. (1978). A description of the Fynbos Biome Project. South African National Scientific Programmes Report No. 28, CSIR, Pretoria.

Kruger, F.J., (1979a). South African Heathlands. Heathlands and Related Shrublands : Vol. 9 A Descriptive Studies (Ed. by R.L. Specht) pp. 19-80. Elsevier, Amsterdam.

Kruger, F.J., (1979b). Conservation - South African Heathlands. Heathlands and related shrublands of the world. Vol. 9 B. Analytical studies. (Ed. by R.L. Specht) pp. 231-234. Elsevier, Amsterdam.

Kruger, F.J., (1981). Use and management of mediterranean ecosystems in South Africa - current problems. Dynamics and management of mediterranean-type ecosystems (Ed. by C.E. Conrad & W.C. Oechel) USDA For. Serv., Gen. Tech. Rep. PSW-58.

Kruger, F.J. & Lamb, A.J., (1978). Conservation of the Kogelberg State Forest. Unpublished report JFRC 79.02, Jonkershoek Forestry Research Centre.

Le Maitre, D.C. (1984). A short note on seed predation in Watsonia pyramidata in relation to season of burn. Jl. S. Afr. Bot. 50, 407-415.

Le Roux, H.H., (1966). Veldbestuur in die wateropvanggebiede van die winterreenstreek van suidwes-Kaapland. For. S. Afr. 6, 1-32.

Levyns, M.R., (1924). Some observations on the effects of bush fires on the vegetation of the Cape Peninsula. S. Afr. J. Sci. 21, 346-347.

Luke, R.H. and McArthur, A.G. (1978). Bushfires in Australia. Australian Govt. Publisher, Canberra.

Marloth, R., (1924). Notes on the question of veld burning. S.

Afr. J. Sci. 21, 342-345.

McArthur, A.G., (1966). Weather and grassland fire behaviour. Commonwealth of Australia, Forestry and Timber Bureau, Leaflet 100.

McArthur, A.G., (1967). Fire behaviour in eucalypt forest. Commonwealth of Australia, Forestry and Timber Bureau, Leaflet 107.

Moll, E.J., Campbell, B.M., Cowling, R.M., Bossi, L., Jarman, J.M. & Boucher, C. (1984). A description of major vegetation categories in and adjacent to the Fynbos Biome. South African National Scientific Programmes Report 83, CSIR, Pretoria.

Mooney, H.A. and Conrad, C.E. (eds.) (1977). Proceedings of the Symposium on the Environmental Consequences of Fire and Fuel Management in Mediterranean Ecosystems. USDA, For. Serv., Tech. Rep. WO-3.

Mutch, R.W. (1970). Wildland fires and ecosystems - a hypothesis. Ecology 51, 1046 - 1051.

Noble, I.R. & Slatyer, R.O. (1980). The use of vital attributes to predict successional changes in plant communities subject to recurrent disturbances. Vegetatio 43; 5-21.

Noble, I.R.,Bary, G.A.V. and Gill, A.M. (1980). McArthur's fire danger meters expressed as equations. Aust. J. Ecol. 5, 201-203.

Orieux, A. (1974). Conditions meteorolgiques et incendies in region mediterraneenne. Rev. For. Fr. n. no. special, Incendies de Forest 1, 122-129.

Pillans, N.S., (1924). Destruction of indigenous vegetation by burning on the Cape Peninsula. S. Afr. J. Sci. 21, 348-349.

Reifsnyder, W.E. (1978). Systems for evaluating and predicting the effects of weather and climate on wildland fires. World Meteorological Organization, Spec. Environ. Rep. No. 11.

Ross, J.C., (1961). Bewaring van Bergopvanggebiede in Suid-Afrika. Report, Department of Agricultural Technical Services, Pretoria.

Rothermel, R.C., (1972). A mathematical model for predicting fire spread in wildland fuels. USDA, For. Serv., Res. Pap. INT - 115.

Rothermel, R.C. and Philpot, C.W. (1973). Predicting changes in chaparral flammability. J. For. 71, 640 - 643.

Snyder, J.R. (1984). The role of fire : Mutch ado about nothing? Oikos 43, 404 - 405.

Takhtjian, A., (1969). Flowering plants : origin and dispersal. Oliver & Boyd, Edinburgh.

Taylor, H.C., (1972). The vegetation of South Africa, with emphasis on the fynbos of the southwestern Cape. University of Cape Town, Public summer school, Jan. 1972.

Taylor, H.C., (1978). Capensis. Biogeography and Ecology of Southern Africa (Ed. by M.J.A. Werger). Junk, The Hague, pp. 173-229.

Van der Merwe, P., (1975). Impossible to save the marsh rose Protea? Veld and Flora 61,4-5.

Van der Zel, D.W., (1981). Optimum mountain catchment management in Southern Africa. S. Afr. For. J. 116, 75-88.

Van Wagner, C.E. (1975). A comparison of the Canadian and American forest fire dnager rating systems. Can. For. Serv., Petawawa Forest Exp. Sta. Info. Report PS - X - 59.

Van Wilgen, B.W., (1982). Some effects of post-fire age on the above--ground biomass of fynbos (macchia) vegetation in South Africa. J. Ecol. 70, 217-225.

Van Wilgen, B.W. & Kruger, F.J., (1981). Observations on the effects of fire in mountain fynbos at Zachariashoek, Paarl. Jl S. Afr. Bot. 47, 195-212.

Von Gadow, K. (1981). Formal management methods in forestry : the decision analysis. S. Afr. For. J. 118, 7-13.

Wein and MacLean (1983). The role of fire in Northern circumpolar ecosystems.

Wellington, J.H. (1955). Southern Africa, a geological study. Vol. 1. Cambribge University Press, Cambribge.

Wicht, C.L., (1945). Report of the committee on the preservation of the vegetation of the southwestern Cape. Special Publication of the Royal Society of South Africa.

Wicht, C.L. & Kruger, F.J., (1973). Die ontwikkeling van bergveld-bestuur in Suid-Afrika. S. Afr. For. J. 86, 1-17.

Wilson, P.A.S., (1984). Managing mountain veld for water. Veld & Flora 70, 35-38.

Winterbottom, J.M. (1968). A check list of the land and fresh water birds of the western Cape Province. Ann. S. Afr. Museum 53 (1).

Wright, H.A. and Bailey, A.W. (1982). Fire Ecology : United States and Southern Canada Wiley, New York.

PART IV RESEARCH FINDINGS

Paper 1. Adaptation of the United States Fire Danger Rating System to fynbos conditions. I A fuel model for fire danger rating in the fynbos biome. South African Forestry Journal 131, 13 - 17.

Adaptation of the United States Fire Danger Rating System to Fynbos Conditions.
Part I. A Fuel Model for Fire Danger Rating in the Fynbos Biome

B.W. Van Wilgen
Jonkershoek Forestry Research Centre
Private Bag X5011
Stellenbosch — 7600

SYNOPSIS

The development of a fynbos fuel model for fire danger rating is described. The fuel model consists of values representing the fuel characteristics of fynbos vegetation, to be used in conjunction with weather data and a fire spread model to produce fire danger indices. The model represents average tall open shrubland vegetation with a post-fire age of 15 years and is compared with values and predictions from a chaparral fuel model. The model is not intended for fire behaviour prediction.

INTRODUCTION

At present there is no system by which fire danger can be quantified in South Africa. Fire danger is a relative term and refers to the likelihood of fire occurrence and to the potential intensity with which a fire will burn under given conditions. The management of large tracts of land by fire is common, especially in mountain catchment areas where it is the only practical tool which can be used to any extent. It is therefore desirable to quantify fire danger, both as an aid to the practice of prescribed burning and for fire-fighting purposes.

A flexible fire danger rating system exists for the United States of America (Deeming *et al.*, 1978). It is based on a physical fire spread model developed by Rothermel (1972). In the system, various vegetation types are characterised in terms of their fuel properties and these characterised vegetation types are termed fuel models. Although the fuel models available at present are considered sufficient for most of the vegetation types in the USA, none of these models fitted the unique fynbos vegetation type found in large areas of the western and southern Cape mountain catchment areas. Further details of the National Fire Danger Rating System are given in part II of this series (Van Wilgen and Burgan, 1984).

The concept of fuel models is described by Deeming and Brown (1975). A fuel model is a collection of numbers representing the fuel properties of vegetation. These are used as constants in the equations of the fire spread model (Rothermel, 1972). The basic fuel information required to solve the equations of the fire spread model in order to produce fire danger indices is given below.

(a) Fuel loadings are expressed as mass per unit area and divided into dead and live components. Dead fuel (litter) is further divided into size classes and live fuel is listed as herbaceous or woody (leaves and twigs only). The size classes for dead fuel are based on the time their moisture content takes to respond to changes in atmospheric conditions and are one hour time lag fuels (0-6 mm), 10 hour time lag fuels (6-25 mm), 100 hour time lag fuels (25-75 mm) and 1 000 hour time lag fuels (> 75 mm).
(b) Fuel moisture and mineral contents.
(c) Fuel bed depth, i.e. the mean height of the vegetation.
(d) Surface area to volume ratios of the fuel particles which comprise the components mentioned in (a) above. Fine fuel particles, for example, have a much larger surface area compared to their volume than coarser fuels.
(e) Mean ash-free fuel energy content for the combined fuel mass expressed in J/g
(f) Dead fuel extinction moisture content expressed as a percentage of dry mass.

This paper describes the development of a fuel model for fire danger rating in fynbos areas and is the first in a series of papers dealing with the adaptation of the fire danger rating system. The uses of the model and the expected ranges of fire danger indices for various conditions in the fynbos biome are given by Van Wilgen and Burgan (1984). This description of the development of a fuel model should be useful to those readers who are unfamiliar with the concept and it gives a background for understanding work reported later.

METHODS

Data used in the model presented here were obtained largely from published sources. These data were supplemented by analysis of the fuel properties of some selected fynbos species. Floristically, fynbos is an extremely diverse vegetation type and this complicates the selection of representative species. Structurally, fynbos is less diverse and is usually considered to consist of three major components. These are the restioid, ericoid and proteoid strata (Taylor, 1978), but quite often the proteoid stratum is absent or scattered. Species which are broadly representative of many others in each stratum in terms of fuel properties must therefore suffice in a fuel model. The species selected as representative were *Restio filiformis* Poir., and *Tetraria ustulata* (L.) C.B.Cl. for the restioid stratum, *Erica plukeneti* L. and *Stoebe plumosa* Thunb. for the ericoid stratum and *Protea repens* (L.) L. for the proteoid stratum. All of these species are widespread and often dominant in many fynbos communities and they are representative of the fuel properties of many similar species in each stratum.

Fuel loadings and fuel bed depths were obtaind from published data (see *Table 1*). Surface area to volume ratios were obtained by measurement of particles of the species mentioned above. Measurements of particle diameters were made using a calibrated microscope. The thickness of *Protea* leaves was determined using calipers. All calculations were made using the mean of 20 measurements. Large, moderate and fine stems of *Restio filiformis* were measured separately. These, together with the leaves of *Tetraria ustulata* and the leaves and stems of *Erica plukeneti,* were treated as cylinders. The stems of *Stoebe plumosa* with clusters formed by short shoots and leaves were treated as cylinders with spheres. Only the leaves of *Protea repens* are considered as fuel, as the stems do not usually burn. The area of *Protea repens* leaves was estimated by means of an area surface meter and leaves were treated as having a uniform thickness equal to the mean (0,55 mm). The surface area of each particle is simply divided by the volume of the particle to obtain the ratio. The fuel energy contents of the species were determined by standard bomb calorimetry (Susott, 1982). Ash content was estimated by thermogravimetric analysis and the heat of combustion was adjusted to an ash-free value (Susott, 1980). Extinction moisture content should be determined in field trials. As this was not possible, a figure based on tested fuel models (Albini 1976) was used.

RESULTS

As the American fire danger rating system is designed to work with imperial units, these are presented in tables, in addition to metric units, for ease of comparison and use wherever applicable.

The available data on fynbos biomass are presented in *Table 1*. Only the data for vegetation with a post-fire age greater than 10 years were considered, as the majority of fires occur in such vegetation.

Surface area to volume ratios for the selected species are presented in *Table 2*. The results of ash-free heat of combustion analysis are presented in *Table 3*.

Allocation of values of the model

It is evident from the figures in *Table 1* that fynbos biomass varies greatly. Coefficients of variation are in excess of 100 %. While some of this variation is undoubtedly due to sampling error or differing methodology, most of the variation is real. In order to estimate fire danger over large areas, such as a State Forest in the South-western Cape, one fuel model representative of the vegetation generally should be used. Such a model is not designed to predict fire behaviour to any degree of accuracy, but rather to produce relative indices of fire danger. The representative vegetation was taken to

TABLE 1. Above-ground biomass of mature fynbos communities in the South-western Cape

Area	Source	Biomass kg/ha			Post-fire age (yr)
		Woody shrubs	Live herbs	Litter	
Kogelberg	Le Maitre (1981a)	7 165+	3 244+	3 905+	20
Zachariashoek	Van Wilgen and Kruger (in prep.)	871+	4 014+	730+	12
Jonkershoek	Van Wilgen (1982)	33 550	2 940	14 300	21
Jakkalsrivier	Kruger (1977)	4 940+	7 776+	2 695+	16
Worcester	Rutherford (1978)	7 594	3 475	358	14
Worcester	Rutherford (1978)	347	13 963	199	10
Cape Peninsula	Kathan (1981)	3 092	1 779	8 000	10
Cape Peninsula	Kathan (1981)	13 117	4 658	25 440	20
Cape Flats	Low (1983)	13 610	970	2 730	11
Means		9 365	4 757	6 484	14.89
Standard deviation		10 231	3 950	8 426	4.51
Coefficient of variation* (%)		109	83	130	30

+ Mean value of sites sampled within area

* $s/\bar{x}$

TABLE 2. Surface area to volume ratios for fuel particles of selected fynbos species

Species	Plant parts	Mean* surface area to volume ratios (m^2/m^3 and ft^2/ft^3)		Standard deviation (m^2/m^3
Restio filiformis	Large stems	182	(598)	33,7
Restio filiformis	Moderate stems	372	(1219)	48,4
Restio filiformis	Fine stems	688	(2258)	121,4
Tetraria ustulata	Leaves	701	(2300)	171,9
Stoebe plumosa	Stems with short shoots and leaves	371	(1216)	79,3
Erica plukeneti	Leaves	715	(2345)	133,2
Erica plukeneti	Stems	142	(467)	27,8
Protea repens	Leaves	420	(1379)	53,0

* n = 20

be a tall open shrubland (Campbell *et al.*, 1981) with a post-fire age of 15 years and with approximately 7 000 kg/ha of woody shrubs and roughly 5 000 kg/ha of herbaceous vegetation and dead material, respectively. Only portions of live vegetation classified as fuel should be included in fuel models (Deeming and Brown, 1975). Fuel in live vegetation comprises only the finer portions (such as leaves and fine twigs) which will burn. As most herbaceous vegetation is fine enough to be classified as fuel (Kruger, 1977; van Wilgen, 1982) the herbaceous load can remain at 5 000 kg/ha. About 32 % of the woody shrub mass is fine enough to be classified as fuel (van Wilgen, 1982). So 7 000 kg/ha of woody shrub mass must be scaled down to 2 240 kg/ha of woody fuel. Dead fuel should be divided into 1, 10, 100 and 1 000 hour time lag classes. Van Wilgen (1982) reported that about 78 % of litter was fine enough to be classified as one hour time lag fuel. The reminder can be allocated to 10 hour, with some 100 hour fuels. Coarse litter is not common in fynbos. As most of the fuel, especially litter, consists of finer material (for example fine restioid stems and ericoid leaves) surface area to volume ratios are weighted towards the finer fractions. The ratios for 10 and 100 hour fuel components are standard by definition (R.E. Burgan, pers. comm.). As herbaceous vegetation and its litter would form most of the fuel, a heat of combustion of 20 000 J/g (8 600 Btu/1b) was used. Durand (1981) reports a range of 18 225 — 20 677 J/g for "fynbos fuels", which supports these figures. The values allocated to the model are shown in *Table 4,* together with values from a chaparral fuel model (Albini, 1976).

TABLE 3. Heat of combustion values for selected fynbos species

Species	Plant parts	Heat of combustion J/g	and Btu/lb	Mean ash (%)	Ash-free heat of combustion* J/g	and Btu/lb
Protea repens	Leaves	21 595	9 286)	1,61	21 948	(9 438)
Erica plukeneti	Stems, leaves and flowers	22 524	(9 686)	3,50	23 341	(10 037)
Tetraria ustulata	Leaves and stems	18 336	(7 884	6,46	19 602	(8 428)
Stoebe plumosa	Leaves and stems	19 149	(8 234)	10.01	21 279	(9 150)
Restio filiformis	Stems	19 712	(8 477)	2,14	20 143	(8 662)

* $HC_A = 100\ HC/(100\text{-}AP)$

Where HC_A = ash-free heat of combustion

HC =heat of combustion (unadjusted)

AP = percentage ash content

Testing of the model

Field testing of the model has not yet been carried out. Data on fire behaviour in fynbos are very limited. *Table 5* gives the only published rate of spread data available at present. These rates of spread range from 0.07 to 1,43 m/s and are based on the measurement of actual fire spread on experimental 50 x 50 m plots during seven fires (le Maitre, 1981b) and on the casual observation of an unspecified number of fynbos fires (Bands, 1977). It may be expected that the model should, under various weather conditions, produce rates of spread roughly within these limits. In adapting the fire danger rating system (Deeming *et al.*, 1978) to South African conditions, it was initially proposed that a model similar to the chaparral model would be the closest approxomation of the fynbos. Predictions of rate of spread using the fynbos and mature chaparral models were

TABLE 4. Values used in the generalised fynbos and the chaparral fuel models

Parameter	Units	Fynbos		Chaparral	
Fuel loads					
1 h time lag dead fuel	Kg/ha (tons/ac)	4 000	(1.80)	7 850	(3.50)
10 h time lag dead fuel		950	(0,45)	8 950	(4,00)
100 h time lag dead fuel		120	(0,05)	120	(0,50)
Herbaceous fuel		5 000	(2,25)	0	(0)
Woody fuel		2 240	(1,00)	25 750	(11,50)
Surface area to volume ratios					
1 h time lag dead fuel	m^2/m^3 (ft^2/ft^3)	671	(2 200)	213	(700)
10 h time lag dead fuel		33	(109)	33	(109)
100 h time lag dead fuel		9	(30)	9	(30)
Herbaceous fuel		549	(1 800)	0	(0)
Woody fuel		457	(1 500)	381	(1 250)
Heat content	J/g (Btu/1b)	2 000	(8 600)	22 100	(9 500)
Fuel bed depth	m (ft)	0,91	(3)	1,83	(6)
Extinction moisture	%	34		20	
Midflame wind conversion factor	—	0,6		0,5	

compared and the results are given in *Figure 1*. These were obtained using Rothermel's (1972) fire spread model under various conditions of one hour fuel moisture content and midflame wind speeds. For the purposes of this exercise, 10 and 100 hour fuel moisture contents were held constant at 10 % and live fuel moisture at 125 %. The slope was zero and predictions were for the direction of maximum spread.

TABLE 5. Published rate of fire spread data for fynbos vegetation in the South-western Cape

Source	Number of fires observed	Rate of spread (m/s) Minimum	Mean	Maximum
Bands (1977)	Not specified	0,07	0,28	1,11
Le Maitre (1981b) (Spring burns)	3	0,12	0,34	0,82
Le Maitre (1981b) (Summer burns)	1	0,18	0,44	1,43
Le Maitre (1981b) (Autumn burns)	3	0,09	0,35	1,07

DISCUSSION

The initial assumption was that the chaparral fuel model would suffice for rating fire danger in the fynbos. Both fynbos and the Californian chaparral are shrublands growing in a mediterranean climatic region, superficially similar in structure and prone to periodic fires. However, there are major differences between the fynbos and the chaparral and these are apparent from *Table 4.* They include the much higher fuel loads, greater fuel bed depth, the coarse nature of the finer dead fuels and the total lack of herbaceous vegetation in mature chaparral. The post-fire succession in chaparral can be divided into three stages. First is the herbaceous stage, lasting up to five years after fire, where the vegetation is dominated by herbs and grasses. These are geen during the rainy season and cured in summer and autumn, when they could burn. Burning on cycles of less than five years would be possible and would probably result in the conversion of chaparral to grassland. Second is a shrub stage, where shrubs overtop the herbaceous vegetation and almost eliminate it completely. The vegetation is not fire prone during this stage (Green, 1981). The third stage occurs when shrubs produce enough dead material to support fires, usually 20 to 30 years after a previous burn. The vegetation becomes extremely fire-prone during the late summer.

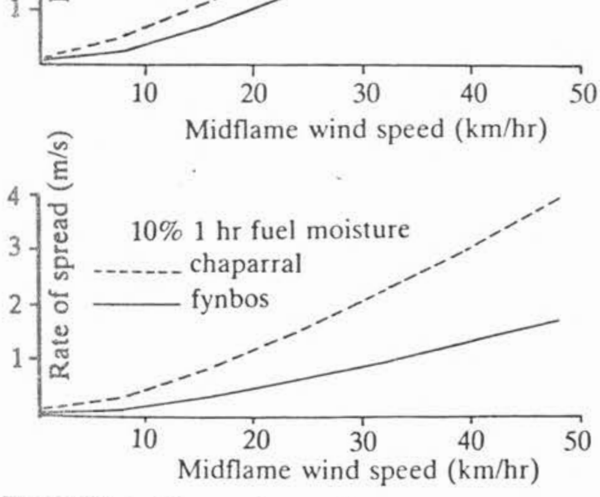


FIGURE 1. Comparison of predicted rates of fire spread using chaparral and fynbos fuel models. See text for details.

In order to reduce the fire hazard and fuel loads, prescribed burning is carried out in chaparral under conditions that will allow moderate intensity fires. In areas where the chaparral is not yet old enough to burn, it is treated by mechanically killing shrubs or spraying them with herbicides, producing sufficient dead material to support a fire (Green, 1977). This prevents the vegetation from reaching the fire-prone third stage. It is not possible to burn on cycles of between six and 20 years without first treating the vegetation.

The fuel characteristics of fynbos have been discussed by Kruger (1977) and van Wilgen (1982). Fynbos communities accumulate enough fuel to sustain a fire at a post-fire age of about four years. Most of this fuel consists of live and dead graminoid and restioid (herbaceous) plants. In the post-fire succession in fynbos, the herbaceous component is overtopped by larger proteoid shrubs after about eight years. In contrast to chaparral vegetation, the herbaceous component persists and the shrubs do not normally dominate to such a great degree. Furthermore, seasonal curing of the herbaceous vegetation is not a feature of fynbos. Fires are therefore possible in any season under suitable weather conditions, or at any stage in the post-fire succession, from four years post-fire age onwards. Thus chaparral fuel models are not at all suitable for use under fynbos conditions.

The predicted rates of spread for fynbos shown in *Figure 1* are well within the range of observed values *(Table 5),* except where combinations of high midflame wind speed (>30 km/h) and low one hour fuel moisture contents (2 %) occur. However, these are extremely hazardous conditions which are rarely if ever realised in nature. Predicted rates of spread for chaparral under the same conditions *(Figure 1)* are higher. This is due to a less dense packing of fuel in the chaparral which allows for faster rates of spread. Chaparral has a much higher fuel load, but the fuel is less densely packed because of the greater fuel bed depth and lower surface area to volume ratios *(Table 4).* As field testing of the fynbos fuel model has not yet been carried out, it should be stressed that the model presented here is not meant to predict fire behaviour accurately. Its main function would be to produce relative fire danger indices. The production and uses of these indices are discussed in part II of this series (Van Wilgen and Burgan, 1984).

More data on the fuel loads and other fuel parameters in fynbos will become available with the passage of time. These, together with fire behaviour observations at experimental and operational fires, will provide data to fill the existing gaps in our knowledge. The ultimate goal would be to produce several fuel models to cover a range of fynbos fuel types, which could be used for both fire danger rating and fire behaviour prediction. This model is seen as no more than a first step in that direction.

ACKNOWLEDGEMENTS

I am extremely grateful for the willing help of staff of the Northern Forest Fire Laboratory, Missoula, Montana, particularly Bob Burgan, Frank Albini, Dick Rothermel, Pat Andrews and Bobbie Hartford. This study would not have been possible without their help. I thank two anonymous referees for useful comment on the manuscript.

REFERENCES

ALBINI, F.A., 1976. *Estimating Wildfire Behaviour and Effects.* USDA, Forest service, General Technical Report INT — 30.

BANDS, D.P., 1977. Prescribed Burning in Cape Fynbos Catchments. *Proceedings of the symposium on the environmental consequences of fire and fuel management in mediterranean ecosystems.* (Ed. by H.A. Mooney and C.E. Conrad), pp. 245-256. USDA Forest Service, Technical Report WO-3.

CAMBELL, B.M., COWLING, R.M., BOND, W., and KRUGER, F.J., 1981. *Structural Characterization of Vegetation in the Fynbos Biome.* South African National Scientific Programmes Report 52, CSIR.

DEEMING, J.E., and BROWN, J.K., 1975. Fuel Models in the National Fire-Danger Rating System. *Journal of Forestry* 73: 347-350

DEEMING, J.E., BURGAN, R.E., AND COHEN, J.D., 1978. *The National Fire Danger Rating System — 1978.* USDA Forest Service, General Technical Report INT 39.

DURAND, B.J., 1981. *A Study of the Short-term Responses of Fynbos to Fire in the Kogelberg State Forest, South Africa.* M.Sc. thesis, University of Cape Town.

GREEN, L.R., 1977. *Fuelbreaks and Other Fuel Modification for Wildland Fire Control.* USDA, Forest Service. Agriculture Handbook No. 499.

GREEN, L.R., 1981. *Burning by Prescription in Chaparral.* USDA, Forest Service. General Technical Report PSW — 51.

KATHAN, L., 1981. *A Study of Certain Ecological Aspects Pertaining to a* Leucadendron laureolum *Community at the Silver Mine Nature Reserve, South Africa.* M.Sc. thesis University of Cape Town.

KRUGER, F.J., 1977. A Preliminary Account of Aerial Plant Biomass in Fynboss communities of the Mediterranean-type Climate Zone of the Cape Province. *Bothalia,* 12: 301-307.

LE MAITRE, D.C, 1981a. *Kogelberg Season of Burn Trial. I: Site Description and pre-fire Community Structure.* Unpublished report, Jonkershoek Forestry Research Station.

LE MAITRE, D.C., 1981b. *Kogelberg season of burn trial II. The Experimental Fires.* Unpublished report, Jonkershoek Forestry Research Station.

LOW, A.B., 1983. Phytomass and Major Nutrients Pool in an 11-year Post-fire Coastal Fynbos Community. *South African Journal of Botany* 2: 98-104.

ROTHERMEL, R.C., 1972. *A Mathematical Model of Fire Spread Predictions in Wildland Fuels.* USDA Forest Service, Research Paper INT 115.

RUTHERFORD, M.C., 1978. Karoo-fynbos Biomass Along an Elevational Gradient in the Western Cape. *Bothalia* 12: 555-560.

SUSOTT, R.A., 1980. *Effect of Heating Rate on char Yield from Forest Fuels.* USDA Forest Service, Research Note INT 295.

SUSOTT, R.A., 1980. *Effect of Heating Rate on Char Yield from* Forest Fuels by Combustible Gas Analysis. *Forest Science* 28: 404-420.

TAYLOR, H.C., 1978. Capensis. *Biogeography and Ecology of Southern Africa* (Ed. by M.J.A. Werger), pp. 171-229. Junk, The hague.

VAN WILGEN, B.W., 1982. Some Effects of post-fire Age on the Above Ground Plant Biomass of Fynbos (Macchia) Vegetation in South Africa. *Journal of Ecology* 70: 217-225.

VAN WILGEN, B.W., and BURGAN, R.E., (1984). Adaptation of the United State Fire-danger Rating System to Fynbos conditions II. Historic fire danger in the fynbos biome. *South African Forestry Journal.* 129: 66-78.

VAN WILGEN, B.W., and KRUGER, F.J., (In prep.) The Vegetation and Plant Communities of the Zachariashoek Catchments.

Paper 2. Fire behaviour in South African fynbos (macchia) vegetation and predictions from Rothermel's fire model. Journal of Applied Ecology 22, 207 - 216.

Journal of Applied Ecology (1985) **22,** 207–216

FIRE BEHAVIOUR IN SOUTH AFRICAN FYNBOS (MACCHIA) VEGETATION AND PREDICTIONS FROM ROTHERMEL'S FIRE MODEL

BY B. W. VAN WILGEN, D. C. LE MAITRE AND F. J. KRUGER*

Jonkershoek Forestry Research Centre, Private Bag 5011, Stellenbosch, 7600, South Africa

SUMMARY

(1) South African fynbos (sclerophyllous shrubland) vegetation is fire-prone, and fire is important in fynbos management. No data on fire behaviour in fynbos are presently available.

(2) The behaviour of fourteen experimental fires in fynbos tall open shrublands is described. Rates of spread ranged from 0·04 to 0·89 m s^{-1}, flame lengths from 2·8 to 7·0 m and fire intensities from 515 to 20 709 kW m^{-1}.

(3) The fire behaviour is compared to predictions from Rothermel's fire spread model, which uses fuel characteristics and environmental conditions to predict fire spread and intensity. Predictions of rate of spread and flame length were good but fire intensity was underestimated where biomass and fire hazard were high.

(4) The results are compared to fire behaviour in other shrubland ecosystems. Rates of fire spread and fire intensity are greater in fynbos than in Scottish heathland, and are equivalent to those reported for Californian chaparral.

(5) The inclusion of fire danger indices and predictions based on Rothermel's model in fynbos fire records will enhance their value. The model can also be useful in fire research, particularly in homogenous vegetation, and represents an improvement on techniques such as the measurement of fire temperature.

INTRODUCTION

Fynbos is a local term describing the sclerophyllous shrubland vegetation of the southwestern Cape Province of South Africa, and includes the vegetation types macchia and false macchia described by Acocks (1953). Most extant fynbos vegetation occurs in mountain areas which are managed as water catchments and for nature conservation. Fires are a feature of these ecosystems (Kruger 1977a; Van Wilgen 1982) and most of the active management of conservation areas involves the use of fire (Kruger 1982). In order to quantify variations in the post-fire response of vegetation and to elucidate factors causing such variation, it is necessary to describe fires accurately. Many studies on the effects of fire have no precise description of the fire which caused the effects described (McArthur & Cheney 1966; Gill & Groves 1981; Hobbs & Gimingham 1984). Models for predicting fire behaviour in natural vegetation have been developed for aiding fire control strategies, but are finding increasing use as guides to the prescription of management fires in conservation areas (Gill & Groves 1981). These models should also aid managers of fire-prone ecosystems in describing fires. One such model is Rothermel's (1972) fire spread model. The model was developed for appraising fire spread and intensity in the United States National Fire Danger Rating System (NFDRS), described by Deeming, Burgan & Cohen

---

* Present address: South African Forestry Research Institute, P.O. Box 727, Pretoria 0001, South Africa.

(1978). It is designed to predict fire behaviour in a continuous stratum of fuel that is contiguous to the ground. Furthermore, the model is designed to simulate a fire that has stabilized into a quasi-steady spread condition. This condition is reached when the fire front has spread far enough from the initial point of ignition to be independent of the influences caused by the opposite front. The initial work on the model was done using fuel arrays composed of uniform sized particles. Three fuel sizes were tested over a wide range of bulk densities. The problem of mixed fuel sizes was then resolved by weighting the varous particle sizes that compose actual fuel arrays by either surface area or loading, depending on the feature of the fire being predicted. Fire behaviour predictions from the model are based on inputs of the physical and chemical makeup of the fuel and the environmental conditions under which it is expected to burn. Fuel characteristics such as estimates of fuel loads, fuel particle sizes, fuel-bed depth and heat yields are summarized in fuel models. A fuel model is a set of values which quantifies a particular vegetation type in terms of its fuel characteristics (Deeming & Brown 1975). The use of predetermined fuel models eliminates the need to measure fuel characteristics in the field. Van Wilgen (1984a) described a fuel model to be used for fire danger rating in fynbos. Such a model cannot be used for fire behaviour prediction until it has been validated in field trials. The fynbos fuel model describes the fuel properties of fynbos tall open shrublands (*sensu* Campbell *et al.* 1981). It was designed to represent the vegetation at sites where replicated burning trials were under way to assess the effects of fire season on the vegetation. This offered the opportunity to test the validity of Rothermel's fire model for fire behaviour prediction in fynbos, using the fynbos fuel model. This paper describes the methods used to measure fire behaviour and compares the behaviour of fires to predictions from Rothermel's fire model.

THE STUDY SITES

Fires were conducted at two sites, the Kogelberg and the Cederberg. The sites are described in detail by Durand (1981) and Le Maitre (1984). They were selected for apparent structural homogeneity of the vegetation with the aim of testing the effects of fire season on vegetation in small (about 50 × 50 m) plots.

Kogelberg

The site is situated in the Kogelberg State Forest at 34°16′S and 19°00′E and is 110 m above sea level. Sandstones of the Nardouw formation of the Table Mountain Group underly the site. Soils are sandy and shallow. The site is mainly level with a maximum slope of 6 degrees. Mean annual rainfall on the site is 1020 mm.

The vegetation was a tall (about 1·8 m) open shrubland. The dominant tall shrub was *Leucadendron laureolum* (Lam.) Fourc. (Proteaceae). The understorey consisted of various *Restionaceae* (*Restio egregius* Hochst. dominant), *Cyperaceae* (*Tetraria* sp.) and fine-leaved shrubs of the *Ericaceae* (*Erica pulchella* Houtt. and *Erica corifolia* L. dominant) and *Asteraceae*.

Cederberg

The site is situated in the Cederberg State Forest at 32°20′S and 19°03′E and is 470 m above sea level. Sandstones of the Peninsula formation of the Table Mountain Group underly the site. Soils are gravelly and shallow. Slopes face northeast with inclinations varying from 6 to 15 degrees. Mean annual rainfall on the site is 660 mm.

The vegetation was a tall (about 1·8 m) open shrubland. Tall shrubs of the family

Proteaceae (*Leucadendron pubescens* R.Br., *Paranomus bracteolaris* Salisb. ex Knight and *Protea laurifolia* Thunb.) predominated. The understorey consisted of various Restionaceae (*Hypodiscus neesii* Mast. dominant) and Poaceae, and fine-leaved shrubs of the families *Asteraceae* (*Stoebe* and *Metalasia* sp.) and *Fabaceae*.

METHODS

Data from fourteen experimental fires, burnt between 1976 and 1984 are included in this paper. Six of these were in the Kogelberg and eight in the Cederberg.

Pre-fire biomass

Methods used in the determination of pre-fire biomass have been described in detail by Durand (1981) and Le Maitre (1984). Regression relationships between stem diameter, total mass and leaf mass were established for dominant shrubs from a sample of shrubs harvested outside the plots. Shrub density was estimated inside the plots by the wandering quarter method (Catana 1963). Shrub stem diameters were measured at the same time, and used to calculate a mean shrub mass. This was multiplied by the density estimate to give biomass. The understorey biomass was determined from a random sample of clip-plots.

TABLE 1. Above-ground dry mass of vegetation components (g m^{-2}) in fynbos shrublands before burning

Plot number*	K3	K2	K4	K8	K6	K7	C1	C7	C4	C6	C2	C8	C12	C9
Number of clip-plots	31	20	18	30	20	20	5	5	5	5	5	5	5	5
Clip plot size (m^2)	1	4	4	1	4	4	4	4	4	4	4	4	4	4
Leucadendron laureolum	312	174	222	97	518	411								
L. pubescens							770	824	736	130	674	486	819	960
Paranomus bracteolaris								6		99		2	200	3
Protea laurifolia											1732			
Other shrubs	148	259	261	477	384	497	112	232	509	122	102	198	320	264
Restioid plants	127	294	296	364	334	400	368	282	449	354	54	491	248	444
Graminoid plants	4	97	132	2	37	57	52	8	25	13	68	15	17	11
Other herbs	3	9	14	1	4	9	22	15	58	17	29	23	9	12
Dead material	375	249	387	298	379	496	440	554	400	488	756	630	751	444
Total above-ground biomass	969	1082	1312	1239	1656	1870	1764	1921	2177	1223	3415	1846	2364	2138

* K. Kogelberg; C. Cederberg.

The number and size of clip-plots varied (see Table 1). Clipped material was separated into growth-form categories as follows:

(i) Shrubs other than dominant shrubs: microphanerophytes and nanophanerophytes of families such as *Ericaceae*, *Fabaceae* and *Asteraceae*.

(ii) Restioid plants: leafless hemicryptophytes of the family *Restionaceae* and, sometimes, *Cyperaceae*.

(iii) Graminoid plants: hemicryptophytes typical of the families *Poaceae* and *Cyperaceae*.

(iv) Other herbs: non-woody species not included in the above categories, and including ferns.

(v) Litter: all dead material including standing dead plant parts.

The samples were stored (for up to 10 days), oven-dried at 80 °C until constant mass had been reached, and then weighed.

Post-fire biomass

Post-fire biomass was estimated immediately after each fire to determine the amount of fuel consumed. The understorey mass was estimated by clipping all remaining material from a random sample of five plots (2 × 2 m). An ocular estimate of the mean percentage of dominant shrub crowns consumed during the fire was obtained from a random sample of about fifty shrubs. The pre-fire shrub leaf mass was reduced by this percentage to obtain an estimate of the fuel consumed.

Fuel moisture contents

Samples of the vegetation were clipped immediately prior to each fire. Two or three samples each of dead material (litter), understorey herbs and woody shrubs were sealed in air tight glass bottles until each could be weighed and dried. All particles sampled had diameters <6 mm. The percentage moisture content was calculated on a dry weight basis and took account of condensation from the sample onto the bottles.

Weather and fire behaviour

Wet and dry bulb temperatures were noted at 1 min intervals for the duration of each fire using an Assmann aspirated psychrometer. The windrun during the fire was estimated using a cup anemometer with a digital counter. Windrun was noted at 1 min intervals. The instruments were stationed about 50 m away from the fires and were held about 1·8 m above the ground.

Rate of fire spread was estimated from a grid of 16–20 points in each plot. Steel wires were tied to pegs at each point by means of nylon line. The other end of each wire was tied to a numbered weight and suspended over a frame outside the plot. When the fire reached the peg, the nylon melted, the weight fell and the time elapsed between ignition and fall was noted using a stopwatch. From these elapsed times, fire isolines and maximum, minimum and mean rates of fire spread could be calculated.

The progress of each fire was photographed and flame length was estimated from the photographs. Shrub heights were measured in each plot prior to the fires, and these provided a scale for estimating flame length.

Fire intensity was estimated using Byram's (1959) formula:

$$I = Hwr \tag{1}$$

where I is the fire intensity (kW m^{-1}), H is the heat yield of the fuel (kJ g^{-1}), w is the weight of available fuel (g m^{-2}), and r is the rate of fire spread (m s^{-1}).

The total biomass on each plot was reduced by the percentage of biomass consumed (Table 2) to obtain available fuel. A heat yield of 20 000 J g^{-1} was determined from a sample of representative fynbos species for use in the fuel model (van Wilgen 1984a). This heat yield was adjusted using Byram's (1959) corrections for fuel moisture.

Fire behaviour predictions

Fire behaviour predictions were made using a Texas Instruments TI-59 programmable calculator, equipped with a special module pre-programmed with Rothermel's fire spread model. Fuel models can be entered on magnetic strips. Weather parameters and fuel moisture contents are then entered manually to produce fire behaviour estimates. The method is described by Burgan (1979). Conditions during the fires were used in conjunction with the fynbos fuel model (Van Wilgen 1984a) to obtain estimates of rate of fire spread, flame length and fire intensity.

TABLE 2. Conditions of fuel and weather during experimental fynbos fires

		Conditions during fires					
Plot Number	Date of burn	Mean air temperature (°C)	Mean relative humidity (%)	Mean windspeed (m s^{-1})	Dead fuel moisture (% dry weight)	Live fuel* moisture (% dry weight)	% biomass consumed
K3	28 September 1976	24·4	20	1·50	3	137	61
K2	23 February 1977	23·9	50	3·56	7	125	80
K4	20 May 1977	26·7	80	2·67	10	147	66
K8	12 April 1978	29·4	90	3·11	12	87	87
K6	12 October 1978	13·9	38	2·67	6	109	68
K7	18 April 1979	15·0	62	3·11	10	109	79
C1	14 November 1983	23·9	37	1·92	6	121	63
C7	14 November 1983	18·9	60	1·03	13	107	59
C4	19 January 1984	31·1	26	3·56	4	113	77
C6	19 January 1984	27·8	33	2·50	3	136	86
C2	15 March 1984	38·3	15	2·83	2	107	66
C8	15 March 1984	37·8	15	1·89	3	58	79
C12	2 May 1984	23·9	33	2·67	5	91	72
C9	2 May 1984	23·9	33	3·11	5	91	74

* Mean of herbaceous and woody samples.

RESULTS

Details of the pre-fire biomass on each are presented in Table 1. Despite the fact that sites were selected for their apparent structural homogeneity, there was considerable variation in the total biomass (from 969 to 3415 g m^{-2} with a coefficient of variation of 36%). The mean pre-fire biomass (1784 g m^{-2}) was nonetheless virtually the same as that used in the fynbos fuel model (1707 g m^{-2}), which means that the fuel model should be a good descriptor of the average stand.

The conditions of fuel and weather during the experimental fires are presented in Table 2. The fires burnt under a fairly wide range of weather conditions. Air temperature ranged from 13·9 to 38·3 °C, relative humidity from 15 to 90% and mean windspeed from 1·03 to 3·56 m s^{-1} (Table 2). This represents the range of conditions under which it is possible to conduct experimental fires. Really hazardous fires, such as those burning under conditions of strong wind, cannot be easily quantified. This precludes an empirical approach and is a

TABLE 3. Observed fire behaviour parameters during experimental fynbos fires compared with predictions from Rothermel's fire model

Plot Number	Rate of fire spread (m s^{-1})		Mean flame length (m)		Fire intensity (kW m^{-1})	
	Observed	Predicted	Observed	Predicted	Observed	Predicted
K3	0·36	0·20	2·4	2·8	2596	2391
K2	0·44	0·60	3·2	4·3	4355	5941
K4	0·21	0·16	2·0	1·5	2030	730
K8	0·47	0·67	4·0	4·6	5908	7359
K6	0·30	0·52	4·3	4·3	3864	6353
K7	0·37	0·51	3·0	4·0	6245	4813
C1	0·32	0·28	4·0	3·1	4096	3194
C7	0·04	0·07	1·4	1·2	515	394
C4	0·89	0·85	7·0	5·5	16 840	11 124
C6	0·52	0·42	5·0	4·0	6704	5093
C2	0·80	0·71	6·0	5·5	20 709	10 027
C8	0·52	0·59	6·5	4·9	13 024	8591
C12	0·55	0·65	5·0	4·9	8956	8640
C9	0·78	0·82	5·0	5·5	14 511	10 799

strong argument for a laboratory-based modelling approach founded on physical principles that dominate the fire spread process.

Fire behaviour predictions from Rothermel's model using Van Wilgen's (1984a) fynbos fuel model gave underestimates of all parameters, which indicated that some adjustment to the fuel model was necessary. Increasing the fuel bed depth estimate has the effect of decreasing the fuel packing ratios and thus increasing rate of spread and intensity estimates. By changing the fuel bed depth estimate from 1 to 1·4 m, estimates of fire

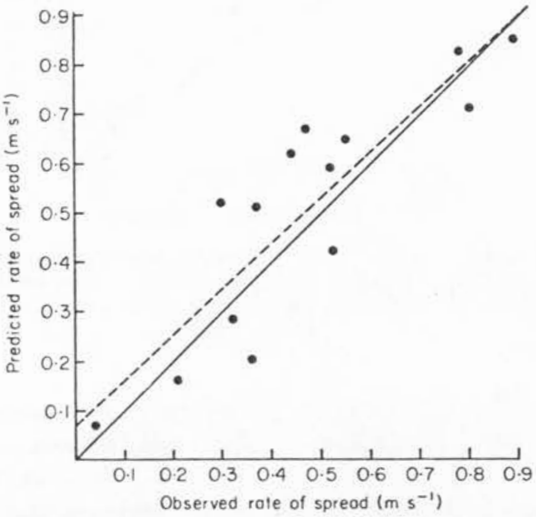


FIG. 1. Observed rates of fire spread versus predictions from Rothermel's fire model for fourteen fynbos fires (●). The solid line (——) is the line of perfect agreement. The doted line (---) is the linear regression ($y = 0{\cdot}92\,x + 0{\cdot}07$, where y is predicted and x observed rate of spread; $r^2 = 0{\cdot}772$, $P < 0{\cdot}01$).

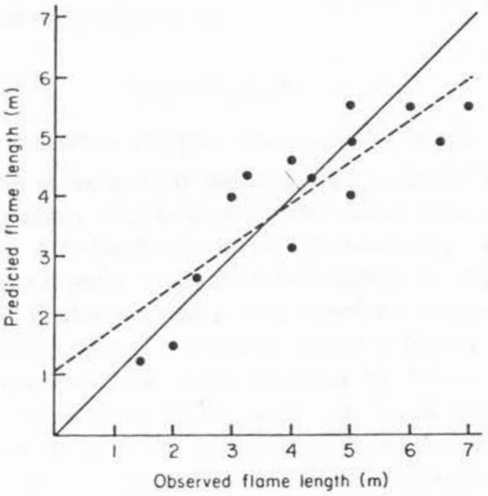


FIG. 2. Observed flame lengths versus predictions from Rothermel's fire model for fourteen fynbos fires (●). The solid line (——) is the line of perfect agreement. The dotted line (---) is the linear regression ($y = 0{\cdot}71\,x + 1{\cdot}01$, where y is predicted and x is observed flame length; $r^2 = 0{\cdot}739$, $P < 0{\cdot}01$).

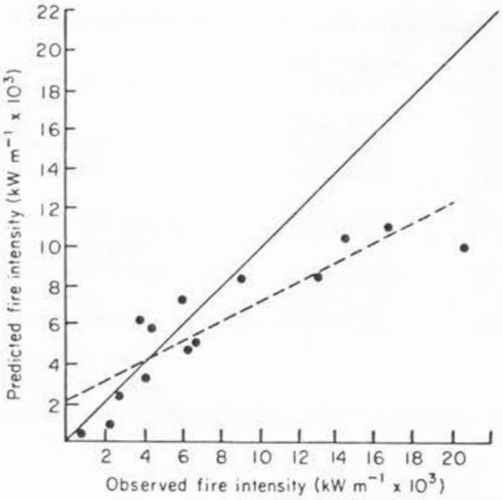


FIG. 3. Observed fire intensities versus predictions from Rothermel's fire model for fourteen fynbos fires (●). The solid line (——) is the line of perfect agreement. The dotted line (---) is the linear regression ($y = 0{\cdot}51\ x + 2086$, where y is predicted and x observed fire intensity; $r^2 = 0{\cdot}769$, $P < 0{\cdot}01$).

behaviour best approximated observed values. Observed and predicted fire behaviour parameters based on this modified fuel model are presented in Table 3. These results are depicted graphically in Figs 1–3.

The values presented here are mean values, as Rothermel's model produces quantitative values of spread and intensity that should be regarded as mean values for the given fuel and environmental conditions. The variation in fire behaviour, even on small plots, can be considerable. For example on plot K2 the rate of spread varied from 0·18 to 1·43 m s^{-1} resulting in observed intensities ranging from 1781 to 14 155 kW m^{-1}. Such differences result from variation in the fuel-bed characteristics and in windspeed and can be seen by the patchiness in the amount of fuel consumed.

DISCUSSION

Fire behaviour in fynbos and other shrublands

Table 4 presents data on shrubland fire behaviour for comparison with results of this study. There is a general paucity of shrubland fire behaviour data (Gill & Groves 1981) and no other fire behaviour data for South African fynbos ecosystems were available. A range of fire behaviour parameters that could reasonably be expected in fynbos are provided by Bands (1977) (Table 4). These were based on biomass estimates (Kruger 1977b) and on personal observation of the rate of spread of fynbos fires. Rates of spread observed in this study were within the limits predicted by Bands (1977). Estimates of available fuel were much higher (from 592 to 2241 g m^{-2} with a mean of 1131 g m^{-2}). Observed fire intensities are roughly equivalent, however, as Bands did not correct heat yield for moisture content. Fires in fynbos spread faster and burn with greater intensity than fires in most other shrublands despite similarities in biomass (Table 4). While this may be due to moderate weather conditions selected when conducting experimental fires, such differences probably arise from differences in the vegetation structure. Scottish heathland, for example, is usually about 0·4 m tall (Gimingham 1972). This implies that the biomass

TABLE 4. Comparative fire behaviour statistics for shrubland vegetation

Vegetation type	Source	Rate of spread (m s^{-1})	Fire intensity (kW m^{-1})	Prefire biomass (g m^{-2})
Cape fynbos	This study	0·04–0·89	515–20 709	970–3415
Cape fynbos	Bands (1977)	0·07–1·11	360–18 900	300–1000*
Natal Drakensberg shrublands	Smith (1983)	0·01–0·20	88–1617	1539–3946
Californian coastal sage scrub	Westman, O'Leary & Malanson (1981)	0·05–0·59	1250–10 852	1865–2077
Californian chaparral	Rothermel & Philpot (1973)	0·04–1·74†	380–35 000†	4375‡
Scottish heathland	Kayll (1966)	0·03–0·12	2430	1592–2334
Scottish heathland	Hobbs & Gimingham (1984)	0·003–0·03	40–1100	882–2740

* Available fuel.
† Predicted values.
‡ Maximum available fuel given in the chaparral fuel model.

is densely packed which will account for the low rates of spread. Chaparral, on the other hand, is a tall shrubland like fynbos, but it lacks the understorey of herbs and shrubs (Van Wilgen 1984a). The figures reported by Rothermel & Philpot (1973) are based on predictions from a chaparral fuel model rather than on actual observation. Rothermel's model predicted a rate of spread of 3·57 m s^{-1} and a fire intensity of 47 400 kW m^{-1} for fynbos fuels when given the hot and dry conditions prevailing during recent large wildfires (Van Wilgen 1984b). While such conditions are rare, they often coincide with large uncontrolled wildfires. Fynbos fires can therefore be as intense as chaparral fires, and are inherently more intense than Scottish heathland fires due to the vegetation structure.

Predictions from Rothermel's model

Significant relationships existed between observed and predicted parameters. Rate of spread and flame length predictions (Figs 1 & 2) were good, particularly as these parameters are not easy to quantify accurately. Fire intensity predictions were low for observed fire intensities above 10 000 kW m^{-1}. This is explained by the relatively high biomass of the plots concerned (C4, C2, C12, and C9). While the fuel model assumes a biomass of 1707 g m^{-2}, biomass on these plots was $>$2000 g m^{-2} (2138–3415). They were, coincidentally, also the plots burnt under relatively hot, dry and windy conditions, and more fuel becomes available as the fire passes from one intensity level to the next (Byram 1959). A single fuel model will clearly not suffice for fynbos.

Practical implications

Although Rothermel's fire spread model could be used to predict fire behaviour in fynbos fuels, it is necessary to view this in perspective. Rothermel's model was designed for fires that are burning steadily in uniform surface fuels. It assumes that fuels, slope and windspeed are homogenous and that fires are free-burning, in other words they remain unaffected by interaction with other fires or by additional sources of ignition. Fire behaviour in heterogenous fuels, particularly on mountain slopes, is difficult to predict (Burgan 1979). Fynbos is heterogenous, and even stands selected for superficial structural homogeneity (such as those reported on here) have large variations in biomass and structure. Fynbos occurs largely in mountainous areas with varied and rugged topography. The techniques used in lighting prescribed fires and controlling wildfires produce interactions between head, flank and backfires. In addition, winds are often variable and unpredictable. This means that fire models are unlikely to be successful in accurately predicting fire behaviour in mountain fynbos.

Rothermel's fire spread model does have a useful role to play in the management of conservation areas in the fynbos, however. It has been used to clarify the nature of fire climates (Van Wilgen 1984b), and is useful for fire hazard prediction (Van Wilgen & Burgan 1984). The management of fynbos mountain ecosystems consists almost exclusively of the application of fire, and sound management decisions will depend on good records of previous fires. It is inadequate merely to record dates and areas of fires, for although this can be used to quantify fire season and frequency, the type of fire involved is not described. In order to compare the results of experimental fires it is important to keep proper weather records which can be used to calculate the indices of a fire danger rating system (Van Wagner & Methven 1978). The recording of such data should become a standard management practice in fynbos. Indices of the NFDRS, based on Rothermel's fire model and a fuel model representative of the vegetation that was burnt should be included in fire records. The effects of management on fynbos vegetation are currently monitored, and good fire records are required to aid in the interpretation of these data, which will form a basis for sound conservation management. A set of fuel models, describing the various major structural types of fynbos, need to be developed for this purpose.

Many studies in fire ecology use the temperature measured during fires as an indication of fire intensity (Kayall 1966; Martin, Cushwa & Miller 1969; Gimingham 1972; MacLean & Wein 1977; James & Smith 1977; Hobbs & Gimingham 1984). Severe criticisms of this approach exist (Van Wagner 1970; Van Wagner & Methven 1978; Alexander 1982; Gill & Groves 1981), and for this reason fire temperatures were not measured in this study. In addition to the difficulties inherent in measuring and describing temperature, direct temperature measurements are not easily related to ecological effects. 'Maximum temperatures in most forest flames are about 800–1000 °C and occur in a single burning pine needle as readily as in a crown fire' (Van Wagner & Methven 1978). Byram's fire intensity is a far more meaningful measure, and has been called 'the single most valid characteristic of a fire's general behaviour and direct impact on above-ground vegetation' (Alexander 1982). As Rothermel's model gives predictions of Byram's intensity, this approach represents a better investment of time and effort than the measurement of fire temperature. Once suitable fuel models have been developed and tested, fires can be described by means of predictions from the fire spread model, which will simplify fire research. This is particularly true for the more homogenous shrublands, such as Scottish heathland and Californian chaparral, and should be encouraged in these cases.

ACKNOWLEDGMENTS

We thank Greg Bailey, Ben Durand, Ross Haynes and Alan Lamb for assistance with field work. Frank Albini, Pat Andrews and Bob Burgan of the Northern Forest Fire Laboratory, Missoula, Montana, U.S.A. provided useful comment. This work forms part of the conservation research programme of the South African Directorate of Forestry and is published by permission of the Deputy Director-General.

REFERENCES

Acocks, J. P. H. (1953). Veld types of South Africa. *Memoir of the Botanical Survey of South Africa*, 28, Government Printer, Pretoria.

Alexander, M. E. (1982). Calculating and interpreting forest fire intensities. *Canadian Journal of Botany*, **60**, 349–357.

Bands, D. P. (1977). Prescribed burning in Cape fynbos catchments. *Proceedings of the symposium on the environmental consequences of fire and fuel management in mediterranean ecosystems* (Ed. by H. A. Mooney & C. E. Conrad), pp. 245–256. U.S.D.A. Forest Service, Technical Report WO-3.

Burgan, R. E. (1979). *Fire Danger/Fire Behaviour computations with the Texas Instruments TI-59 Calculator: Users manual.* U.S.D.A. Forest Service, General Technical Report INT-61.

Byram, G. M. (1959). Combustion of forest fuels. *Forest Fire; Control and Use* (Ed. by K. P. Davies), pp. 155–182. McGraw Hill, New York.

Campbell, B. M., Cowling, R. M., Bond, W. & Kruger, F. J. (1981). *Structural characterization of vegetation in the fynbos biome.* South African National Scientific Programmes Report 52. CSIR, Pretoria.

Catana, A. J. (1963). The wandering quarter method of estimating population density. *Ecology*, **44**, 349–360.

Deeming, J. E. & Brown, J. K. (1975). Fuel models in the national fire danger rating system. *Journal of Forestry*, **73**, 347–350.

Deeming, J. E., Burgan, R. E. & Cohen, J. D. (1978). *The National Fire Danger Rating System—1978.* U.S.D.A. Forest Service, General Technical Report INT-39.

Durand, B. J. (1981). *A study of the short-term response of fynbos to fire in the Kogelberg State Forest, South Africa.* M.Sc. Thesis, University of Cape Town.

Gill, A. M. & Groves, R. H. (1981). Fire regimes in heathlands and their plant-ecological effects. *Heathlands and Related Shrublands of the World. B. Analytical Studies* (Ed. by R. L. Specht), pp. 61–84. Elsevier, Amsterdam.

Gimingham, C. H. (1972). *Ecology of Heathlands.* Chapman & Hall, London.

Hobbs, R. J. & Gimingham, C. H. (1984). Studies on fire in Scottish heathland communities. I. Fire characteristics. *Journal of Ecology*, **72**, 223–240.

James, T. D. W. & Smith, D. W. (1977). Short-term effects of surface fire on the biomass and nutrient standing crop of *Populus tremuloides* in southern Ontario. *Canadian Journal of Forestry Research*. **7**, 666–679.

Kayll, A. J. (1966). Some characteristics of heath fires in N.E. Scotland. *Journal of Applied Ecology*, **3**, 29–40.

Kruger, F. J. (1977a). Fire. *Fynbos ecology—a preliminary synthesis* (Ed. by J. H. Day, W. R. Siegfried, G. N. Louw & M. L. Jarman). South African National Scientific Programmes Report Number 40, CSIR, Pretoria.

Kruger, F. J. (1977b). A preliminary account of aerial plant biomass in fynbos communities of the mediterranean-type climate zone of the Cape Province. *Bothalia*. **12**, 301–307.

Kruger, F. J. (1982). Conservation: South African Heathlands. *Heathlands and Related Shrublands of the World. B. Analytical Studies* (Ed. by R. L. Specht), pp. 231–234. Elsevier, Amsterdam.

Le Maitre, D. C. (1984). *Aspects of the structure and phenology of two fynbos communities.* M.Sc. thesis, University of Cape Town.

MacLean, D. A. & Wien, R. W. (1977). Nutrient accumulation for postfire jack pine and hardwood succession patterns in New Brunswick. *Canadian Journal of Forestry Research*, **7**, 562–578.

Martin, R. E., Cushwa, C. T. & Miller, R. L. (1969). Fire as a physical factor in wildland management. *Proceedings of the Tall Timbers Fire Ecology Conference*. **9**, 271–288.

McArthur, A. G. & Cheney, N. P. (1966). The characteristics of fires in relation to ecological studies. *Australian Forestry Research*, **2**, 36–45.

Rothermel, R. C. (1972). A mathematical model for predicting fire spread in wildland fuels. U.S.D.A. Forest Service Research Paper INT-115.

Rothermel, R. C. & Philpot, C. W. (1973). Predicting changes in chaparral flammability. *Journal of Forestry*, **71**, 640–643.

Smith, F. R. (1983). *Responses of four shrub species to timing and behaviour of fire in the Natal Drakensberg.* M.Sc. thesis, University of Natal.

Van Wagner, C. E. (1970). *On the validity of temperature data in forest fire research.* Internal Report PS-20, Petawawa Forest Experiment Station, Ontario.

Van Wagner, C. E. & Methven, I. R. (1978). Discussion: Two recent articles on fire ecology. *Canadian Journal of Forestry Research*, **8**, 491–492.

Van Wilgen, B. W. (1982). Some effects of post-fire age on the above-ground biomass of fynbos (macchia) vegetation in South Africa. *Journal of Ecology*, **70**, 217–225.

Van Wilgen, B. W. (1984a). Adaptation of the United States Fire Danger Rating System to fynbos conditions. I. A fuel model for fire danger rating in the fynbos biome. *South African Forestry Journal*. **129**, 61–65.

Van Wilgen, B. W. (1984b). Fire climates in the southern and western Cape Province and their potential use in fire control and management. *South African Journal of Science*. **80**, 358–362.

Van Wilgen, B. W. & Burgan, R. E. (1984b). Adaptation of the United States Fire Danger Rating System to fynbos conditions. II. Historic fire danger in the fynbos biome. *South African Forestry Journal*. **129**, 66–78.

Westman, W. E., O'Leary, J. F. & Malanson, G. P. (1981). The effects of fire intensity, aspect and substrate on post-fire growth of Californian coastal sage scrub. *Components of Productivity of Mediterranean Climate Regions—Basic and Applied Aspects* (Ed. by N. S. Margaris & H. A. Mooney), pp. 151–180. W. Junk, The Hague.

(*Received 6 June 1984; revision received 18 September 1984*)

Paper 3. Adaptation of the United States Fire Danger Rating System to Fynbos conditions. II Historic fire danger in the fynbos biome. South African Forestry Journal 129, 66 - 78.

Adaptation of the United States Fire Danger Rating System to Fynbos Conditions.

Part II. Historic Fire Danger in the Fynbos Biome

B.W. van Wilgen[x] and R.E. Burgan*

[x] *Jonkershoek Forestry Research Centre*
Private Bag X5011
Stellenbosch — 7600
South Africa

**Northern Forest Fire Laboratory*
Drawer G
Missoula
Montana 59806
USA

SYNOPSIS

Fire danger indices from nine weather stations in the Fynbos Biome were obtained using historic weather data and a fynbos fuel model as inputs for the United States National Fire Danger Rating System. The indices produced were compared with the occurrence of recorded wild-fires. The system proved sufficiently robust to reflect the expected fire danger patterns in the biome accurately. A unimodal cycle of high fire danger in summer and low in winter is prevalent in the west and a bimodal pattern of high fire danger in summer and winter occurs in the south-east. Fire size correlated well with high fire danger. Some uses of the system are discussed and adoption of the system is recommended.

INTRODUCTION

The problem of accurate and standardised ratings of fire danger is one often addressed by managers of fire-prone ecosystems. The managers of the fynbos vegetation of the Southern and South-western Cape Province are no exception. Fynbos is a fire-prone vegetation type and prescribed burning is used as a management tool (Bands, 1977).

Wild-fires frequently occur and these may damage property or crops. Many management decisions relating to prescribed burning and wild-fire control can be aided by ratings of fire danger (see, for example, Fisher, 1980). There is no standarised basis whereby fire danger can be assessed in South Africa. The United States National Fire Danger Rating System (NFDRS, Deeming *et al.*, 1978) has a physical basis and should therefore be applicable world-wide. In Part I of this series (van Wilgen, 1984) a fuel model to be used for fire danger rating in the fynbos biome was described. In this study we used the fynbos model together with historic climate data from nine stations in the biome as inputs for the United States NFDRS in order to test the system under South African conditions, to determine the seasonal and secular incidence of fire danger and to quantify the ranges of the indices which can be expected within the biome.

Features of the Fynbos Biome

The Fynbos Biome corresponds geographically with the Capensis Region delimited by Taylor (1978) as one of the plant biogeographic regions of Southern Africa. Much of this area has been developed by farming activities or by urbanisation. The majority of the remaining natural vegetation belongs to Acocks (1953) veld types 69 (macchia) and 70 (false macchia), which occur mainly in undeveloped mountain areas. These two veld types are known collectively as mountain fynbos (Kruger, 1979). These mountain areas are managed primarily for water production. The dominant climate in the western half of the biome is mediterranean, with wet winters and relatively dry summers. The rainfall ranges from 250 to 2 500 mm or more per year. The rainfall increases with altitude in the mountain areas and some mountain peaks receive over 3 000 mm/a. Moving eastwards, the rainfall becomes more evenly distributed throughout the year. Föhn-like berg winds often occur along the southern coastal regions, notably in winter, and are accompanied by sudden increases in temperature and decreases in humidity which result in high fire hazard conditions. Kruger and Bigalke (in press) discuss the characteristics of fynbos fire regime and fire behaviour with reference to weather factors in some detail. Wicht and de Villiers (1963) have described weather conditions and fire danger at the southern coastal town of Hermanus. They show that certain synoptic conditions could be used to predict high fire danger in that area, but do not offer any definite system to be used in the biome as a whole.

Brief description of the system

The United States National Fire Danger Rating System (NFDRS) is described by Deeming *et al.* (1978). The system uses weather data to simulate trends in the moisture content of fuels, which largely affect fire danger. In order to predict the expected rate of fire spread and intensity of free burning fires, the system uses Rothermel's (1972) fire spread model. This model requires the physical and chemical make-up of the fuel and the environmental conditions in which it is expected to burn as inputs. These are obtained from weather data and the simulated moisture content of fuels and from the specific fuel model for the vegetation type concerned. The structure of the system is shown in *Figure 1*. Weather observations are usually made at a standard or basic observation time, usually 14h00, when fire danger is normally at its highest. At this time observations relating to the previous 24 hours are also made.

Four indices of fire danger are produced by the NFDRS. The spread component rates the forward rate of spread of a head fire. The energy release component is related to the available energy per unit of area within the flaming front at the head of a fire. The ignition component rates the probability that a firebrand will cause a fire requiring supression action. These components are linearly related to the particular aspect of the fire problem being rated, so that if the component doubles, a doubling of the rated activity can be expected. The burning index combines the spread and energy release components into a number related to the contribution of fire behaviour to the effort of containing a fire. The burning index is linearly related to flame length, but the relationship between fire containment and flame length is not necessarily linear.

In practice, the components can easily be obtained in the field. Weather kits which can be worn on a belt are available and contain all the instruments necessary to measure weather parameters. A handheld, preprogrammed calculator can then be used to obtain the indices. The procedure is described with examples by Burgan (1979). Further details on the actual procedure are not applicable here and the reader should contact the authors should these be required.

METHODS

Weather records from a total of nine weather stations were used as input data for the NFDRS. Relevant details of the stations are given in *Table 1* and their positions are shown in *Figure 2*. A daily weather record consisting of 24 hour minimum and maximum temperature, 24 hour minimum and maximum relative humidity, rainfall, hours of sunshine and total windrun was used. The NFDRS requires observations at a standard time each day, usually at 14h00, when fire danger is most likely to be at its highest. For the purposes of this exercise the 24 hour maximum temperature and 24 hour minimum relative humidity were used as the values at 14h00. The state of the weather (a number reflecting the degree of cloudiness or kind of precipitation) was taken to be 6 if the rainfall on that day exceeded 5 mm, 0 if the sunshine hours exceeded 11 hours, 1 if the sunshine hours were between 5,5 and 11 hours, 2 if shunshine hours were between 1,1 and 5,5 hours and 3 if the sun shone for less than 1,1 hours. The wind speed at the standard time was taken as twice the mean for the day. This was done to allow for the fact that wind speeds are never steady throughout the day and that fire danger must represent the worst case each day. Examination of other records has shown that the maximum wind speed is often much more than double the mean wind speed. As the NFDRS requires precipitation duration rather than amount, a precipitation rate of 6,25 mm/h was assumed (25 mm every four hours). The slope class was taken as 2 (26 - 40 % slope) and the climate class was taken as 2 or 3 (see *Table 1)*. The fynbos fuel model described in part 1 of this series (Van Wilgen, 1984) was used. The various NFDRS components were calculated for each day of the weather records and summarised. Data from known wild-fires close to any of the weather stations analysed were obtained in order to compare the occurrence of wild-fires with the fire danger as rated by the NFDRS.

RESULTS

The mean burning index for each individual month was obtained and the means and standard deviations of these values were calculated for each month of the year. Results are shown in *Figure 3*. These graphs show the smoothed means, but the daily fluctuations can be great. Examples of the day to day fluctuations in burning index are shown in *Figure 4*.

The ranges of burning indices encountered in each fire danger class (see below) at each station are given in *Table 2*. One third of the total number of days analysed, those at the top of the burning index range, were taken to represent high fire danger at each station. The middle third was taken to represent moderate fire danger and the lower third low fire danger. The top five per cent was taken as representative of extreme fire danger. The seasonal distribution of these categories of fire danger was then determined for each station and the results are given in *Figure 5*.

Data from recorded wild-fires (dates of occurrence and area burnt) were compared with the highest burning index reached during the time of the fire at a nearby weather station. The area burnt was plotted against the highest burning index reached during the fire. Results are shown in *Figure 6*.

DISCUSSION

The seasonal and geographic patterns of fire occurrence in the fynbos biome have been discussed in recent publications (Kruger, 1977 and 1979; Horne, 1981; Kruger and Bigalke, in press). Kruger (1977) proposed two hypothetical patterns of fire occurrence for "western" and "eastern" fynbos areas. The fire danger rating system, as used here, has proved sufficiently robust to reflect these predicted patterns. A bimodal pattern of fire danger, with peaks of high fire danger in midsummer and midwinter, is evident in the south-eastern stations (Outeniqua and Langkloof) and differs somewhat from that proposed by Kruger (1977). The high fire danger in winter in the southern coastal regions of the fynbos biome can be attributed largely to the occurrence of bergwinds (Wicht and de Villiers, 1963). Only the month of May at Outeniqua and April at Langkloof are significantly lower (at the 5 % level)

FIGURE 1. Structure of the National Fire Danger Rating System, Modified from Deeming et al.*, 1978.*

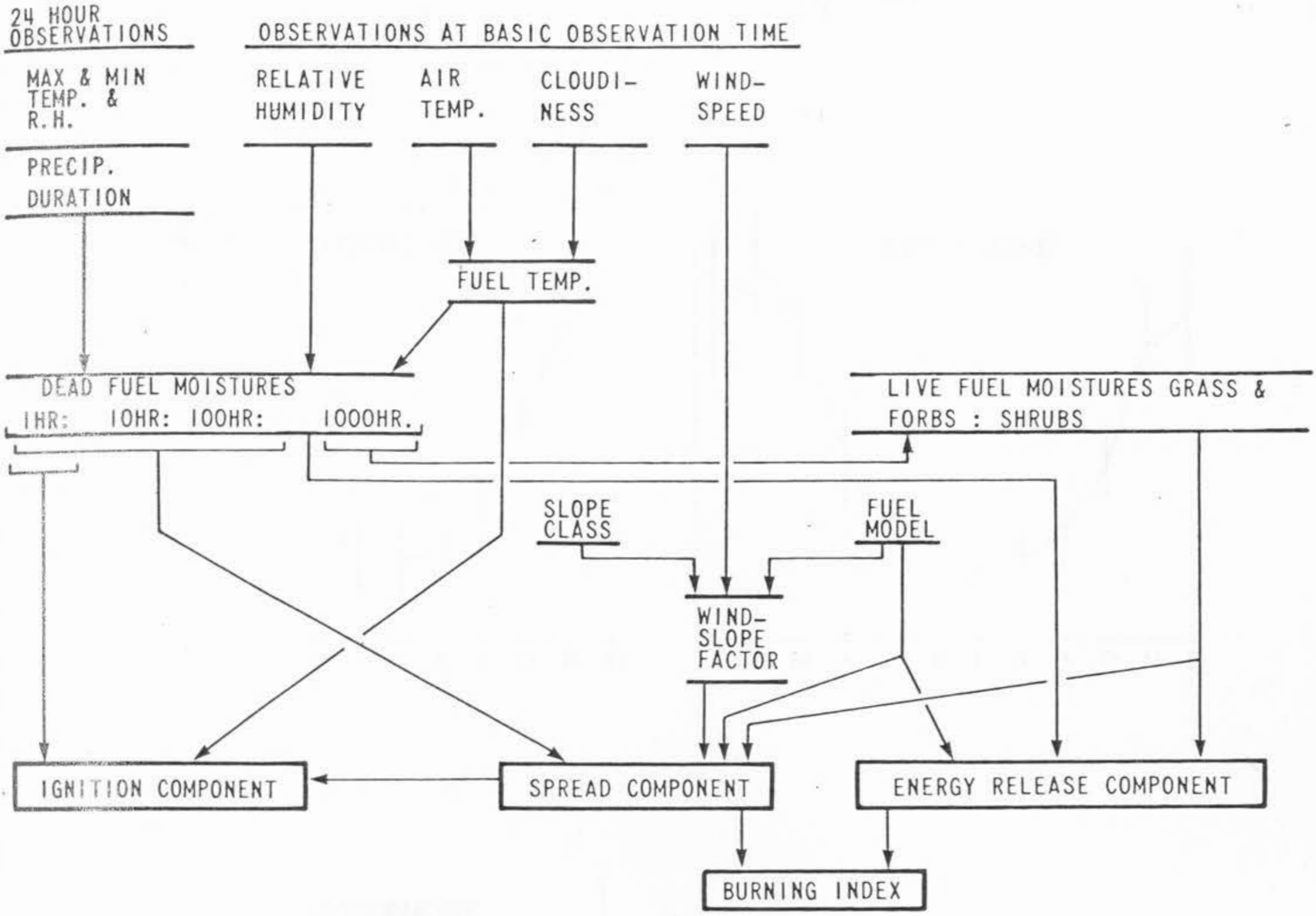
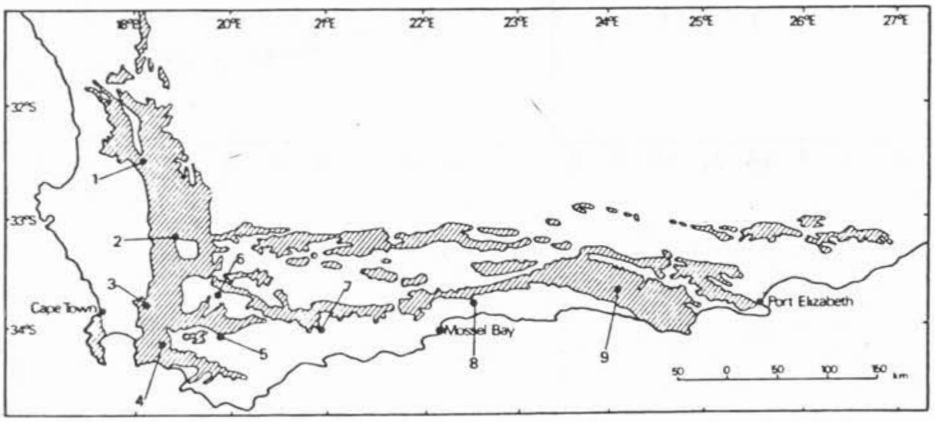


FIGURE 2. Position of weather stations in the fynbos biome used to determine fire danger (see Table 1*). Shaded areas show the extent of mountain fynbos (after Acocks, 1953). Stations are: 1 = Citrusdal, 2 = Gydo, 3 = Bien Donné, 4 = Jakkalsrivier, 5 = Tygerhoek, 6 = Robertson, 7 = Karringmelkrivier, 8 = Outeniqua and 9 = Langkloof.*



than any other month. The fluctuations in mean fire danger from month to month at these stations are therefore not very marked, although individual days do tend to be markedly higher than average (see *Figure 4)*. Stations with a clear summer high and winter low cycle do tend to have uniformly low fire danger in the winter months, on the other hand. These lows are significantly different at the 5 % level from the summer highs.

The ranges of burning index values which demarcate the low, moderate, high and extremely fire danger categories *(Table 2)* are useful to fire managers. Although they do vary somewhat from station to station, the general boundaries are remarkably similar. Their applicability is further illustrated in *Figure 6.* For this data set at least, no fires were reported when the burning index was below 35. This corresponds to low fire danger. Where the burning index was between 36 and 70 (moderate fire danger) small fires of less than 2 000 ha were reported. High fire danger (burning index between 71 and 95) was accompanied by fires of up to

FIGURE 3. Annual cycles of mean monthly burning index at nine weather stations in the fynbos biome determined from the climatic records. Bars represent the 5 % confidence interval of the mean.

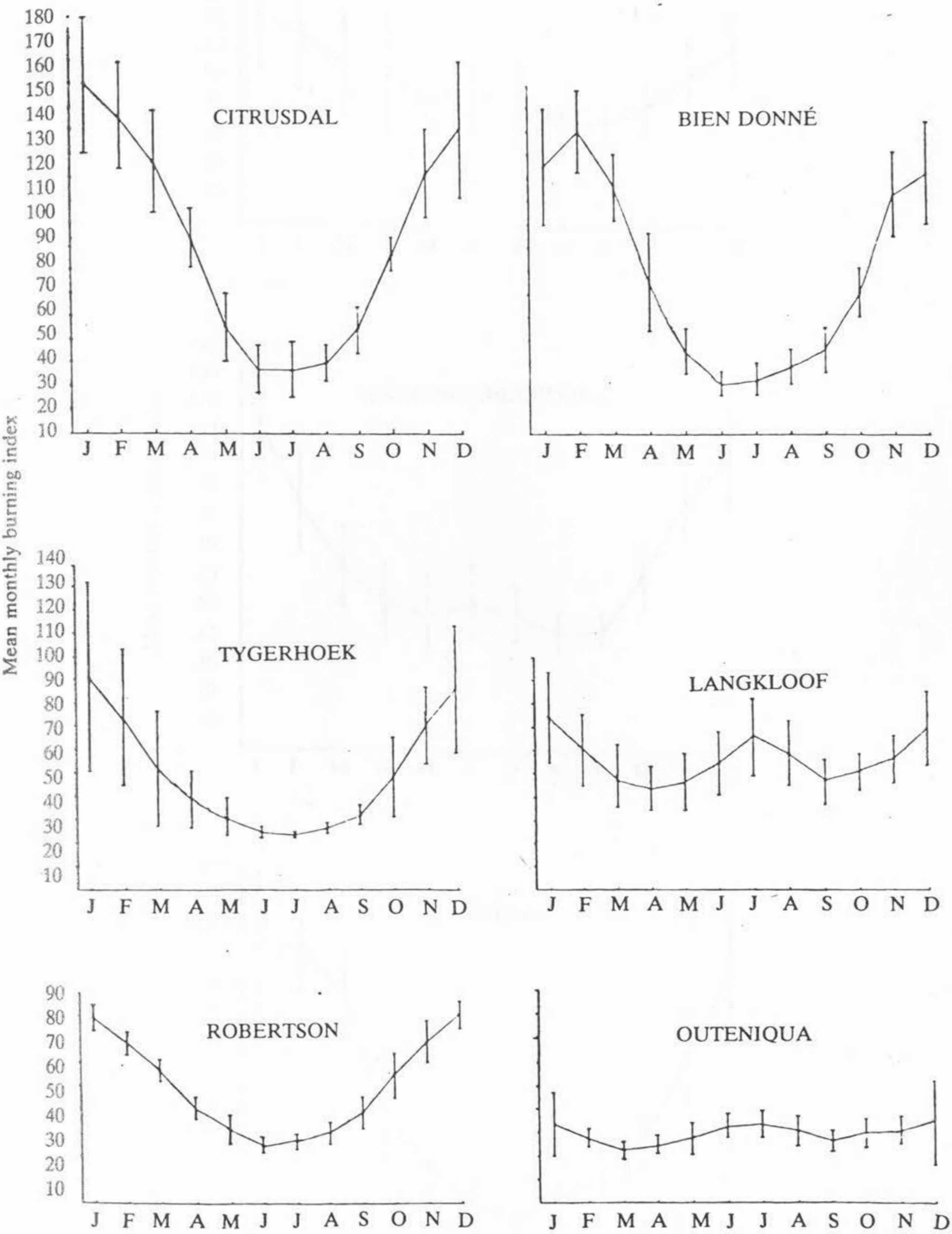


FIGURE 3. (Cont.). Annual cycles of mean monthly burning index at nine weather stations in the fynbos biome determined from the climatic record. Bars represent the 5 % confidence interval of the mean.

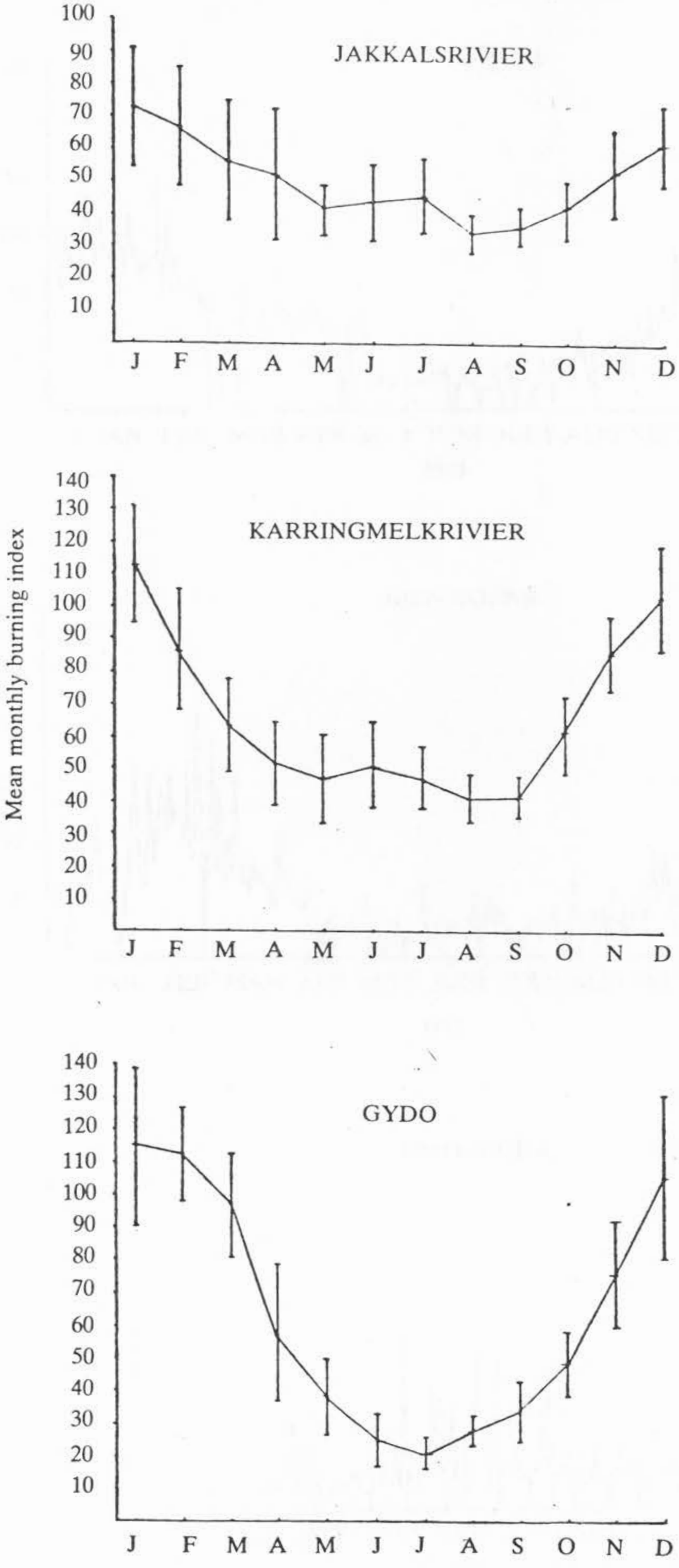
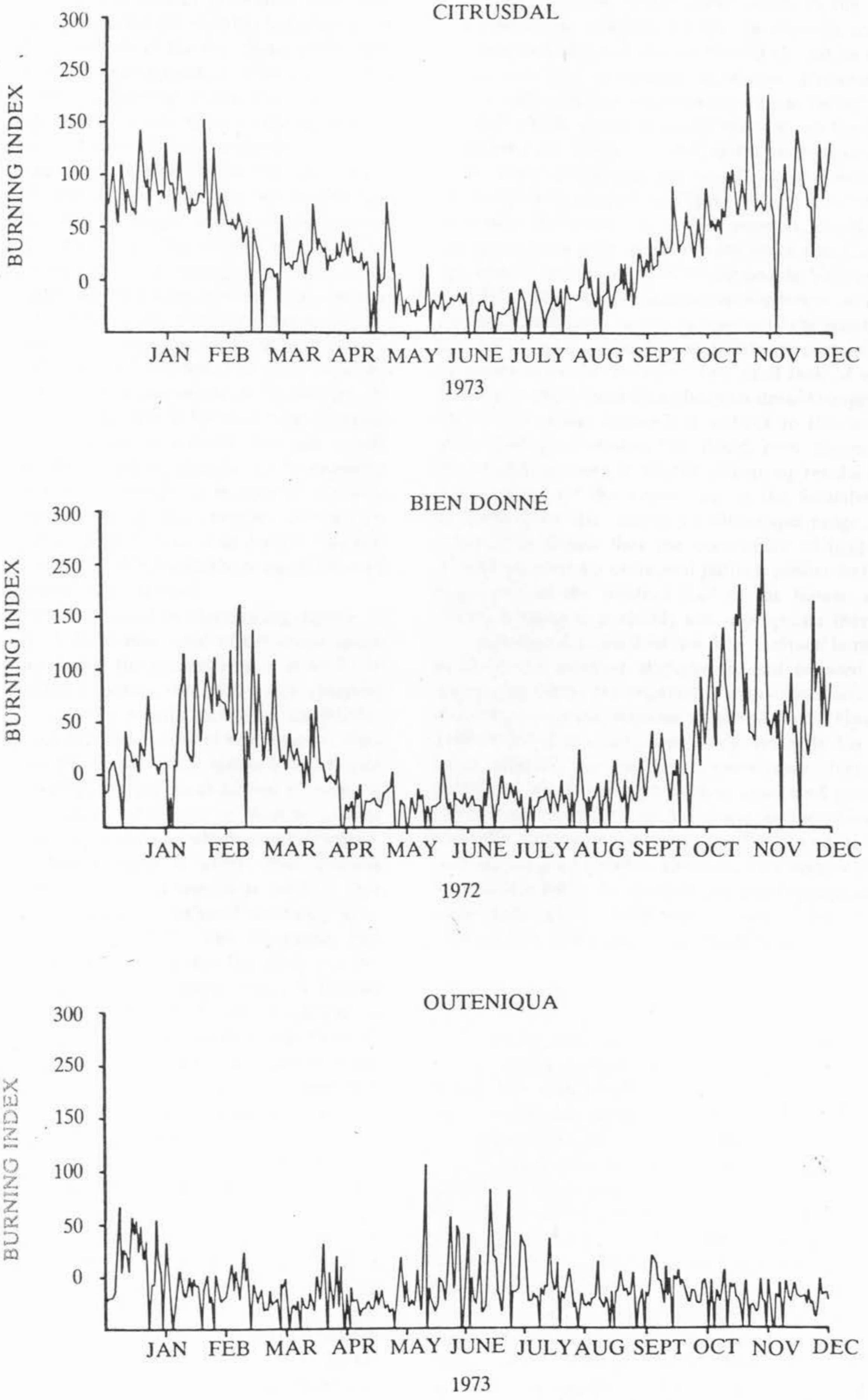


FIGURE 4. Examples of the daily run of fire danger (burning index) at the three stations in the fynbos biome.



5 000 ha in extent. Very large fires (up to 14 500 ha) were accompanied by extreme fire danger with burning indices in excess of 95. A far better indication of the actual ranges of burning indices associated with fires would have been obtained if the weather variables were measured at the actual site of the fire. Some of the fires shown in *Figure 6* were some distance from the weather station at which the burning index was calculated. Future research on site should improve the estimation of the boundaries of fire danger categories.

This system of rating fire danger will have many advantages, but the major advantage lies in the fact that such ratings will no longer rely on the subjective judgements of individuals. The indices generated by the system will aid ecosystem managers to make decisions regarding fire management, for example, the size of fire-fighting force required, whether or not to initiate a prescribed burn, control of public access and informing the public of current conditions. The mean seasonal occurrence of the various categories of fire danger, as shown in *Figure 5*, can be useful for long-term planning of operations. The mean number of days per month when a certain category of fire danger can be expected can be used to select a month or months in which to plan for prescribed burning, for example. The advantages of using the NFDRS system in formal management are compared in *Table 3* with the present informal fire management strategy applied.

The system is also useful in illuminating aspects of the fire ecology of the biome. One of the major questions facing managers is the correct season in which to burn. Kruger (1977) points out that understanding fynbos ecology would be greatly assisted if the fire regimes under which the biota evolved were known. Any attempt to reconstruct past fire regimes without data sources such as well-preserved fossil carbon in annually laminated Quarternary Sediments, or from long-lived trees with regular annual rings would be a purely speculative exercise. Nevertheless it seems that without major vegetation (i.e. fuel) change it is unlikely that past fire regimes would have differed markedly from the modern one (Kruger, 1977). The hypothesis that the largest fires will occur when the fire danger is the highest is substantiated by the data in *Figure 6*. If most of the area was historically burnt under conditions of high fire danger, and assuming that there has been no meaningful change in the climate or vegetation for some time, then a second hypothesis can be proposed, namely that the vegetation will be adapted to survive fires occurring in those seasons where prolonged high fire danger is most prevalent and that this would indicate the ecologically correct time to burn. Strong seasonal trends in weather would have influenced the occurrence of fires and therefore the evolutionary pressure on the vegetation. Natural fires can occur only if some source of ignition is present. Published sources (Wicht, 1945; Kruger, 1977; Horne, 1981; Kruger and Bigalke, in press) show that natural fires are caused by lightning and rolling rocks. These ignition sources, especially sparks from rolling rocks, are not strongly seasonal and it can therefore be safely assumed that natural ignition was historically possible during periods of high fire danger. From the data presented here, it would appear that two broad categories of fire regime exist in the biome. Plant communities in the western half should be adapted to fires in summer and early autumn and those in the south-east should be adapted to survive fires in summer or winter. Because of the moist nature of the south-eastern areas owing to even rainfall which results in much lower mean fire danger, fires are most likely to occur under extreme conditions only. Such conditions are usually experienced when there are berg winds (see *Figure 4*), which occur mainly in winter. So winter, as well as summer, could well be an appropriate time to burn in the south-east Cape. It is apparent from the work of Wicht and de Villiers (1963) that this pattern is present in the south-west at Hermanus and it may be a common feature of the south-facing coastal ranges, although berg winds are certainly more frequent towards the east. The total lack of weather stations in the inland Swartberg mountain ranges in the north-east of the biome is a setback to this investigation. Ecological studies (W. Bond, pers. comm.) have shown that burning in winter and spring results in poor regeneration of the vegetation in the Swartberg and that this is not the case in the Outeniqua range. Horne (1981) has shown that the occurrence of fires in the Swartberg shows a unimodal pattern similar to that encountered in the western half of the biome, so that winter burning is probably not appropriate there.

Another drawback of the data analysed here is that most of the weather stations are not situated in the mountains where the vegetation in question occurs. For the two mountain stations analysed here (Gydo and Jakkalsrivier) the data were only available for a very short period (four and seven years respectively). Nonetheless, the fire danger indices generated tend to be very similar to those from low-lying stations. Generally speaking, mountain environments have lower temperatures and higher rainfall. From the fire danger point of view, this is offset by the fact that wind speeds are generally much higher. This may account for the similarity between low-lying and mountain stations.

CONCLUSION

This investigation has shown that the United States NFDRS reflects expected fire conditions in the fynbos biome. The indices obtained are reasonable and correlate well with actual fire occurrence.

In practice, the success of the system will depend largely on the user. In order to interpret the full meaning of fire danger indices and how they related to actual fire behaviour, the user will need some field experience in the use of the system. Fire danger indices should be recorded daily at field management centres and the daily values should be plotted against the long-term mean. The field manager would then be in a good position to make fire-related decisions. The systemic recording of the incidence of fire danger will result in a record which will aid in policy-making decisions over the whole biome and will also help to explain the eco-

FIGURE 5. Seasonal distribution of the mean number of days per month in different fire danger catagories (see text). Hatched bars represent the occurrence of extreme fire danger.

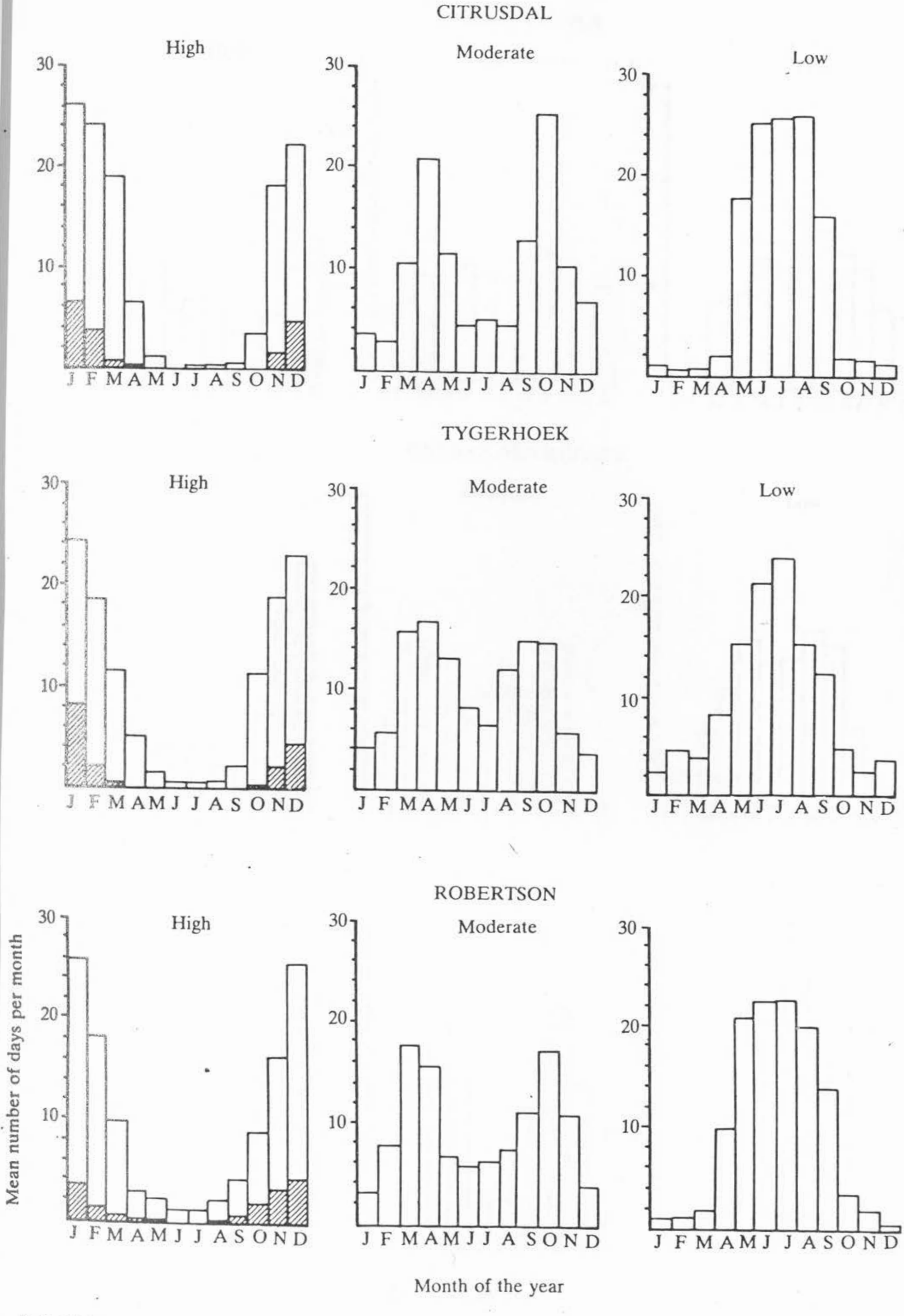


FIGURE 5. (Cont.) Seasonal distribution of the mean number of days per month in different fire danger catagories (see text). Hatched bars represent the occurrence of extreme fire danger.

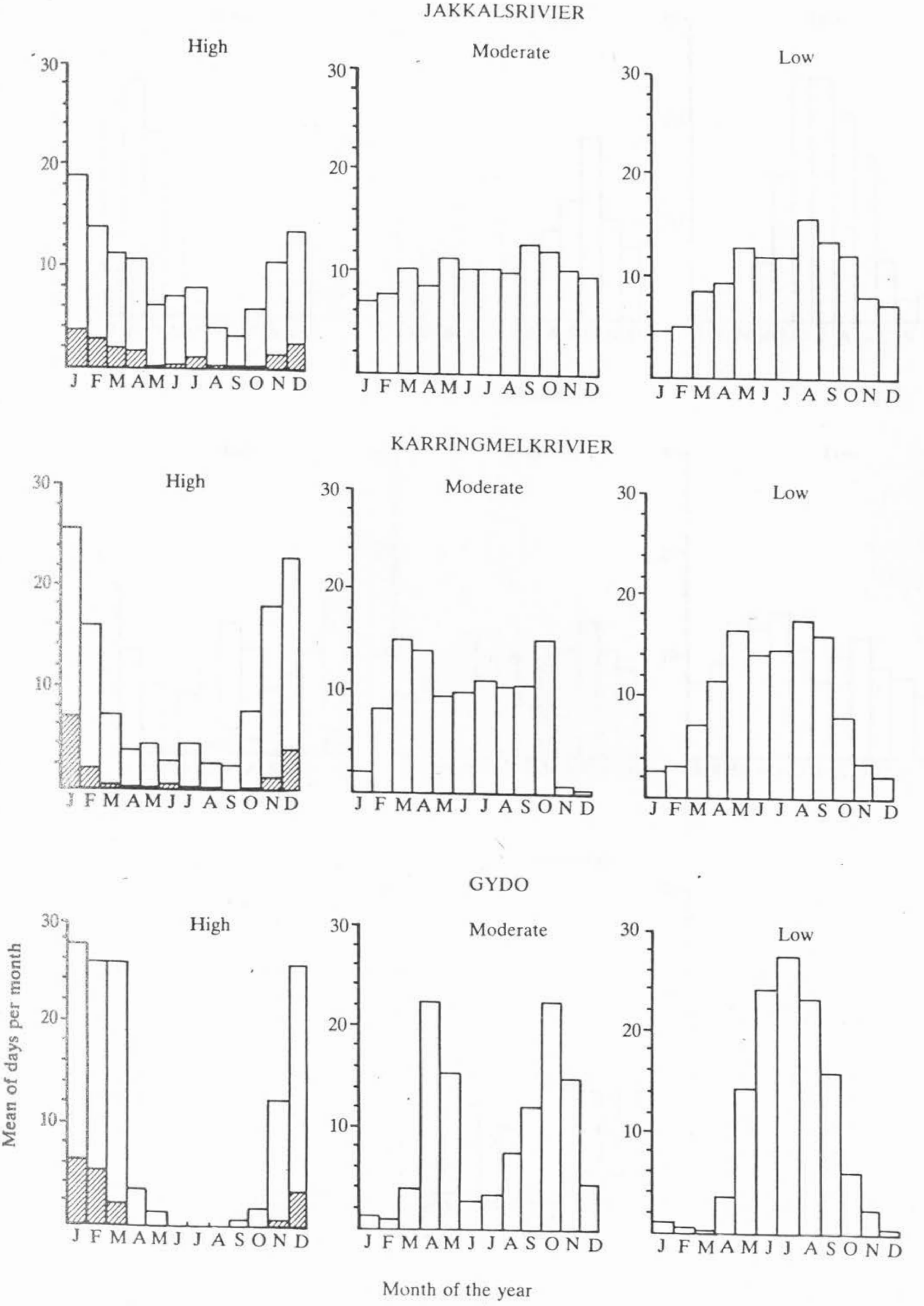


FIGURE 5. (Cont.) Seasonal distribution of the mean number of days per month in different fire danger catagories (see text). Hatched bars represent the occurrence of extreme fire danger.

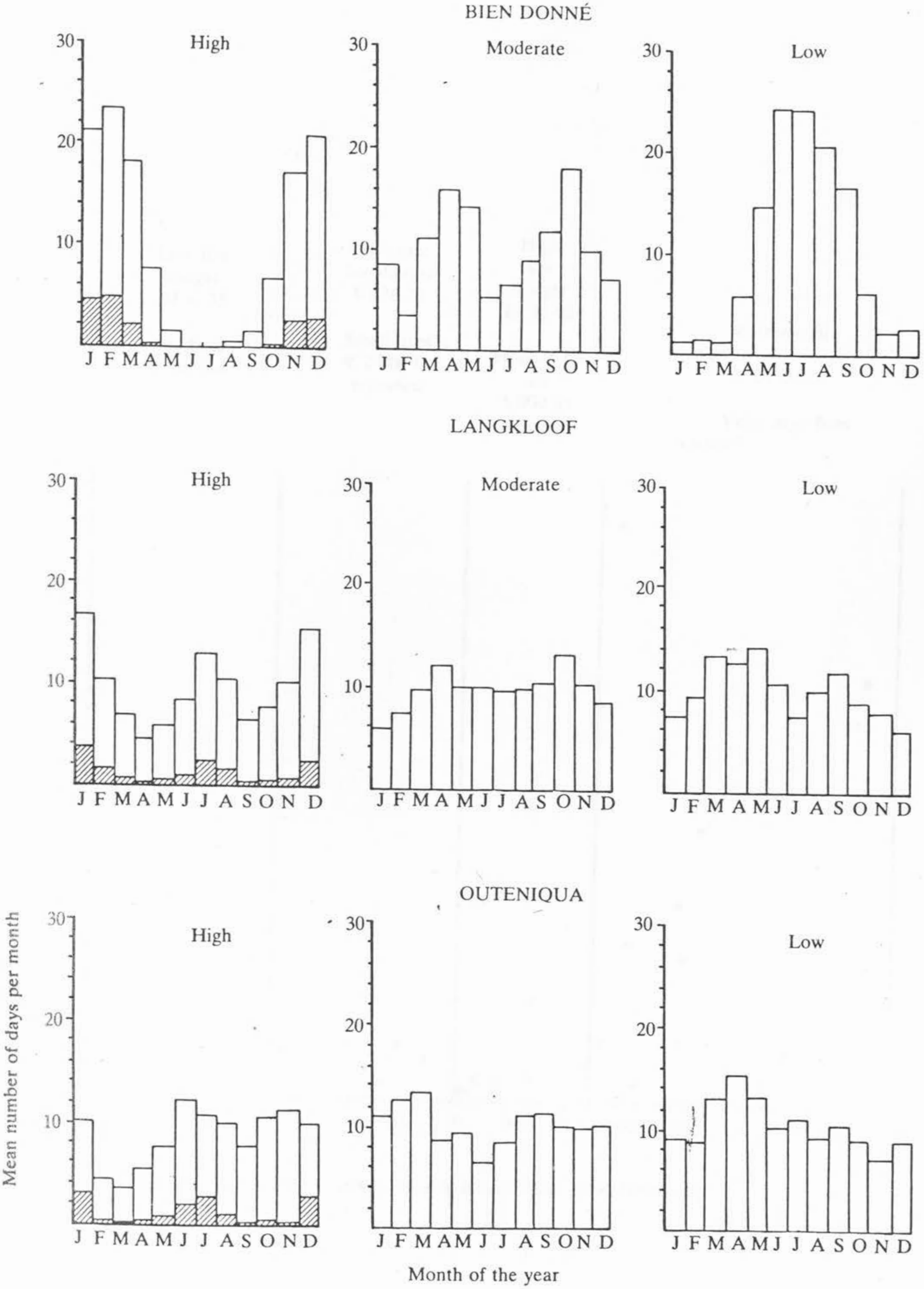


FIGURE 6. The relationship between the area burnt by wild-fires and the maximum fire danger index from the nearest weather station.

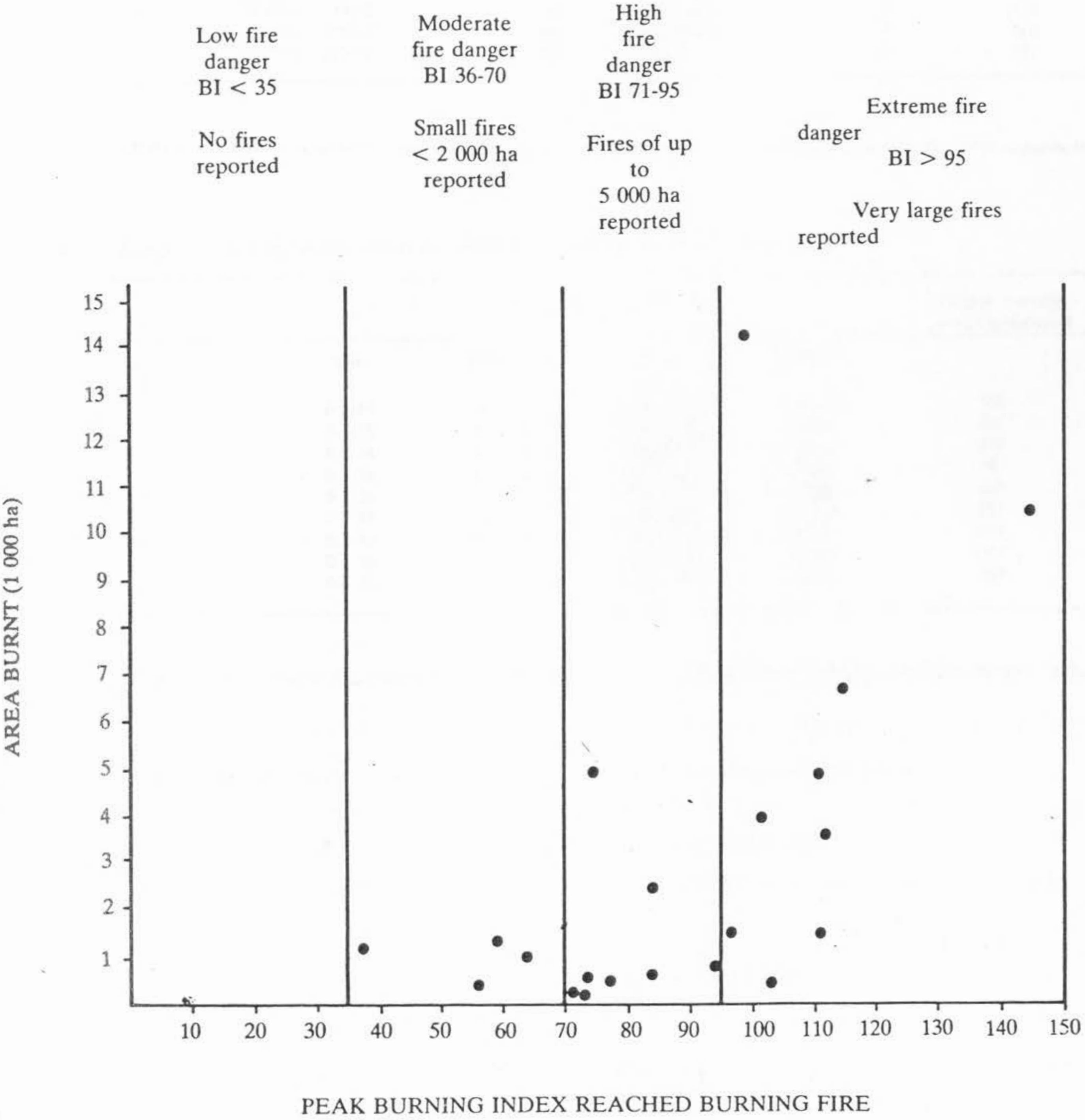


TABLE 1. Salient features of nine weather stations in the fynbos biome

Station name	Posision		Elevation (m)	Length of record analysed	Climate class used*	Mean annual rainfall (mm)
Citrusdal	32°33'S,	18°59'E	198	8 yrs 4 mths	2	371
Gydo	33°13'S,	19°20'E	975	4 yrs 1 mth	2	829
Bien Donné	33°50'S,	18°59'E	138	9 yrs	2	817
Jakkalsrivier	34°09'S,	19°08'E	660	7 yrs	2	961
Tygerhoek	34°09'S,	19°54'E	152	6 yrs 1 mth	3	463
Robertson	33°50'S,	19°54'E	156	16 yrs	2	272
Karringmelkrivier	34°08'S,	20°46'E	198	9 yrs 8 mths	2	410
Outeniqua	33°59'S,	22°25'E	204	9 yrs 3 mths	3	663
Langkloof	33°47'S,	23°35'E	722	15 yrs	3	617

*Climate class 2 represents subhumid areas with rainfall deficient in summer. climate class 3 represents subhumid areas with rainfall adequate in all seasons.

TABLE 2. Ranges of burning index values for different classes of fire danger (see text).

Station	Burning index ranges				Highest burning index encountered
	Low	Moderate	High	Extreme	
Citrusdal	0 - 45	46 - 104	105 - 184	≥185	312
Gydo	0 - 35	36 - 81	82 - 138	≥139	204
Bien Donné	0 - 34	35 - 85	86 - 183	≥184	279
Jakkalsrivier	0 - 34	35 - 63	64 - 117	≥118	190
Tygerhoek	0 - 28	29 - 54	55 - 125	≥126	223
Robertson	0 - 32	33 - 60	61 - 106	≥107	237
Karringmelkrivier	0 - 40	41 - 79	80 - 146	≥147	251
Langkloof	0 - 36	37 - 66	67 - 124	≥125	235
Outeniqua	0 - 22	23 - 33	34 - 69	≥ 70	197

TABLE 3. Comparison between fire management strategies with and without the use of a formal fire danger rating system

Management using formal system	Management without formal system
1. Fire danger is accurately quantified.	1. Fire danger is estimated.
2. Fire danger can be calculated by newly appointed staff.	2. Estimations of fire danger rely largely on experience.
3. Use of the system will force staff to keep records of climatic data, which are of importance to all management procedures.	3. No (or very few) climatic records are kept.
4. Management decisions are based on quantified indices and are therefore less variable.	4. Management decisions are based on experience and vary greatly among individuals.
5. Fuel characteristics (fuel models) of vegetation in the area must be formally determined. This is initially time consuming, but once complete no further quantifications are necessary and no experience is necessary.	5. Fuel characteristics must be estimated. Accuracy of estimates depends on experience.

logical responses of the ecosystem to fire. Adoption of the system is strongly recommended.

ACKNOWLEDGEMENTS

Staff of the Northern Forest Fire Laboratory were most helpful in discussing aspects of the fire danger rating system. We are particularly grateful to Dick Rothermel, Frank Albini and Pat Andrews. Jasper Hoon of Elsenburg (Department of Agriculture) and Frank Rogers of the Jonkershoek Forestry Research Centre helped to obtain climate data. We thank two anonymous referees for useful comment on the manuscript.

REFERENCES

ACOCKS, J.P.H., 1953. Veld Types of South Africa. *Memoir of the Botanical Survey of South Africa*, 28, Government Printer, Pretoria.

BANDS, D.P., 1977. Prescribed Burning in Cape Fynbos Catchments. *Proceedings of the symposium on the environmental consequences of fire and fuel management in mediterranean ecosystems* (Ed. by H.A. Mooney and C.E. Conrad) pp. 245-256. USDA, Forest Service, Technical Report WO-3.

BURGAN, R.E., 1979. *Fire Danger/Fire Behaviour Computations with the Texas Instruments TI-59 Calculator: Users Manual.* USDA Forest Service, General Technical Report INT-61.

DEEMING, J.E., BURGAN, R.E., and COHEN, J.D., 1978. *The National Fire Danger Rating System* — 1978. USDA Forest Service. General Technical Report INT-39.

FISHER, W.C., 1980. Fire Management Techniques for the 1980's *The 1980 Ames Forester*, 23 - 28.

HORNE, I.P., 1981. The Frequency of Veld Fires in the Groot Swartberg Mountain Catchment Area, Cape Province. *South African Forestry Journal* 118: 56 - 60.

KRUGER, F.J., 1977. Fire. *Fynbos Ecology: A Preliminary Synthesis*. (Ed. by J. Day, W.R. Siegfried, G.N. Louw and M.L. Jarman). South African National Scientific Programmes Report No. 40. CSIR.

KRUGER, F.J., 1979. Introduction. *Fynbos Ecology: A Premiliminary Synthesis* (Ed. by J. Day, W.R. Siegfried, G.N. Louw and M.L. Jarman). South African National Scientific Programmes Report No. 40., CSIR, Pretoria.

KRUGER, F.J., and BIGALKE, R.C., in press. Fire in the Fynbos. *Proceedings of the SCOPE symposium on the ecological effects of fire in South Africa*. (Ed. by P. de V. Booysen).

ROTHERMEL, R.C., 1972. *A Mathematical Model for Predicting Fire Spread in Wildland Fuels*. USDA Forest Service, Research Paper INT-115.

TAYLOR, H.C., 1978. Capensis. *Biogeography and Ecology of Southern Africa* (Ed. by M.J.A. Werger). pp. 171 - 229.

VAN WILGEN, B.W., 1984. Adaptation of the United States Fire Danger Rating System to Fynbos Conditions. I. A fuel model for fire danger rating in the fynbos biome. *South African Forestry Journal*. 129, immediately preceeding this page.

WICHT, C.L., 1945. *Report of the Committee on the Preservation of the Vegetation of the Southwestern Cape*. Special Publication of the Royal Society of South Africa, Cape Town.

WICHT, C.L., and DE VILLIERS, Y.R., 1963. Weertoestande en Brandgevaar by Hermanus. *Journal of Geography* 2, 25 - 36.

Paper 4. Fire danger during large wildfires in fynbos vegetation in the western Cape Province.

FIRE DANGER DURING LARGE WILDFIRES IN FYNBOS VEGETATION IN THE WESTERN CAPE PROVINCE

B.W. van Wilgen
Jonkershoek Forestry Research Centre
Private Bag X5011
STELLENBOSCH
7600

SUMMARY

Fire danger during a fire in January 1984, which burnt 37 000 ha over 10 days, is reported in terms of indices of the United States National Fire Danger Rating System (NFDRS). The occurrence of similar conditions is determined from the historic weather record. The NFDRS reflected above average fire danger conditions prior to and during the fires. Indices in seven other large wildfires are presented. The values are equivalent to those in the 1984 wildfire. The energy release component is the best steady indicator of high fire danger conditions and should be used to formally define such conditions for management purposes. The system should be adopted to aid in the recognition of similar conditions in future. Increased fire awareness should lead to the possible prevention of similar occurrences in future. The mean rate of spread in the January 1984 fire was about 2 km per day, and ranged from 0.5 to 6 km per day. These data are used to show that the size of wildfires before settlement would have been in excess of 100 000 ha.

INTRODUCTION

Large wildfires in excess of 10 000 ha occur occasionaly in fynbos and pose the most serious and expensive fire control problems. Between 20 and 29 January 1984 devastating wildfires burnt a total of 37 000 ha in the Du Toitskloof and Franschhoek, Villiersdorp and Rawsonville mountains in the western Cape. These fires cost the lives of 9 employees of the Directorate of Forestry as well as large sums of money for firefighting and containment operations. These fires are the largest on record for the region (see Bands, 1977).

Trials are currently being conducted into the adaptation of the United States National Fire Danger Rating System (NFDRS, Deeming et al, 1978) to local fynbos conditions (see Van Wilgen, 1984; Van Wilgen & Burgan, 1984). These fires were used to examine the conditions prevailing in terms of fire danger indices of the NFDRS. This investigation aimed to quantify the fire danger during the January 1984 fires and to determine the occurrence of similar conditions from the climatic record. Fire danger indices for other large wildfires in the region were calculated and compared to the data for the 1984 fire. The data were used to determine the relative importance of the various indices of the NFDRS for predicting conditions when large wildfires can occur. Such data are important from a fire management point of view, as the identification and timely recognition of extreme conditions could possibly lead to the prevention of similar occurrences in future. Such information may also assist in understanding the environmental conditions under which fynbos biota evolved.

METHODS

Weather data prior to and during the January 1984 fires were obtained from the Zachariashoek weather sation. This station is situated at 33° 49′S and 19° 02′E at an altitude of 740 m above sea level. The fires at DuToitskloof and Franschhoek approached to within 2 km of the station at times. The data record was used as an input to the NFDRS following the method described by Van Wilgen & Burgan (1984). A fynbos fuel model (Van Wilgen, 1984), which describes the fuel properties of a fynbos tall open shrubland, was used to represent the vegetation in the NFDRS analysis. Four components of the NFDRS, the ignition component, energy release component, spread component and burning index were calculated on a daily basis. The ignition component rates the probability that a firebrand will cause a fire requiring suppression action. The energy release component is a number related to potential fire intensity (available energy per unit area). The spread component is a rating of the forward rate of spread of a head fire, while the burning index combines the energy release and spread components into a number related to the contribution of fire behaviour to the effort of containing a fire.

The progress of the January 1984 fire was mapped by drawing the position of the fire front at 18h00 on each consecutive day of the fire. This was done after the fire, in consultation with field staff who were present at the fire. Mean, minimum and maximum daily rates of spread were determined by linear measurement between daily isolines in the map.

Weather data from the past 42 years (1941 - 1983) were available from the Bien Donne weather station, about 4 km from the Zachariashoek station. These data were analysed by the NFDRS in the same way as for the Zachariashoek station. Mean monthly fire danger indices were calculated for comparison with those prevalent during the fires. The cumulative frequency distributions of the daily fire danger indices over 42 years were calculated in order to determine the mean percentage occurrence of extreme conditions. Fire danger indices during seven other large (> 5 000 ha) fires on record for the region (Bands 1977) were calculated with data from nearby weather stations. The weather stations used were Bien Donne (3 fires), Citrusdal (3 fires) and De Keur (1 fire). The Citrusdal station is situated at 32° 34′ S, 18° 59′ E and the De Keur station at 32° 58′ S, 19° 18′ E.

RESULTS

The weather conditions prevailing during the January 1984 fires are given in Table 1. Fire danger indices for the days of the

TABLE 1 : Weather conditions prevailing at the Zachariashoek weather station during recent wildfires

Date	Maximum temperature (°C)	Minimum relative humidity (%)	Mean windspeed (Km/hr)
20.1.84	26,7	14	20,8
21.1.84	25,0	36	28,8
22.1.84	27,2	22	16,0
23.1.84	27,8	34	19,2
24.1.84	30,0	30	19,2
25.1.84	30,0	33	27,2
26.1.84	33,9	18	14,4
27.1.84	27,2	42	16,0
28.1.84	23,3	43	14,4
29.1.84	23,3	30	14,5

fire are given in Table 2. The daily fluctuations in four fire danger indices prior to and during the fires are shown in Figure 1. Cumulative percentage distribution of the four fire danger indices over 42 years at the Bien Donne weather station are shown in Figure 2. Of these distributions, only that of the energy release component shows a sigmoidal form. This is because the energy release component seldom drops below about 5 and never reaches zero. All other indices frequently reach zero during periods of rain; this simply means that while fires are not likely to ignite, spread or burn, they nonetheless retain the potential to release some energy.

These results show that the ignition component had a value of 84 on the first day of the fires (Table 2). Ignition components of > 84 occurred on 0,4% of days over 42 years (Figure 2). This is 1,45 days per year on average. Similar statistics for the maximum values of the energy release component, spread component and burning index are 0,9%, 1,9% and 2,9% respectively. A statistic of possibly greater significance is the historic occurrence of prolonged high fire danger similar to conditions experienced during these fires. Data in Table 2 show that the ignition component was > 52 for an unbroken period of 7 days. At the same time the burning index was > 154. The data from the NFDRS analysis for 42 years at Bien Donne were examined to determine the historic occurrence of similar conditions. The results are shown in Table 3. These conditions occurred during 10

Table 2. Fire danger indices during the January 1984 fire.

Date	Fire danger indices Ignition Component	Energy Release Component	Spread Component	Burning Index
20-1-1984	84	36	238	193
21-1-1984	58	31	327	209
22-1-1984	60	34	160	157
23-1-1984	52	32	190	164
24-1-1984	58	32	193	168
25-1-1984	65	32	309	206
26-1-1984	66	35	147	154
27-1-1984	38	30	143	141
28-1-1984	33	30	122	130
29-1-1984	44	32	130	139
30-1-1984	49	30	221	173
31-1-1984	67	33	241	187

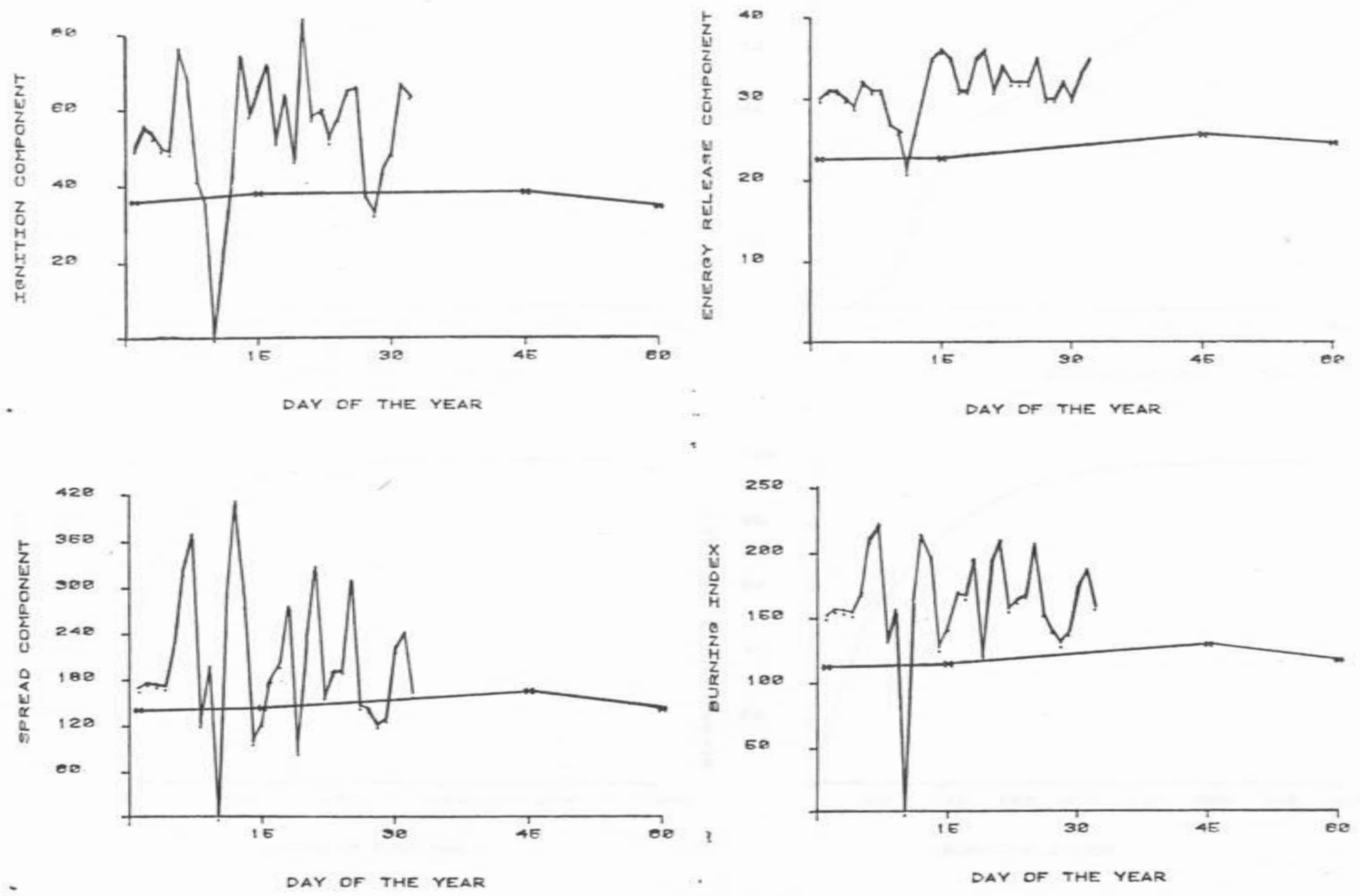


FIGURE 1: Fluctuations in daily values of four fire hazard indices from 1 January to 1 February 1984 at Zachariashoek. Straight lines indicate the seasonal mean values of these indices calculated from 42 years of data at Bien Donne.

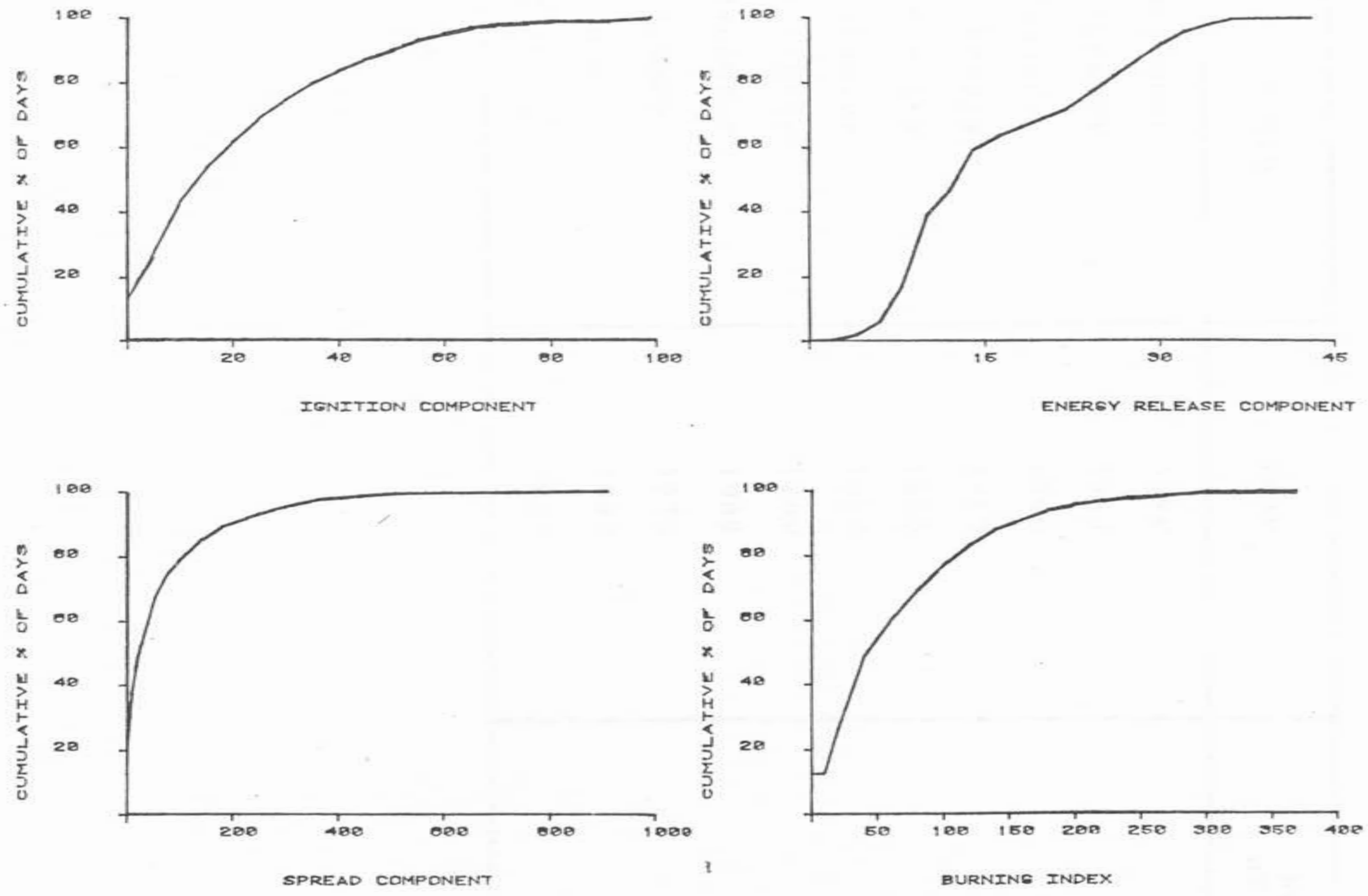


FIGURE 2: Cumulative percentage frequencies of four fire hazard indices calculated from 42 years of weather data at Bien Donne.

TABLE 3: Historic occurrence at Bien Donne of extreme fire hazard (one week periods where the ignition component and burning index are above 52 and 154 respectively each day).

Month	Year	Number of weeks
December	1942	1
December	1943	1
January	1946	1
February	1948	1
February	1955	1
December	1956	1
November	1960	1
December	1969	1
January	1975	1
January	1980	1
January	1984	1

out of a total of 2 184 weeks (0,46%). This is equivalent to about one week every four years on average, which means in effect that similar conditions can be expected for about one week in every fourth fire season.

Mean daily fire danger indices during the 8 largest wildfires on record for the region are given in Table 4. The means and ranges of indices that occurred during the fires are plotted against the mean value for the fire season (December - March) at the relevant station in Figure 3. The mean values for each of the components were above the long-term mean for the fire season except for a few values at the Citrusdal station where mean fire danger is higher than in other areas. The spread component, ignition component and burning index all showed considerable fluctuations during the fires concerned (Figure 3). The energy release component, on the other hand, showed little fluctuation and was cosistently above 25 during all of the fires concerned.

A map of the progress of the January 1984 fire is presented in Figure 4. The maximum daily rates of spread as determined from isolines in Figure 4 are presented in Table 5. Rates of spread are slower than those reported for fires burning over short distances (van Wilgen et al 1985) but this is to be expected due to factors such as diurnal and nocturnal fluctuations in weather conditions, and topographical or fuelbed barriers.

TABLE 4: Mean daily fire danger indices during 8 large (5 000 ha) wildfires in the Western Cape Province

				Mean daily fire hazard during the fire			
Locality	Dates of fire	Area burnt (ha)	Weather station	Ignition component	Spread component	Energy release component	Burning Index
Hottentots-Holland Mountains	14 - 31 December 1942	11 200	Bien Donne	62.0	219	32.3	170
Hottentots-Holland Mountains	20 January - 3 Feb. 1958	17 130	Bien Donne	39.5	160	27.3	136
Du Toits Kloof Mountains	16 Feb. - 4 March 1971	18 000	Bien Donne	45.7	244	29.0	166
Villiersdorp Mountains	20 - 31 January 1984	37 000	Bien Donne	44.3	97	34.5	124
Cederberg	7 - 10 December 1972	27 000	Citrusdal	29.0	121	27.0	123
Cederberg	15 - 19 February 1975	5 950	Citrusdal	46.0	143	35.0	140
Cederberg	12 - 18 December 1975	13 500	Citrusdal	51.3	144	28.4	137
Koue Bokkeveld Mountains	31 January - 9 Feb. 1976	30 000	De Keur	40.5	80	33.9	112

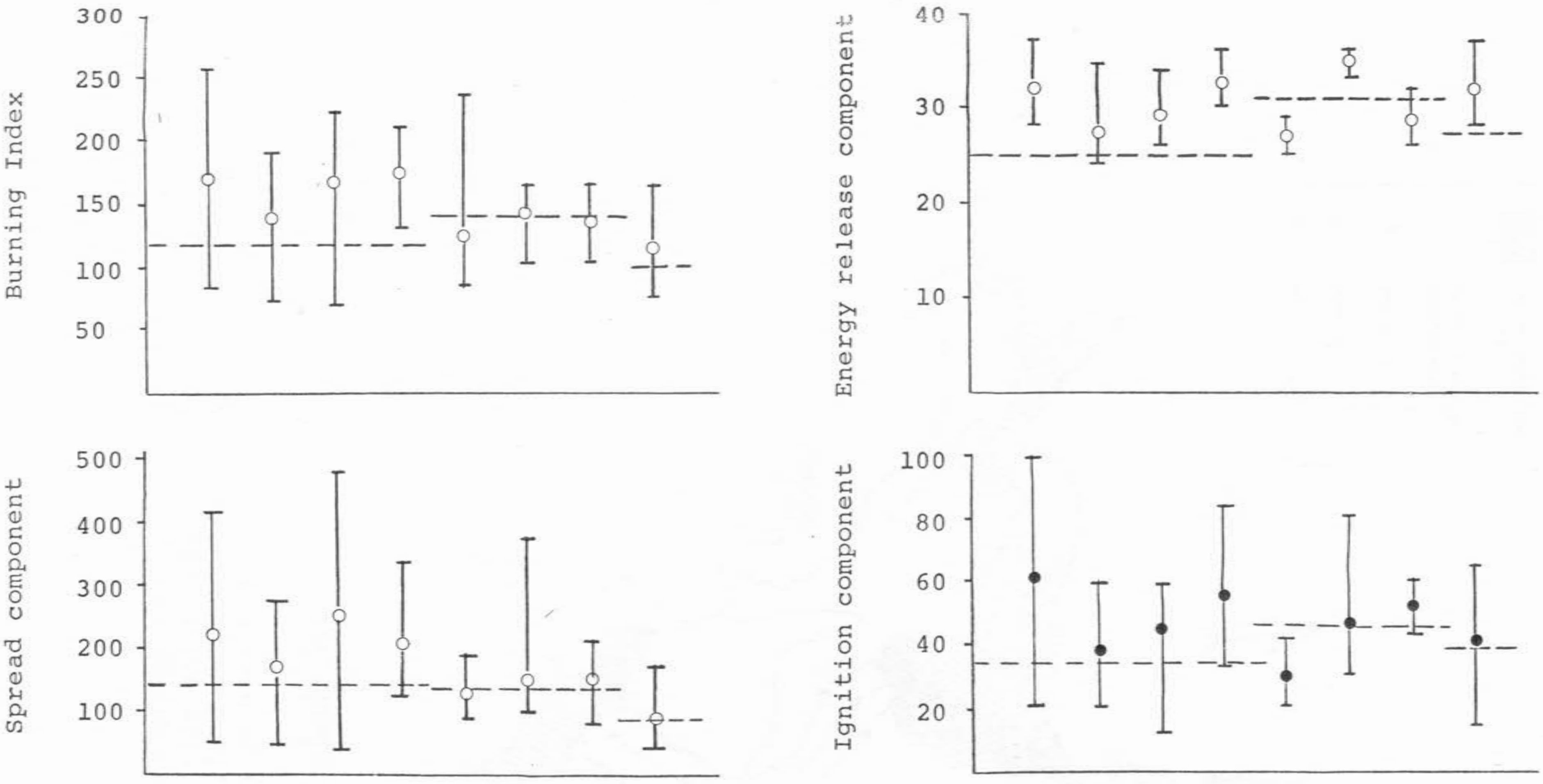


Figure 3 :

Mean daily values for four fire hazard indices during 8 wildfires in the Western Cape Province. The dashed lines (---) indicate the mean value of the index for the fire season (Dec. - March) at the station where the index was calculated. The fires, from left to right, are in the same order as given in Table 4. The three stations used were Bien Donne, Citrusdal and De Keur.

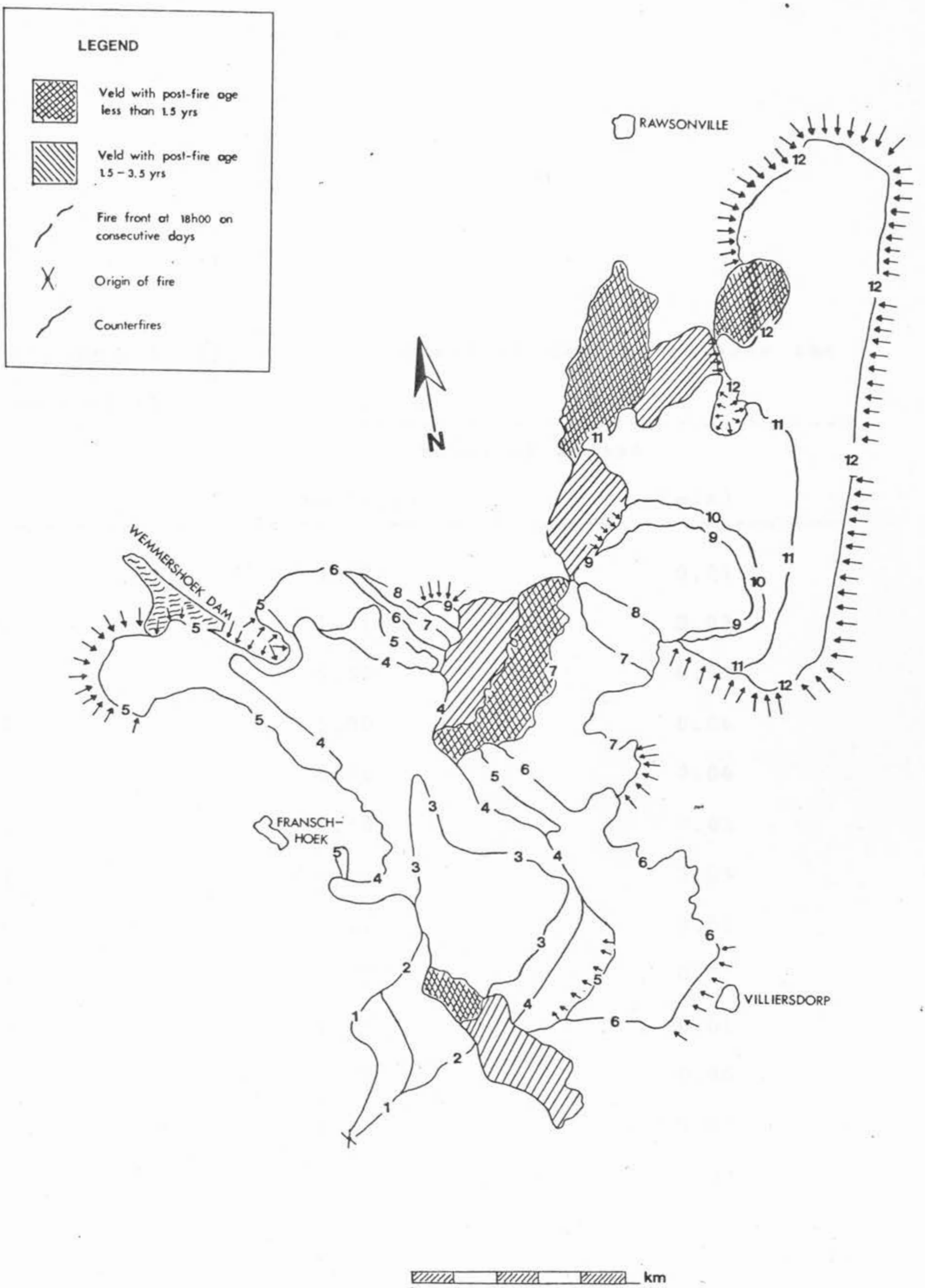


FIGURE 4 : Isolines of the progress of the January 1984 fire. The lines represent the position of the fire front at 18h00 on consecutive days of the fire. The first day of the fire was 20 January 1984.

Table 5. Maximum daily rates of spread as determined from the mapped advance of the fire.

Date	Rates of spread (km/day)	(m/s)
20-01-1984	3.47	0.04
21-01-1984	1.81	0.02
22-01-1984	4.58	0.05
23-01-1984	5.00	0.06
24-01-1984	3.06	0.04
25-01-1984	2.50	0.03
26-01-1984	4.31	0.05
27-01-1984	1.11	0.01
28-01-1984	2.50	0.03
29-01-1984	0.56	0.01
30-01-1984	3.19	0.04
31-01-1984	6.25	0.07
Mean rates for 12 days (from map)	2.16	0.03

DISCUSSION

The data given in Figure 1 show clearly that fire danger was well above the long-term mean both before and during the January 1984 fires. Rain on the 10th of January temporarily reduced fire danger, but conditions quickly returned to relatively high levels. The analysis of historic conditions at Bien Donne show that these conditions are (Table 3) occur about once in every fourth fire season on average, but are rare in their overall occurrence throughout the year (Figure 2). The frequency of other large wildfires that occurred between 1942 and 1977 (Bands 1977) is equivalent in frequency to the occurrence of prolonged extreme fire danger (Table 3). The data in Figure 3 show that the energy release component is the most stable indicator of high fire danger conditions. The mean fire season (December - March) ERC is 24.7, 27.0 and 30.9 at Bien Donne, De Keur and Citrusdal respectively. The mean ERC during all of the fires was above 27 and never fluctuated below 25 during any of the fires, except on the last day of the fire in 1958, where it reached a value of 24. Due to its stable nature, the ERC provides the best reference index for recognizing conditions which can lead to large wildfires. If daily records of fire danger (particularly the energy release component) are kept, and compared to long term means, then the likelyhood of major fires occurring can be assessed. For example, the level of fire danger indices prior to the January 1984 fires (Figure 1) would have indicated the severity of the conditions.

Certain preventative measures, such as increased alert and firefighting preparadness and total bans on open-air fires may increase the chances of early detection and containment of fires as well as reduce the risk of accidental fire. Such measures would be implemented relatively rarely (possibly for not more than a week or two each year) as extreme conditions are not common, and they should be seriously considered.

The data presented here also allow for speculation on the nature of historic wildfires in the pre-settlement fynbos environment. It would seem likely that pre-settlement fires in the inland areas of the fynbos biome could potentially have burnt large areas under rather rare suitable conditions. The recent fires burnt 37 000 ha despite considerable efforts to contain them, and despite the fact that much of the region is agriculturally developed and thus no longer flammable. Many natural fires, such as those ignited by lightning, burn only small areas before being extinguished by unsuitable conditions. Should natural fires have occurred under extreme conditions in the past, however, they could have burnt much larger areas. The longest fire on record (Bands 1977) burnt for 18 days. Assuming that no barriers occurred to impede fires from spreading, and using a mean rate of spread of 2 km per day (Table 5) in all directions, circular fires would burn about 400 000 ha in 18 days. This is an overestimate for a number of reasons. Firstly, fires are never circular, and the figure of 2 km per day is for the direction of maximum spread.

Secondly, barriers such as the sea, rivers, cliffs or recently burnt veld would have prevented fires from spreading in some directions. Nonetheless, fires could have burnt up to 100 000 ha at a time, which is almost an order of magnetude different to the size of wildfires today. Huge late summer fires of rather infrequent nature and relatively high severity would most probably have been part of the environment in which the present unique fynbos biota evolved. With prescribed burning, further reductions in the size of fires can be expected; smaller fires of 500 to 1 000 ha, burnt somewhat later into autumn for safety reasons, will become the rule. These changes are sudden when seen on an evolutionary time-scale. The ecological implications of such changes in the fire regime are poorly understood and should be invesigated so that the consequences for fynbos catchment conservation can be predicted.

REFERENCES

Bands, D.P. (1977). Prescribed burning in Cape fynbos catchments. Proceedings of the symposium on the environmental consequences of fire and fuel management in mediterranean ecosystems. (Ed. by H.A. Mooney & C.E. Conrad) USDA Forest Service General Technical Report WO-3).

Burgan, R.E., (1979). Fire Danger/fire behaviour computations with the Texas Instruments TI-59 calculator: Users Manual. USDA Forest Service, General Technical Report INT-61.

Deeming, J.E., Burgan, R.E. & Cohen, J.D., (1979). The National Fire Danger Rating System - 1978. USDA Forest Service, General Technical Report INT-39.

Rothermel, R.C., (1972). A mathematical model for fire spread predictions in wildland fuels. USDA Forest Service, Research Paper INT-115.

Van Wilgen, B.W., (1984). Adaptation of the United States Fire Danger Rating System to fynbos conditions I. A fuel model for fire danger rating in the fynbos biome. South African Forestry Journal 129,61-65.

Van Wilgen, B.W. & Burgan, R.E. Adaptation of the United States

Fire Danger Rating System to fynbos conditions II. Historic fire danger in the fynbos biome. South African Forestry Journal 129,66-78.

Van Wilgen ,B.W., Le Maitre, D.C. and Kruger, F.J. (1985). Fire behaviour in South African fynbos (macchia) vegetation and predictions from Rothermel´s fire model. Journal of Applied Ecololoy 22, 207-216.

Paper 5. Fire climates in the southern and western Cape Province and their potential use in fire control and management. South African Journal of Science 80, 358 - 362.

Reprinted from
South African Journal of Science *Vol. 80* *August 1984*

Fire Climates in the Southern and Western Cape Province and Their Potential Use in Fire Control and Management

B. W. van Wilgen

The climate of the southern and western Cape Province is examined with respect to fire potential. Five major fire climate zones, which differ in magnitude of mean fire potential and in seasonal fluctuations are recognised. The uses of these zones in the fire management of the area are discussed.

Die verband tussen klimaat en brandpotensiaal van die suidelike en westelike Kaapprovinsie is ondersoek. Vyf hoofsones wat verskil in hul gemiddelde brandpotensiaal en seisoenswisseling van brandpotensiaal is geïdentifiseer. Die toepassing van brandbestuur word aan die hand van hierdie klassifikasie bespreek.

The southern and western Cape Province has important mountain catchment areas, which are managed by the Directorate of Forestry to ensure a sustained yield of high quality water and for nature conservation. Most of the vegetation cover in these mountain areas consists of mountain fynbos (Acocks'[1] veld types 69 and 70), a sclerophyllous shrubland which is prone to periodic fires. The Directorate of Forestry faces a fire management problem in these areas firstly in relation to wild-fire control, and secondly from the point of view of prescribed burning operations, which are carried out to reduce fuel loads, to enhance catchment water yield, to control woody weeds and to rejuvenate the fire-adapted vegetation.

The dominant climate in the western half of the region is Mediterranean, with wet winters and relatively dry summers. Rainfall ranges from 250 to 2500 mm or more per year, increasing with altitude. Towards the east, the rainfall becomes more evenly distributed throughout the year. Föhn-like bergwinds often occur along the southern coastal regions, and are accompanied by sudden increases in temperature and decreases in humidity which result in severe fire hazards. Some descriptions of the influence of climate on fires in the region exist but no formal classification of the region into fire climate zones has been attempted. Kruger and Bigalke[2] have discussed the characteristics of fynbos fires with reference to weather factors, while Wicht and de Villiers[3] have described weather conditions and fire danger at the southern coastal town of Hermanus. Reifsnyder[4] has ranked the major Köppen[5] climate zones in order of descending fire-weather severity as follows: Cs, Cw, Cf, Dw, Bs, Aw, ET, EF and BW.* The Köppen designations in the fynbos biome are Cs, Cf and BS[6] and it is thus a very fireprone region by this classification.

The delineation and definition of areas that experience similar climatic conditions from the standpoint of potential fire risk is needed in order to apply meteorology to fire management. Such areas could be called fire climate areas, and should greatly enhance fire-weather forecasts and the planning of management operations. While fire-weather forecasts have reached various levels of sophistication in many countries,[4] no formal system exists in South Africa. The study reported here was conducted to define fire climate zones in the southern and western Cape.

Weather and plant fuels are the two most important factors determining fire potential. Fynbos fuels contain substantial amounts of litter, and although they are somewhat coarser than grassland fuels, they are nonetheless finely divided and can rapidly become flammable under suitable weather conditions.[7] Fuel moisture provides the link between weather and potential fire behaviour. Any system of defining fire climates should thus be based upon the effects of weather variables on fuel moisture. Studies of this nature have been carried out in the United States of America. Fire climate zones were delineated for Arizona and New Mexico[8] based on values of an adjusted equilibrium moisture content of the fire fuel complex. Similar zones were described for coastal Alaska by Finklin,[9] who related climatic variables to an index of fire danger. In this study I have used the energy release component of the U.S. National Fire Danger Rating System (NFDRS),[10] based on a fynbos fuel model and climatic features to define preliminary fire climate zones in the southern and western Cape.

Methods

This study was based on the climatic records from 40 weather stations in the southern and western Cape. A daily weather

---

*Köppen's climate zones are as follows: Cs = temperate (warm) climate with winter rainfall; Cw = temperate (warm) climate with summer rainfall; Cf = humid temperate (warm) climate with sufficient rainfall in all seasons; Dw = boreal (snow) climate with cold, dry winters; Bs = arid (steppe) climate; Aw = tropical climate with summer rainfall; ET = tundra (snow) climate; EF = permanent frost (snow) climate; and Bw = desert climate.

The author is at the Jonkershoek Forestry Research Centre, Private Bag X5011, Stellenbosch 7600, South Africa.

Table 1. Salient features of 40 weather stations in the fynbos biome.

Station name	Position	Fire season	Mean ERC for fire season	Length of record (months)
Bien Donne	33°50′S 18°59′E	JFM	25.37	510
Calitzdorp	33°32′S 21°41′E	NDJ	23.17	42
Citrusdal	32°34′S 18°59′E	JFM	31.32	142
De Doorns	33°28′S 19°40′E	NDJ	27.97	143
De Keur	32°58′S 19°18′E	JFM	28.13	60
Elgin	34°08′S 19°02′E	DJF	14.13	144
Elsenburg	33°51′S 18°50′E	DJF	21.23	60
Franschhoek	33°53′S 19°04′E	DJF	23.50	51
Graafwater	32°09′S 18°36′E	NDJ	27.67	121
Groot Constantia	34°02′S 18°25′E	JFM	13.80	197
Gydo	33°13′S 19°20′E	JFM	27.47	49
Hollaagte	34°12′S 21°50′E	DJF	12.37	46
Jakkalsrivier	34°09′S 19°08′E	DJF	12.00	84
Joubertina	33°47′S 23°35′E	DJF	14.90	178
Jonaskraal	34°24′S 19°54′E	DJF	19.83	120
Karringmelkrivier	34°08′S 20°46′E	DJF	18.07	123
Klawer	31°47′S 18°38′E	NDJ	30.30	121
Koo	33°41′S 19°51′E	NDJ	19.47	42
Koringberg	33°01′S 18°41,E	JFM	32.43	45
Landau	33°36′S 18°58′E	DJF	27.30	108
Langgewens	33°17′S 18°42′E	JFM	33.67	110
Langkloof	33°49′S 23°51′E	DJF	24.03	27
Malmesbury	33°27′S 18°44′E	DJF	26.77	74
Moreesburg	33°09′S 18°40′E	JFM	28.37	121
Nietvoorbij	33°54′S 18°52′E	DJF	19.97	195
Oudtshoorn	33°38′S 22°15′E	NDJ	27.33	155
Outeniqua	33°55′S 22°25′E	JJA	10.43	196
Philadelphia	33°40′S 18°35′E	JFM	25.53	106
Porterville	33°01′S 19°00′E	DJF	27.13	123
Prinskraal	34°38′S 20°07′E	NDJ	12.97	122
Protem	34°16′S 20°05′E	NDJ	17.70	122
Riebeeck West	33°21′S 18°52′E	JFM	30.27	124
Riversdale	34°05′S 21°15′E	NDJ	17.73	122
Riverside	33°21′S 19°18′E	JFM	28.00	20
Robertson	33°50′S 19°54′E	DJF	22.83	204
Tygerhoek	34°09′S 19°54′E	DJF	18.20	95
Vredenburg	32°54′S 18°00′E	DJF	18.27	125
Welgevallen	33°56′S 18°51′E	JFM	19.10	161
Weltevreden	33°56′S 20°37′E	DJF	26.50	66
Wolseley	33°27′S 19°12′E	DJF	30.70	108

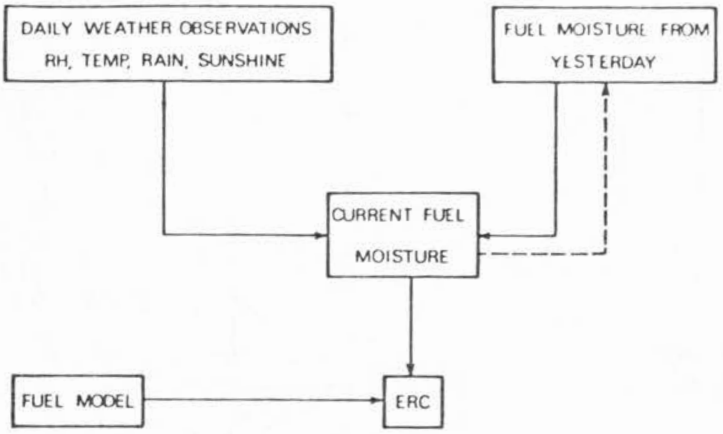


Fig. 1. Schematic representation of the derivation of the energy release component (ERC) by the National Fire Danger Rating System (simplified from Deeming *et al.*[10]).

record was used consisting of minimum and maximum temperature, minimum and maximum relative humidity, rainfall and hours of sunshine over a 24-hour period. These records were transformed to suitable inputs for the NFDRS in the manner described by Van Wilgen and Burgan.[11] A fynbos fuel model[7] represented the fuel properties of the vegetation of the region. (A fuel model is a set of values quantifying parameters such as fuel loads, particle sizes and packing ratios which represent the fuel properties of a particular vegetation type.) The results of this study are thus based on the assumption that fynbos vegetation characteristics do not vary over the region. This assumption is not correct but by holding fuels constant one may use the results of the model to reflect the differences in climate alone.

The energy release component (ERC) of the NFDRS was chosen to represent potential fire danger. The ERC is related to potential fire intensity expressed as the available energy per unit area at the head of a fire, and is calculated by simulating fluctuations in fuel moisture content based on fluctuations in weather. The changing moisture contents of the vegetation affect the amount of fuel that will be consumed in a fire, and thus fire intensity. This satisfies the requirement[9] that fire climate should be based on the effects of weather variables on fuel moisture. These moisture data, together with information from the fuel model are used to calculate the ERC (see Fig. 1). The weather record from each of the 40 weather stations was analysed by the NFDRS, and a mean ERC for each month was calculated from the daily values. For the purpose of this exercise the fire season was defined as the three-month period with the highest mean ERC.

The average ERC values for the fire season were plotted on a map of the region and used to define isolines of average ERC, thereby delineating zones of equal fire potential in the fire season, a first step in defining fire-climate zones. The annual trend of mean monthly ERC values at each station was then examined in order to detect possible changes in the character of the fire season across the region, and these were used to consolidate fire-climate zones.

Definition of fire climate zones

Table 1 shows the salient features of the weather stations used, together with the months of the fire season and the corresponding mean ERC values. The positions of stations and zones of equal fire potential are shown in Fig. 2. Most stations had the highest ERC values over three months in late summer-early autumn (December to February or January to March), although some had a peak in summer (November to January). Only one station (Outeniqua) showed a peak of ERC in winter (June to August). The distribution of fire season groups is shown in Fig. 3. Examination of the annual cycle of mean monthly ERC values at each station showed strong seasonal trends in the inland areas, whereas curves for southern coastal areas tended to be much flatter. It is apparent from Fig. 2 that coastal areas tend to have a lower fire potential than inland areas in general, owing to the tempering influence of maritime factors on fuel moisture.

The lowest mean ERC values (10 – 20) occur south of the south-facing coastal mountain ranges, that is the Hottentots-Holland, Langeberg, Outeniqua and Tsitsikamma mountains, as well as in the narrow band along the west coast. It is possible to divide the region into three major zones of equal fire potential on the basis of these considerations. These are the southern coastal areas with mean ERC values in the fire season between 10 and 20, inland areas with corresponding ERC values between 20 and 35, and a western coastal area (ERC of 10 to 20) under the maritime influence of the cold Atlantic Ocean. The southern coastal and inland areas would be subdivided into eastern and western halves for management purposes. This is not done on the basis of the ERC analysis, but forecasts for the two areas for the same period will differ, mainly because of the size of the area involved. There is often a considerable time lag in weather changes between the west and the east due to the movement of weather fronts from west to east. Such a division will also allow for east-west climatic gradients such as the increasing percentage of summer rain towards the east.[12]

The boundaries of these fire-climate zones are shown in Fig. 4. Examples of the annual trends in monthly mean ERC values at selected weather stations are shown in Fig. 5. The major features of each zone are discussed below.

(i) *Western coastal zone.* This zone extends from the Cape Peninsula northwards in a fairly narrow (10 km) band along the west coast. Within this zone, mean fire potential is lowest in the winter but seasonal fluctuations about the mean are not marked. Fires are most likely under occasional, extreme conditions of high temperature, low relative humidity and high wind in summer. Much of this zone is occupied by cultivated land or Strandveld of the West Coast,[1] which is likely to carry fire less often than fynbos because of lower fuel loads, sparse canopy and relatively many succulents.[2]

(ii) *Western inland zone.* This zone extends from the western coastal zone as far as an arbitrary line connecting the towns of Sutherland and Barrydale, and north of the Langeberg mountains, including the north-facing slopes of this range. The zone is characterized by strong seasonal trends in fire potential and a high mean fire potential in the summer months. Although winter fires are possible under exceptional, rare circumstances, they hardly ever occur. Fires are common in summer on the other hand, when they also burn the largest areas.[2]

(iii) *Southwestern coastal zone.* This zone extends from Cape Town in the west to Mossel Bay in the east, and south of the Hottentots-Holland, Riviersonderend and Langeberg mountains. Fire potential is highest in the summer months but annual fluctuations about the mean are not marked. Fires are most likely under extreme conditions in summer. Large fires also occur occasionally in winter under bergwind conditions.[3]

(iv) *Eastern inland zone.* This zone extends from the western inland zone eastwards. Although the zone has an even rainfall throughout the year, high evapotranspiration in summer is responsible for what is effectively a winter rainfall regime. There is thus a significant seasonal cycle of mean fire potential with a peak in summer, when most fires occur.[13]

(v) *Southeastern coastal zone.* This zone extends from Mossel Bay eastwards and south of the Outeniqua and Kouga mountains. It is characterized by very little fluctuation in mean ERC throughout the year. The annual fire-potential cycle is essentially bimodal, with fires experienced under occasional suitable conditions in both winter and summer.[11] The weather conditions that

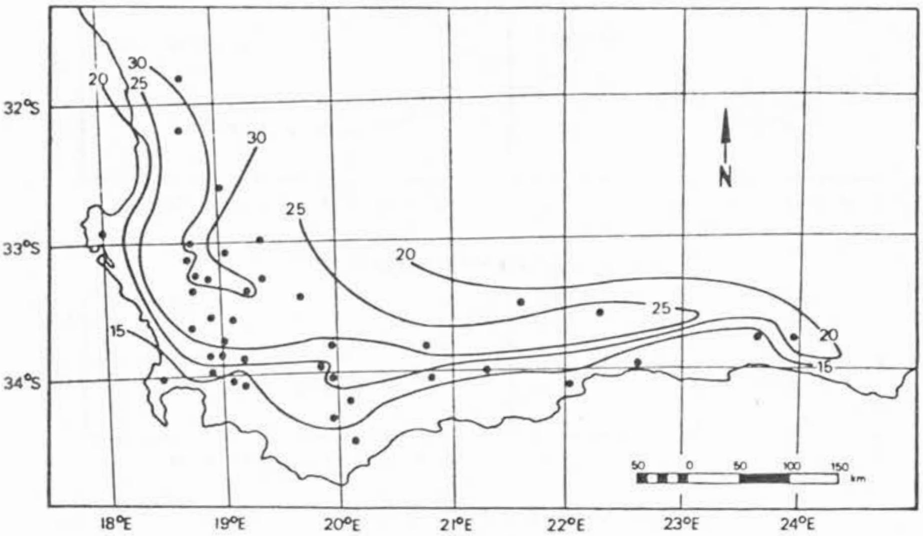


Fig. 2. Isolines of mean energy release component (ERC) during the fire season (see text). Dots indicate the position of weather stations.

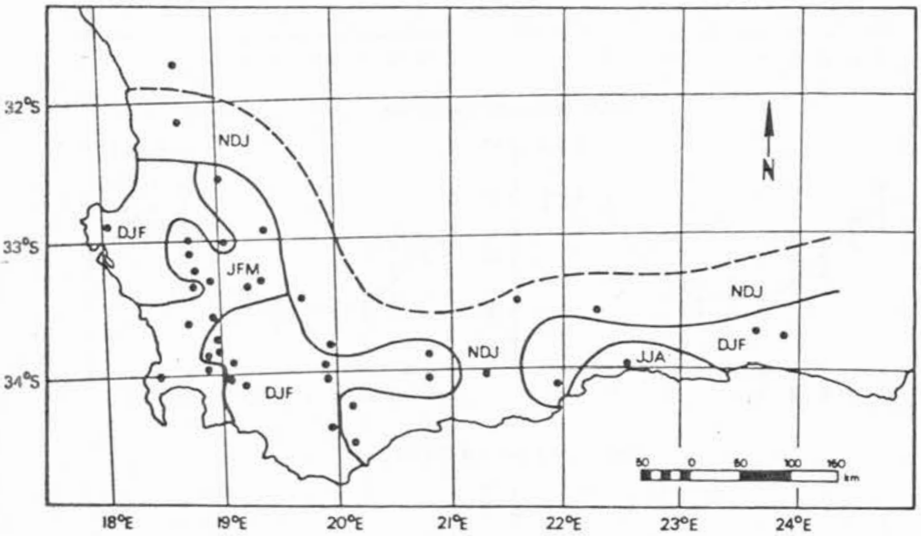


Fig. 3. Distribution of fire season classes (the three-month period of highest mean energy release component). Dots indicate the position of weather stations.

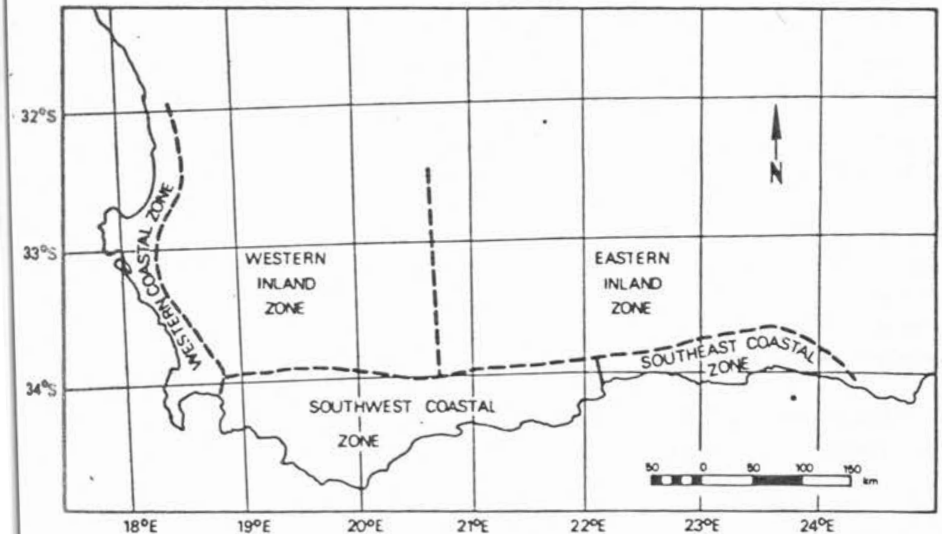


Fig. 4. Fire climate zones based on fire potential during the fire season.

favour large fires occur rather irregularly. Winter bergwinds lead to conditions of high fire potential[14] and this explains the June-August maximum at the Outeniqua station.

Discussion

The fire-climate zones presented here represent geographical regions within which the average climatic features vary little. Three facets of the fire management problem are served by these fire-climate zones: (i) fire weather forecasting, (ii) prescribed burning, and (iii) wild-fire control.

Accurate fire-weather forecasts will greatly assist mountain catchment managers in planning fire-related operations. Fire-weather forecasts should contain all the elements necessary to derive the indices of the NFDRS, and should be made separately for the fire-climate zones prseented here. It is important at this stage that weather forecasters and mountain catchment managers combine their expertise if there is to be progress in this field. It is hoped that this study will provide a useful basis for achieving this.

The fire-climate zones described here can be used as a foundation for prescribed fire management zones. Burning by prescription implies that fires will be deliberately started only when a certain set of conditions is met. The chances of meeting these conditions will vary among the different fire-climate zones, which will necessitate the recognition of different conditions for burning in each zone. For example, fire danger is invariably high in summer and early autumn in the inland zones, which means that fires will burn freely at that time. Similar simulations on the south-facing slopes of the Outeniqua mountains show that the mean fire danger in the southeastern coastal zone is low.[11] Occasional extreme conditions do occur, for example during bergwinds, and it is under these exceptional conditions that large fires are possible. Thus prescribed burning operations in this zone will probably have to take place under special conditions, such as those immediately following bergwinds, if such fires are to be successful.

Fynbos vegetation is adapted to fire. If fires were strongly seasonal in the past, there would have been evolutionary pressure to survive fires at that time of the year when the danger of fire was high.[11] Figure 5 shows the differences in seasonal variation in fire danger between the coastal and inland zones. In inland areas the chances of fire outside the defined fire season are low, whereas the fire season component in the moist coastal areas is far less distinct, with fires occurring under occasional suitable conditions. Bond and others[15] have shown that winter and spring burning results in poor regeneration of serotinous Proteaceae in the eastern inland zone; the same response is to be found in the western inland zone (Van Wilgen and Viviers, in preparation), but this response is not general and is much less marked in the southwestern coastal zone.[15] Casual observations from the southeastern coastal zone (J. Midgley, personal communication) have shown that there may be little variation in response to burning in different seasons but that there is a marked dependence on the intensity of burning, with the most vigorous regenera-

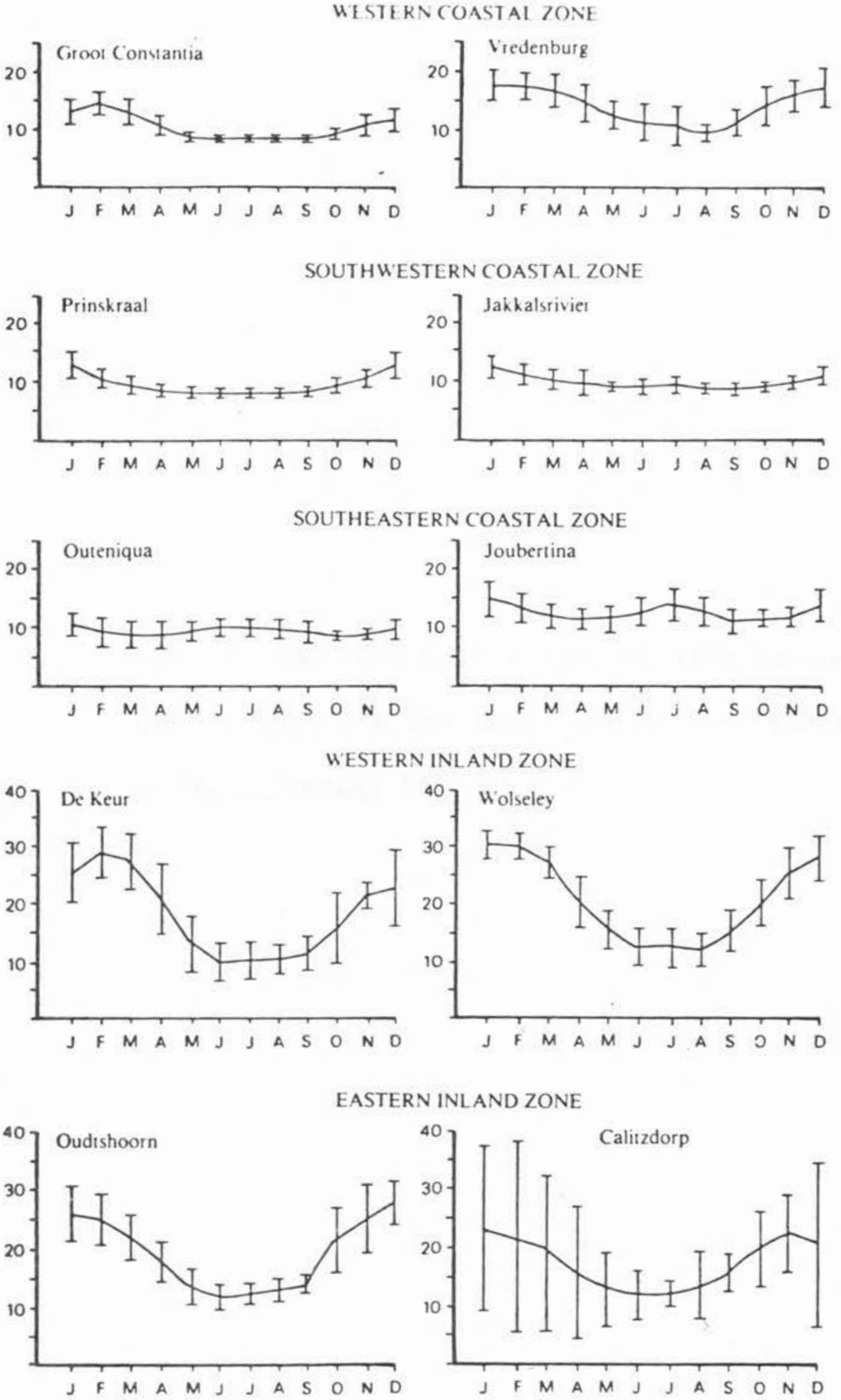


Fig. 5. Annual cycle of mean monthly energy release component at two stations in each of the five fire climate zones. The bars are the 95% confidence limits of the mean. The wide confidence interval at Calitzdorp is largely due to the short observation period (3.5 years).

tion following high intensity fires. This is to be expected from an evolutionary point of view; the incidence of fires is not strongly seasonal, but fires may be quite intense as they are restricted to rare conditions which can lead to a fierce conflagration. If prescribed burning is to be timed so as to result in good regeneration of the vegetation, then burning prescriptions for coastal and inland zones should differ. Fires in the inland zones should be restricted to the late summer and early autumn (February to April). In the coastal zones the burning season is less critical, but should be selected under conditions that lead to moderately intense fires. The fire-climate zones as described here should therefore be useful management divisions. However, more research into the responses of the biota to fire is needed in order to test the hypotheses presented above.

Fuggle[17] has stressed the variability of climatic patterns in the southern and western Cape, and he urges caution where interpolations between climatic stations are attempted. This study has highlighted the lack of weather stations in the mountain areas of the Cape. Most recording stations have been established in the lowlands to collect data for use in agriculture, and agriculture is almost non-existent in the mountains. There are a few high-lying stations in the western half of the biome, but none in the eastern half. The results presented here represent the classification of fire climates that is feasible with available information. A more meaningful classification and therefore sounder fire (and other) management policies can only be achieved once reliable data on the climatic patterns in the Cape mountains are obtained. The establishment of weather stations in the mountain catchment areas should receive the highest priority.

I thank collegues at the Jonkershoek and Saasveld forestry research centres for useful comment on the manuscript. Japser Hoon of the Department of Agriculture provided assistance in obtaining weather data and Lisa Klaussner gave assistance in data processing. This work forms part of the Conservation Forestry Research Programme of the Directorate of Forestry.

1. Acocks J.P.H. (1953). Veld types of South Africa. *Mem. Bot. Surv. S. Afr.* **28**, Government Printer, Pretoria.
2. Kruger F.J. and Bigalke R.C. Fire in the fynbos (1984). In *The Ecological Effects of Fire in South African Ecosystems*, edit. P. de V. Booysen and N.M. Tainton. Springer, Berlin.
3. Wicht C.L. and de Villiers Y.R. (1963). Weerstoestande en brandgevaar by Hermanus. *J. Geog.* **2**, 25 – 36.
4. Reifsnyder W.E. (1978). *Systems for evaluating and predicting the effects of weather and climate on wildland fires.* Spec. Environ. Rep. 11, WM0496. World Meteorological Organization, Geneva.
5. Köppen W. (1931). *Grundriss der Klimakunde.* De Gruyter, Berlin.
6. Schulze B.R. (1947). The climate of South Africa according to the classifications of Köppen and Thornthwaite. *S. Afr. Geog. J.* **29**, 32 – 42.
7. Van Wilgen B.W. (1984). Adaptation of the United States Fire Danger Rating System to fynbos conditions. I. A fuel model for fire danger rating in the fynbos biome. *S. Afr. For. J.* **129**, 61 – 65.
8. Fosberg M.A. and Furman R. (1973). Fire climates in the southwest. *Agric. Meteorol.* **12**, 27 – 34.
9. Finklin A.I. (1982). *Fire-climate zones of coastal Alaska.* USDA Forest Service Gen. Tech. Rep. INT-128, Washington, D.C.
10. Deeming J.E., Burgan R.E. and Cohen J.D. (1978). *The National Fire Danger Rating System — 1978.* USDA Forest Service, Gen. Tech. Rep. INT-39, Washington, D.C.
11. Van Wilgen B.W. and Burgan R.E. (1984). Adaptation of the United States Fire Danger Rating System to fynbos conditions II. Historic fire danger in the fynbos biome. *S. Afr. For. J.* **129**, 66 – 78.
12. Campbell B.M. (1983). Montane plant environments in the Fynbos Biome. *Bothalia* **14**, 283 – 298.
13. Horne I.P. (1981). The frequency of veld fires in the Groot Swartberg Mountain Catchment Area, Cape Province. *S. Afr. For. J.* **118**, 56 – 60.
14. Le Roux P.J. (1969). *Brandbestryding in Suid-Kaapland met spesiale verwysing na chemiese metodes van beheer.* MSc thesis, University of Stellenbosch.
15. Bond W.J., Vlok J. and Viviers M. (1984). Variation in seedling recruitment of Cape Proteaceae after fire. *J. Ecol.* **72**, 209 – 221.
16. Kruger F.J. (1972). *Jakkalsrivier catchment experiment: Investigation of the effects of spring and autumn burn on vegetation.* Station Report, Jonkershoek Forestry Research Centre.
17. Fuggle R.F. (1981). *Macro-climatic patterns within the Fynbos Biome.* Unpublished report, Fynbos Biome Project, CSIR, Pretoria.

Paper 6. The effect of season of fire on serotinous Proteaceae in the western Cape and the implications for fynbos management. <u>South African Forestry Journal</u> 133, 49 - 53.

The Effect of Season of Fire on Serotinous Proteaceae in the Western Cape and the Implications for Fynbos Management

B.W. van Wilgen and M. Viviers

Jonkershoek Forestry Research Centre, Stellenbosch

SYNOPSIS

A survey of the regeneration of serotinous Proteaceae following fire in different seasons was conducted in the Western Cape. Seedling regeneration was best following late summer-early autumn burns and differed significantly from regeneration following winter and spring burns. These results are explained in terms of a rodent predation hypothesis. Some anomalies arise in the data, where good regeneration followed spring burns. These usually occur on the south-facing coastal ranges. In such cases rodent predation may be pre-empted by early germination. Some hypotheses which may explain differences in regeneration success are discussed and these need to be tested. Examples from other fynbos taxa are used to emphasise the advantages of a late summer-early autumn burning regime for most fynbos areas. As the Western Cape probably has a long history of spring burning it is considered important that burning should be conducted in late summer-early autumn in future to ensure effective conservation of the fynbos. The implications for prescribed burning as a fire management tool are discussed.

INTRODUCTION

The fynbos vegetation (macchia in Acocks, 1953) of the Cape Province is fire prone. The fynbos mountain catchment areas are managed by prescribed burning (Bands, 1977), mainly to reduce fire hazard, to control woody weeds, to enhance water run-off and to rejuvenate fire-adapted vegetation. As nature conservation is one of the major goals of catchment management, these prescribed fires should ideally be timed to ensure the survival of the component species of the ecosystem.

The effects of season of burn on fynbos vegetation are still little understood, but it is usually assumed that summer would be the most natural season to expect fires and that this would be when fires would have the least detrimental effect on the vegetation (Bands, 1977; Van Wilgen and Burgan, 1984). The study of Proteaceae and their response to season of fire has received some attention in the past. Jordaan's (1949) pioneer work presented the hypothesis that fires from January to March were safe, from April to June unfavourable and from July to December unsafe for the regeneration of *Protea repens* (L.) L., based on the embriology of that species. He presented the results of field experiments (Jordaan, 1965; 1982) which supported his original hypothesis and concluded that observations on the effects of fire on individual species of the Proteaceae in different months of the year was an important research priority (Jordaan, 1982). A common survival trait among the Proteaceae comprises the retention of seed in flower heads or woody capitula for a number of years (serotiny). Thus Kruger *et al.* (1977) were able to show that *Protea repens* could regenerate successfully after a fire in September, from the previous season's seed stored in serotinous flower heads on the plant. Bond *et al.* (1984) surveyed the seedling recruitment of serotinous Proteaceae following 31 fires in the inland mountain ranges of the Southern Cape. They showed that seedling recruitment differed significantly with fire season. Seedling establishment was most successful following atumn burns. Summer burns were often less favourable, with greater variability from fire to fire, and winter and spring burns led to very poor seedling establishment. They concluded that successive fires in winter and spring could rapidly cause local extinction in the serotinous Proteaceae. In a separate study Bond (1984) showed that this seasonal difference could be attributed to predation of dormant seeds by rodents before germination in winter. Unlike those in the Southern Cape, rodent densities in the Western Cape are supposedly low (Bond *et al.*, 1980; Bigalke, 1979). Bond (1984) argues that Western Cape sites should therefore show little seasonal variation in postfire seedling densities. This is also supported by the work of Kruger (1972), who found no differences in the survival of *Leucadendron xanthoconus* (O. Knutze) K. Schum seedlings following spring and autumn fires in the Groenlandberg (34° 09'S, 19 °09'E) despite the fact that the seedlings only germinated in winter.

In this paper we report on a survey of areas in the Western Cape similar to that undertaken by Bond *et al.* (1984) in the Southern Cape. The survey was undertaken to establish whether seedling recruitment varied with season of burn to the same extent as that observed in the inland ranges of the Southern Cape. In order to rationalise burning policies in the Cape fynbos areas, the effects of season of burn on Proteaceae recovery in the Western and Southern Cape are compared.

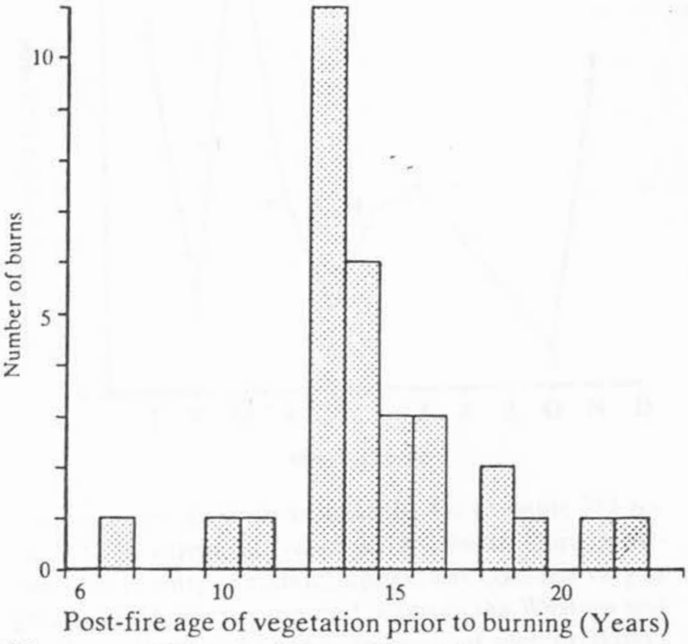
METHODS

Seedling regeneration was surveyed in 31 burns of known date where less than three years had passed since the fire, but where at least one winter season had passed to allow germination. Populations of fire-killed Proteaceae were located by the presence of dead shrubs. These dead shrubs could be identified to species by their characteristic capitula. A systematic sample grid was located within each of these populations. Transects 5 to 15 m apart were walked, placing 1 × 1 m quadrats at 3 to 5 m intervals, depending on plant density. Sixty-six quadrats were enumerated per sample. Up to four samples were enumerated in each burnt area. Some populations were extremely scattered, so that sampling by means of 1 × 1 m quadrats was inadequate. In these cases 20 m^2 circular plots were used at 5 m intervals along the transects. Numbers of adults and seedlings of each species were counted in each sample and the seedling to adult ratio was determined. Pre-fire vegetation age was determined from local fire records and verified through node counts on dead adult plants. A total of 31 burnt areas were enumerated. Circular plots were used at 10 of these.

RESULTS

A total of 20 species of serotinous Proteaceae were encountered in the survey *(Table 1)*. For the purposes of analysis, the seedling and adult numbers for each species in each burn were taken as one observation, giving a total of 73 observations in 31 burns spread over 11 months of the year (no December burns were located). The species and number of observations for each are given in *Table 1*. The age class distribution of veld prior to burning is shown in *Figure 1*. Data were grouped according to the month of burn. An analysis of covariance comparing the seedling: adult numbers in the various groups (months) showed highly significant differences between adjusted means and between slopes ($P<0,005$). The data fall into two groups, that is summer and autumn months (November to April inclusive) for which the slope is large, indicating a high seedling: adult ratio and winter and spring (May to October) for which the slope is small. Exceptions in summer/autumn are February for which the slope was small and December for which no data are available. The relationship between seedling: adult ratio and month of burn is illustrated in *Figure 2*. It is clear that the best regeneration follows fires in March and April, whereas fires from May to October are followed by very poor regeneration. This is more marked in the genus *Protea* than in *Leucadendron (Figure 2)*.

FIGURE 1. Distribution of veld age classes at the time of burning.



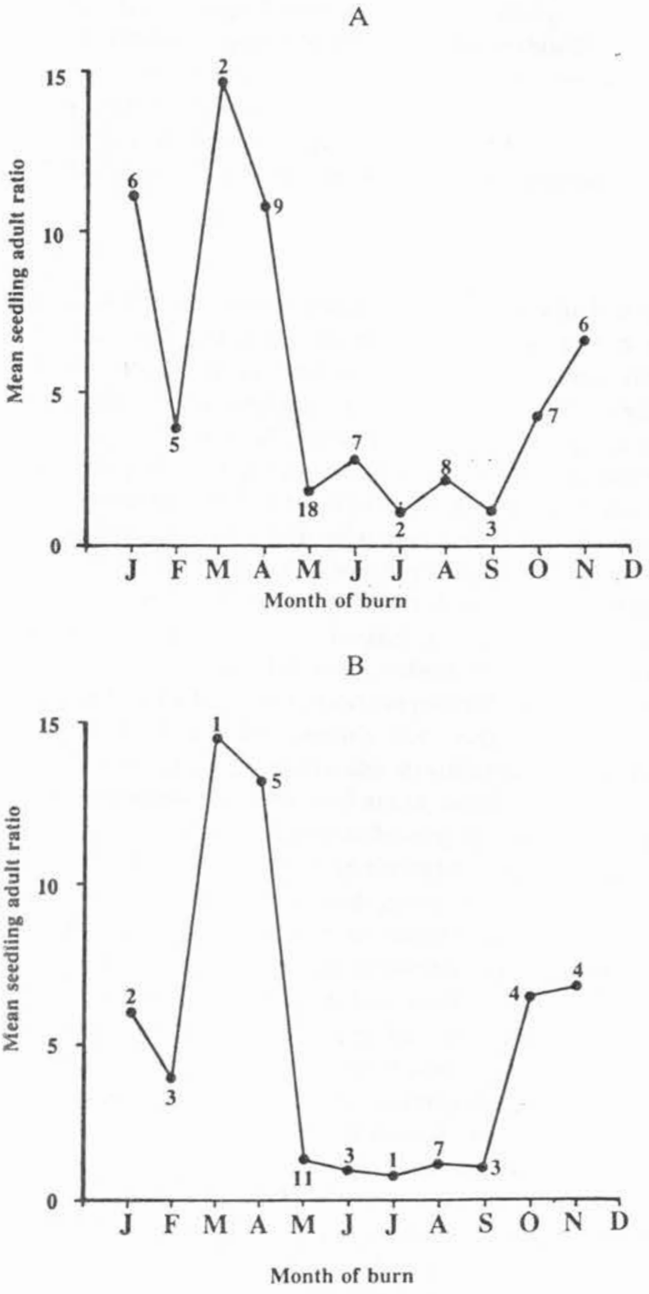
DISCUSSION

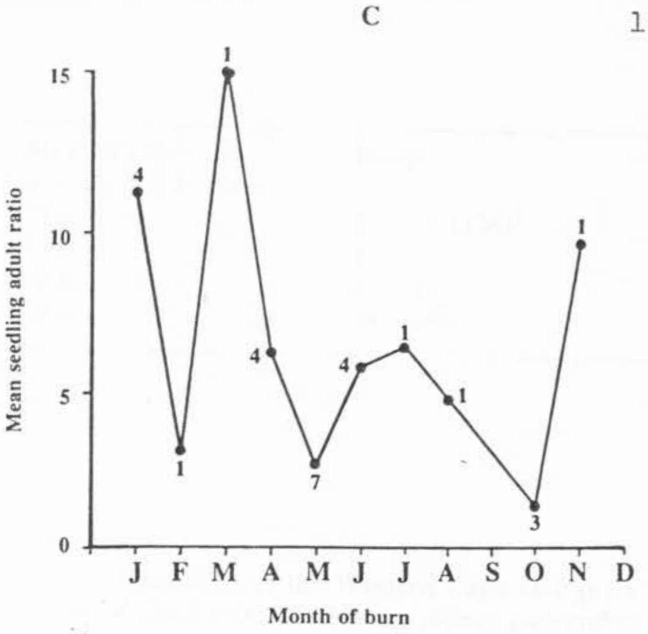
The data presented in *Figure 1* show that the post-fire age of the vegetation was greater than 13 years in most cases. This means that Proteas would have been mature and able to reproduce following fire. The results of this survey show that, contrary to the expectations of Bond (1984), there is a significant response by serotinous Proteaceae to season of burn in the Western Cape. The conclusions drawn from this study are much the same as those given by Bond *et al.* (1984) and listed here in the introduction. The relatively poor regeneration which followed fires in February *(Figure 2)* is also in accordance with Bond's findings, that is that seedling recruitment following summer fires is often less favourable and/or highly variable.

TABLE 1. Species of serotinous Proteaceae encountered in the survey. The number of burns at which each species was encountered is given in brackets.

Protea repens (L.)L.	(14)	*Aulax umbellata* (Thunb.) R.Br.	(2)
P. neriifolia R.Br.	(13)	*P. compacta* R.Br.	(1)
Leucadendron xanthoconus (O. Knutze) K. Schum.	(11)	*P. coronata* Lam.	(1)
P. laurifolia Thunb.	(6)	*P. nana* (Berg.) Thunb.	(1)
L. laureolum (Lam.) Fourc.	(5)	*P. magnifica* Link.	(1)
L. salicifolium (Salisb.) I. Williams	(5)	*P. pendula* R.Br.	(1)
L. eucalyptifolium Buek. ex Meisn.	(2)	*P. lorifolia* (Salisb. ex Knight) Fourc.	(1)
L. microcephalum (Gandoger) Gandoger et Schinz.	(2)	*P. longifolia* Andr.	(1)
P. lacticolor Salisb.	(2)	*L. dubium* Buek.	(1)
P. acuminata Sims	(2)	*L. comosum* (Thunb.) R. Br.	(1)

FIGURE 2. Graphical representation of the ratio of seedlings to adults following different months of burn. Ratios were derived using the total number of adults and seedlings from all burns for the month. The number of burns included for each month is indicated on the graphs. The three graphs are: A — all species, B — Protea only; C — *Leucadendron* only.





The observation that rodent densities appear to be low in the Western Cape (Bigalke, 1979) led Bond (1984) to speculate that seasonal variation in Proteaceae seedling recruitment would be less marked than in the Southern Cape. More recent data on rodent densities at two localities in the Western Cape are presented in *Table 2*. It is apparent that rodent densities in these two areas (Cedarberg and Jonkershoek) do not differ greatly from estimates for the inland Swartberg range in the Southern Cape. Bigalke (1979) has reported that rodent densities in the fynbos are low when compared with those in other environments, for example 361 rodents/ha in a tropical grass/bush habitat in Zaire. However, the density of rodents apparently does not vary as greatly as what was supposed between the Western and Southern Cape and so similar levels of seed predation may be expected in both areas, accounting for our results in terms of Bond's rodent predation hypothesis.

Some data points used in our analyses could be regarded as outliers. For example, *Leucadendron xanthoconus* had a seedling: adult ratio of 25:1 (11 adults, 278 seedlings) following a June fire at Sir Lowry's Pass and *Leucadendron microcephalum* had a ratio of 16:1 (6 adults, 98 seedlings) following a May fire at Botrivier. Both of these ratios are abnormally high for the particular month (see *Figure 2)*. So although winter and spring burns usually reasult in the poor regeneration, this is not always the case and there may be geographical variations. Our survey covered a large area (from the Cedarberg at 32 °15'S, 19 °00'E to the Langeberg at 34 °00'S, 21 °30'E) and the sample is not large enough to determine conclusively the geographical variability in response to season of burn. The indications are, however, that the vegetation on southern coastal mountain ranges will show less response to season of fire than inland areas. Van Wilgen (1984) has shown that the likelihood of fires occurring in inland areas is strongly seasonal (based on climatic variables), whereas fires in southern coastal areas are more likely during exceptional conditions which are not strongly seasonal. Strong seasonal trends in weather would have influenced the occurrence of fires and exerted evolutionary pressure on the vegetation. Plants should have adapted to fires in those seasons where prolonged high fire danger is most prevalent. So although late summer early autumn is probably the most appropriate time to burn in most inland areas, season of burn may be of less importance in the southern coastal ranges.

Serotinous Proteaceae show a summer drought-avoiding dormancy in many areas (Deall and Brown, 1981; Bond, 1984) with germination following a tem-

TABLE 2. Rodent density data for fynbos localities

Source	Area	Mean number of animals per hectare	Range
Breytenbach (1982)	Swartberg	31,2	4 — 58 (138)[1]
De Hoogh (1968)	Cedarberg	17,0	8 — 21[2]
S.A. Botha (unpublished)	Cedarberg	32,0	6 — 43
S.A. Botha (unpublished)	Jonkershoek[3]	60,3	14 — 90

1 exceptional value
2 5 % confidence limits
3 frequently burnt fire-break, possibly atypical

perature plus moisture (stratification) cue which is met by the cold and wet conditions of winter. This is not always so, however, and in some cases moisture alone can trigger germination (Kruger, 1972; Brits, 1983). We have no way of knowing if the seedlings in our sample germinated very soon after burns and had no predation or not. For example, Kruger (1972) reported that seeds of *Protea lacticolor* and *Leucadendron salicifolium* germinated very soon after burns in September and November. In terms of the rodent predation hypothesis, regeneration in such cases would be less affected by season of burn because rodent predation is preempted by early germination (apparently stimulated by moisture alone). Presumably the seeds of species in these areas do not require the stratification cue necessary elsewhere. In semi-arid areas, seedlings would not survive if they germinated following spring or summer showers because of ensuing drought. There would be selection for dormancy and germination cues which would ensure germination in winter, when the probability of drought occurring before the seedling is established is low. There is therefore likely to be a segregation of germination strategies between species and/or genetic variants between humid and semi-arid fynbos. Heavy predation should follow spring fires in the latter case because seeds cannot germinate before the onset of winter conditions. This hypothesis may explain some of our outliers as well as the good regeneration observed by Kruger (1972). However, it does not explain the "profuse" germination of *Leucadendron xanthoconus* one year after a spring fire (Kruger, 1972). This seems to indicate that rodent predation was not high and that rodent densities may vary considerably from place to place, thus affecting germination, or alternately that the seeds of *L. xanthoconus* are not attractive to rodents. The question of seed dormancy, germination and the importance of rodents in the various areas of the Western Cape requires further study to test these hypotheses. What is certain at this point is that season of burn has a significant effect on the regeneration of Proteaceae (notably in the genus *Protea)* and that spring and winter burning should be avoided, especially in semi-arid areas.

Van Wilgen (1981) has shown that most prescribed burning operations in the Western Cape take place in spring, at which time weather conditions are conducive to safe burns, but this practice is at present being discouraged (Kruger, 1982). Spring burning would obviously result in degradation of populations of serotinous Proteaceae. There are examples from other fynbos taxa which emphasise the advantages of a late summer/early autumn burning regime. We present a few of these here to illustrate the point. Lamb (1982) reported seedling to adult ratios ranging from 0,38:1 following September burns to 27:1 following January burns for *Mimetes splendidus* Knight, a myrmechochorous (ant-dispersed) member of the Proteaceae. He attributes the difference to (1) higher intensity fires in late summer which may help to stimulate germination (see also Brits, 1983) and (2) the availability of the current seed crop which will enhance the available soil-stored seed. Kruger (1978) and Le Maitre (1984) have shown that *Watsonia pyramidata* (Andr.) Stapf, a fynbos geophyte, flowers profusely after autumn burns, but hardly at all following spring burns. The reasons for this are still unclear, but the species has apparently adapted to autumn burns, after which seed production is enhanced and sexual reproduction is ensured through seed predator satiation. Examples from the fauna include the geometric tortoise *(Psammobates geometricus)* (Linnaeus, 1958), a fynbos endemic reptile. The eggs, which are laid in spring, have a peak hatching period in April-May. Fires after the hatching period would destroy both adults and young, but fires in February or March would ensure survival of the population (Greig, 1982). Spring burning would also affect fynbos birds. Winterbottom (1968) found that the main breeding period in the Hottentots-Holland Mountains was in four months from July to October, with 68 % of all nests recorded during that period. For the four-month period December to March only 4 % of nests were recorded. Although the season of bird breeding is a response to food availability rather than to season of infrequent fires, spring burns will nonetheless cause a setback to breeding bird populations. This should be prevented in view of the dwindling populations and the possible importance of birds as pollinators in the fynbos (Siegfried, 1983).

While conducting the study we have noticed that serotinous Proteaceous shrubs are far more scarce in the Western Cape than in the Southern Cape and that, where they do occur, the stand size is much smaller. For example, of 56 burnt areas visited in the Swartberg, 52 had stands of Proteaceous shrubs which could be enumerated (J. Vlok, pers. comm.). In this survey 73 burnt areas were visited, of which only 31 had adequate populations of Proteaceous shrubs. There is no real evidence to show that this is not a natural occurrence, but it may be due to the longer history of human influence on the fire regime in the Western Cape, when compared with the more remote Swartberg, Kouga and Kammanassie ranges in the Southern Cape. Spring burns are mainly of human origin (Van Wilgen, 1981; Horne, 1981) and if repeated often enough, could lead to local extinction of seed reproducing proteas. In view of the possibility of already depleted shrub populations, it is of the utmost importance that prescribed fires be restricted to the late summer/early autumn period.

The implications for fire management of fynbos and the problems that arise are clear. If the aim of management is to maintain all the species present then prescribed burning seasons should be strictly defined to exclude ecologically unfavourable seasons (which may vary geographically) and then defined by opportunity (the occurrence of suitable weather conditions) in the ecologically favourable season. In many areas the late summer/early autumn period would constitute the ecologically favourable season. Because this is the period of highest fire danger, managers will be reluctant to burn as fires are potentially uncontrollable and the safety of workers and adjacent property cannot always be ensured. There are as yet no guide-lines as to safe limits under which prescribed burns may be conducted.

Once these limits are determined, their seasonal occurrence should be established from weather records to assess the feasibility of late summer/early autumn prescribed burning. Another priority is to establish the extent (if any) of areas where season of burn is not as critical for species survival, such as the south-facing coastal ranges. Should this be valid, the task of managing such areas should become less problematic.

ACKNOWLEDGEMENTS

We thank Messrs G. Hockey and A. Simmers for assistance with field work, Mr F.J. Kruger of the South African Forestry Research Institute for useful comment and Dr L.P. Fatti of the CSIR for carrying out the statistical analyses.

REFERENCES

ACOCKS, J.P.H., 1953. Veld Types of South Africa. *Memoir of the Botanical Survey of South Africa* 28, Government Printer, Pretoria.

BANDS, D.P., 1977. Prescribed Burning in Cape Fynbos Catchments. In: H.A. Mooney and C.E. Conrad (Eds). *Symposium on the environmental consequences of fire and fuel management in mediterranean ecosystems.* USDA Forest Service General Technical Report WO-3.

BIGALKE, R.C. 1979. Aspects of Vertebrate Life in Fynbos, South Africa. In: R.L. Specht (Ed.). *Heathlands and related shrublands: Descriptive studies.* Elsevier, Amsterdam.

BOND, W., FERGUSON, M., and FORSYTH, G., 1980. Small Mammals and Habitat Structure along Altitudinal Gradients in the Southern Cape Mountains. *S. Afr. J. Zool.* 15: 34 — 43.

BOND, W.J., 1984. Fire Survival of Cape Proteaceae-influence of Fire Season and Seed Predators. *Vegetatio.* 56(2): 65-74.

BOND, W.J., VLOK, J., and VIVIERS, M., 1984. Variation in Seedling Recruitment in Fire Adapted Cape Proteaceae and its Causes. *J. Ecol.* 72: 209-221.

BREYTENBACH, G.J. 1982. *Small Mammal Responses to Environmental Gradients in the Groot Swartberg of the Southern Cape.* M.Sc. thesis, University of Pretoria.

BRITS, G.J., 1983. *Some Adaptations in Seed Regeneration of Fynbos Proteaceae.* Paper read to S.A.A.B., Pretoria, January 1983.

DEALL, G.B., and BROWN, N.A.C., 1981. Seed Germination in *Protea magnifica* Link. *S. Afr. J. Sci.* 77: 175-176.

DE HOOGH, R.J., 1968. *Report of Practical Work in South Africa.* University of Wageningen, 153 pages.

GREIG, J.C., 1982. The Geometric Tortoise — Symptom of a Dying Ecosystem. *Veld & Flora* 68: 106-108.

HORNE, I.P., 1981. The Frequency of Veld Fires in the Groot Swartberg Mountain Catchment Area, Cape Province. *S. Afr. For. J.* 118: 56-60.

JORDAAN, P.G., 1949. Aantekeninge oor die Voortplanting en Brandperiodes van *Protea mellifera* Thunb. *J. S. Afr. Bot.* 15: 121-125.

JORDAAN, P.G., 1965. Die Invloed van 'n Winterbrand op die Voortplanting van Vier Soorte van Proteaceae. *Tydskr. Natuurw.* 5: 27-31.

JORDAAN, P.G., 1982. The Influence of a Fire in April on the Reproduction of Three Species of the Proteaceae. *J. S. Afr. Bot.* 44: 1-4.

KRUGER, F.J., BANDS, D.P., DURAND, B.J., and HAYNES, R.A., 1977. *Ecology and Management of the Cape Fynbos: Toward the Conservation of a Unique Biome Type.* Second internatioonal symposium of S. Afr. Wildl. Man. Assoc., Pretoria, July 1977.

KRUGER, F.J., 1972. *Jakkalsrivier Catchment Experiment: Investigation of the Effects of Spring and Autumn Burns on Vegetation.* Unpublished report, Jonkershoek Forestry Research Centre.

KRUGER, F.J., 1978. *Some Aspects of the Demography of* Watsonia pyramidata *(Andr.) Stapf in relation of fire.* Paper read at the joint SAAB and GSSA congress, Bloemfontein, January, 1978.

KRUGER, F.J., 1982. Use and Management of Mediterranean Ecosystems in South Africa — Current Problems. In: C.E. Conrad and W.C. Oechel (Eds). *Dynamics and management of mediterranean-type ecosystems.* USDA Forest Serv. General Technical Report PSW-58.

LAMB, A.J., 1982. *Preliminary Report on the Status of* Mimetes splendidus *Knight in the Langeberg and Recommendations for its Conservation.* Unpublished report, Jonkershoek Forestry Research Centre.

LE MAITRE, D.C., (1984). A Short Note on Seed Predation in *Watsonia pyramidata* (Andr.) Stapf. in Relation to Season of Burn. *Jl. S. Afr. Bot.* 50: 407-415.

SIEGFRIED, W.R., 1983. Trophic Structure of Some Communities of Fynbos Birds. *Jl. S. Afr. Bot. 49: 1-43.*

VAN WILGEN, B.W., 1981. An Analysis of Fires and Associated Weather Factors in Mountain Fynbos Areas in the South-western Cape. *S. Afr. For. J.* 119: 29-34.

VAN WILGEN, B.W., (1984). Fire Climates in the Southern and Western Cape Province and Their Potential Use in Fire Control and management. *S. Afr. J. Sci.* 80: 358-362.

VAN WILGEN, B.W., and BURGAN, R.E., 1984. Adaptation of the United States Fire Danger Rating System to Fynbos Conditions II. Historic Fire Danger in the Fynbos Biome. *S. Afr. For. J.* 129: 66-78.

WINTERBOTTOM, J.M., 1968. A Check List of the Land and Fresh Water Birds of the Western Cape Province. *Ann. S. Afr. Museum* 53(1).

Paper 7. Factors influencing burning by prescription in mountain fynbos catchment areas. South African Forestry Journal 134 (in press).

FACTORS INFLUENCING BURNING BY PRESCRIPTION IN MOUNTAIN FYNBOS CATCHMENT AREAS

B.W. VAN WILGEN and D.M. RICHARDSON
South African Forestry Research Institute
Jonkershoek Forestry Research Centre
Private Bag X5011
Stellenbosch 7600

SYNOPSIS

The fynbos vegetation in the mountains of the Cape is managed by applying what is termed prescribed burning. Burns are carried out under conditions of weather and fuel that are selected to ensure a safe and efficient burn. Formal prescriptions for burning in fynbos do not exist, but air temperature and days since last rain are the most important factors currently used to select days for burning. The conditions currently favoured by managers for burning were used to define preliminary prescriptions. Strict selection for time since last rainfall currently limits the number of suitable days available but could become less important if strict attention is given to other factors. Suitable conditions of wind, temperature and humidity will also limit the number of days suitable for burning. The seasonal occurrence of prescribed conditions were examined at seven weather stations in four zones of fire climate in the fynbos biome. Burning should take place in March and April in the inland zones, but may be undertaken from November to April in the southwest coastal zone. Fires in the humid southeast coastal zone should take place only when the desired fire intensity can be achieved. This may be in winter or summer, but more research is needed to determine the optimum season in this zone. Suitable burning days are rare in the recommended seasons and suggestions for the efficient use of available burning days are made.

INTRODUCTION

The fynbos mountain catchment areas controlled by the Forestry Branch of the Department of Environment Affairs are managed by burning to ensure a sustained yield of high quality water, to reduce fire hazard, to control woody weeds and to rejuvenate the fire-adapted vegetation. Early management of these areas consisted mainly of protection from fire. This proved both impractical and ecologically unwise, and a policy of prescribed burning was adopted (Bands 1977). Green (1981) defines prescribed burning as the application of fire to wildland fuels under specified conditions of weather, fuels and topography so that specific objectives are accomplished safely.

The policy on the season of burning in the western Cape was outlined during 1970 (unpublished records, Forestry Branch). The correct fire season was given as late summer or early autumn, because most plant species have produced seed and are dormant by then. It would have been risky, however, to burn then as much of the vegetation, having been protected from fire in the past, was old with heavy fuel loads. Burning was therefore provisionally restricted to late autumn, after the first good rains, or early spring, after the vegetation had become sufficiently dry to support a burn. Subsequent research on the effects of fire season (Bond 1984, van Wilgen and Viviers 1985) has shown the need to burn in the summer or early autumn in many areas.

This period coincides with the occurrence of peak fire danger in most areas (van Wilgen and Burgan 1984). Managers are faced with the problem of burning at such times and yet ensuring the safety of workers and property, through control of fires. The selection of suitable burning days is currently based on the experience of field managers. Firebreaks have been burnt since 1880 in places (Kruger 1982), but official instructions have always prohibited burning in hazardous seasons. Large compartment burns have been undertaken since about 1970. The emphasis has been on safety and calm, moderate conditions a few days after rain in spring or late autumn have been favoured.

Two major problems face the catchment manager when decisions on burning must be taken. Firstly, there are no detailed prescriptions of weather conditions under which burning operations can be conducted effectively and with acceptably small risk. The most important factors affecting fire behaviour are fuel loads, relative humidity and rainfall (through their effect on fuel moisture content), wind speed and direction and air temperature. Ranges of these parameters within which burning should take place need to be established. Secondly, there is the problem of anticipating changes in weather after commencement of the burning operation. Changes in wind speed and direction, in particular, during a burning operation can cause fires to escape.

Five zones of fire climate have been defined in the fynbos biome (Van Wilgen 1984). Potential fire behaviour in different seasons in these zones varies. Given similar fuel conditions in each zone, weather conditions required to ensure safe and effective burns should be similar as well. Prescriptions may vary between zones with regard to acceptable seasons and the frequency of occurrence of weather within prescribed limits, however. These zones should therefore be treated separately.

In this study we investigated the conditions currently favoured by managers for burning and the factors that have influenced the decision to burn. The occurrence of the most prevalent selected conditions is examined in four fire climate zones in the region to determine the feasibility of using the prescriptions during a given season.

METHODS

The conditions under which burning operations are conducted were determined from fire records and observations at burns. The dates of 104 burning operations within two kilometers of weather stations at Jakkalsrivier, Jonkershoek, Kogelberg and Zachariashoek (see Table 1) were drawn from Departmental records, and weather data on the day of the fire and rainfall figures for preceding days were obtained. In addition, periodic measurements of air temperature, relative humidity and wind speed were

TABLE 1 : Salient features of weather stations from which data during burning operations were obtained

Station	Position	Date Established	Mean Annual Rainfall (mm)	Altitude (m)
Jakkalsrivier	34°10'S 19°10'E	1966	961	660
Jonkershoek (Swartboschkloof)	33°57'S 18°55'E	1975	1700	425
Kogelberg	34°16'S 19°01'E	1976	1150	110
Zachariashoek	33°49'S 19°02'E	1968	1210	750

taken at 10 burns that were visited. The date of last rainfall was obtained from the nearest weather station. The day of the week on which each burn was carried out was noted and the percentage of burns for each day was calculated for the 114 burns.

Principal components analysis (P.C.A.) was used to examine the variables air temperature (AIRTEMP), relative humidity (RH), wind speed (WIND) and number of days since last rain (LASTRAIN) for each burn, to determine the major factors currently influencing the decision to burn. The principal eigenvector of the correlation matrix was extracted using the PROC FACTOR routine of SAS (Ray 1982). Components were retained if their corresponding eigenvalues were greater than one (Ray 1982).

Preliminary prescriptions were defined based on the most prevalent conditions selected during burning operations. The mean seasonal (monthly) occurrence of conditions within prescription at representative weather stations in each of four fire climate zones was determined using programmes developed by Bradshaw and Fisher (1981). Details of the weather stations from which data were analysed are given in Table 2. Bradshaw and Fisher´s methods require that a preferable (narrow) range, and an acceptable (wider) range of conditions should be defined. The number of parameters chosen can vary but if more parameters are specified the chances of meeting prescriptions decreases. The occurrence of the suitable range of each parameter was compared with its

TABLE 2 : Salient features of weather stations in the fynbos biome selected for analysis

Station	Position	Fire climate zone[*]	Mean annual Rainfall (mm)	Altitude (m)	Length of record (months)
De Keur	32°58'S 19°18'E	Western inland	597	955	60
Wolseley	33°27'S 19°12'E	Western inland	601	274	108
Elgin	34°08'S 19°02'E	Southwest coastal	967	335	144
Jakkalsrivier	34°10'S 19°10'E	Southwest coastal	961	660	84
Oudtshoorn	33°38'S 22°15'E	Eastern inland	252	332	155
Outeniqua	33°55'S 22°25'E	Southeast coastal	663	204	196
Joubertina	33°47'S 23°35'E	Southeast coastal	475	617	178

[*] (after van Wilgen, 1984)

overall occurrence to determine which parameters are most limiting.

RESULTS

Weather data for the 104 burns are summarised in Figure 1. Most burning operations took place when the maximum air temperature was between 20 and 28 °C, the mean wind speed between 4 and 12 km hr^{-1}, and between two to six days after the last rainfall. There was a wide range of minimum relative humidity during burns. Final communality estimates from the P.C.A. revealed that the variable WIND was not well accounted for by components retained in the initial analysis and this variable was omitted from subsequent analyses. Two principal components (Table 3) summarise data categorising the considerations that governed the decision to burn. The components together explain 88,34% of the variation in the data. Component I is a contrast between RH, with a loading of 0,89896, and TEMP, with a loading of -0,89128, and reflects the relationship between these variables. Component II has a very large positive loading (0,98747) for LASTRAIN and very small loadings on the remaining variables. The final commmunality estimates (Table 3) show that all variables are well accounted for by the two components. TEMP, RH and LASTRAIN have all influenced the decision to burn. TEMP and RH are related (see Discussion) and as no measurement of relative humidity is currently made before burning, TEMP must have been important in selecting conditions for burning. LASTRAIN is easily determined and has clearly influenced management decisions. Day of the week

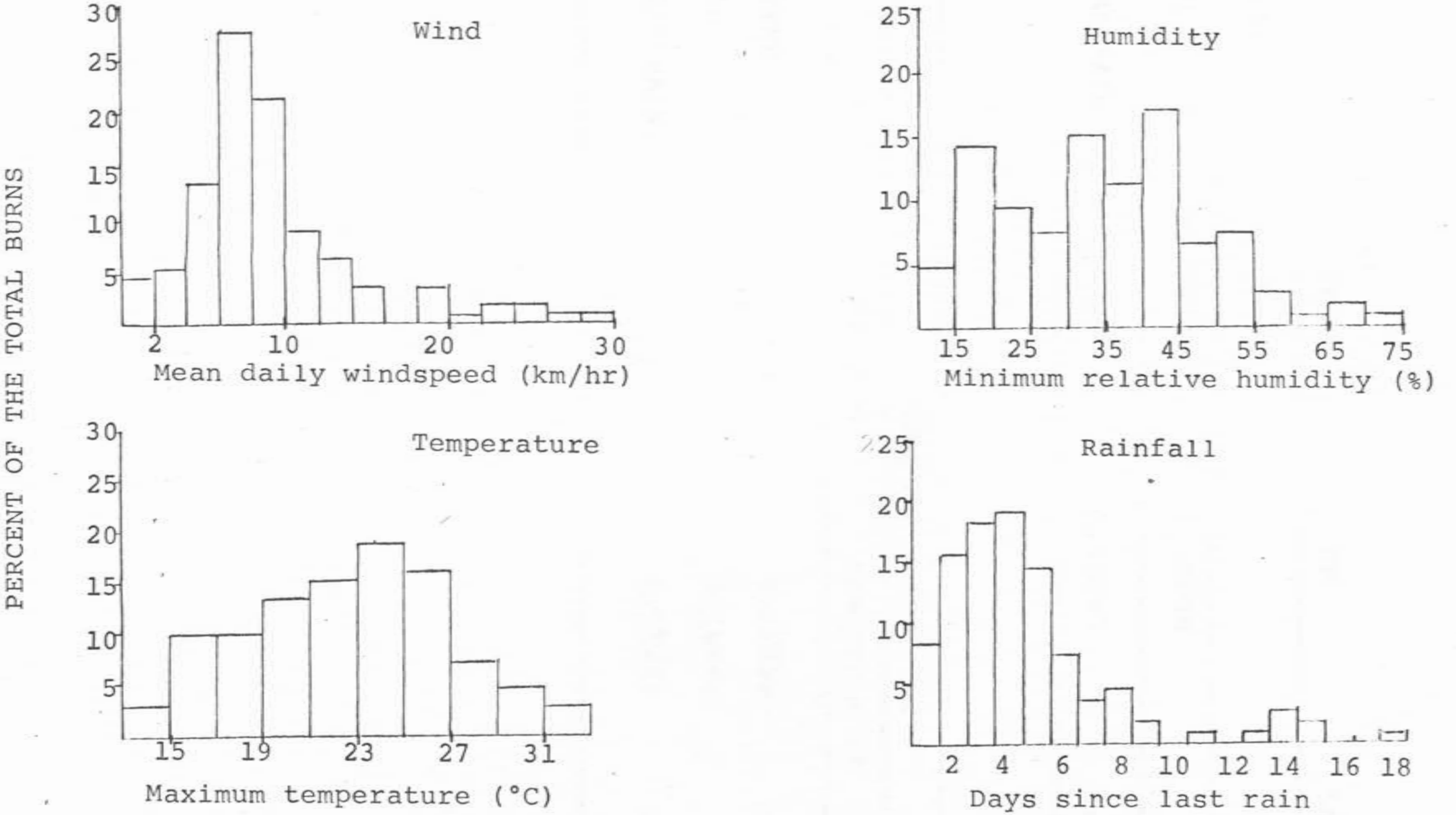


FIGURE 1 : Distribution of classes of four important fire weather parameters during 114 burning operations in the Western Cape Forestry Region.

TABLE 3 : Correlation matrix for the variables TEMP, RH and LASTRAIN for 114 burns in the fynbos. Component loadings and final communality estimates (h^2) for the variables are shown

	TEMP	RH	LASTRAIN
TEMP	1,00000		
RH	-0,60341	1,00000	
LASTRAIN	0,11117	0,13548	1,00000

Variable	Component loadings		Communality (h^2)
	Component I	Component II	
TEMP	-0,89128	0,20898	0,83805
RH	0,89896	0,16590	0,83565
LASTRAIN	0,03759	0,98747	0,97651

was also found to influence the decision to burn, as very few burns were carried out on Fridays and none on Saturdays or Sundays (Figure 2).

The ranges of preferred and acceptable conditions for prescribed burns used to determine the occurrence of suitable days are given in Table 4. Two sets of prescriptions are defined. One includes a restriction on days since last rain, while a second set excludes this but has more stringent requirements with regard to remaining parameters. Figures 3 to 5 and Table 5 show the overall occurrence of each parameter at the stations examined. The occurrence of preferable and acceptable days for prescribed burning for both sets of prescriptions are depicted in Figures 5 and 6. Days on which all components of weather are within the preferable prescribed limits are rare, and seldom exceed more than 3 days per month. Acceptable days, with less stringent requirements, are obviously more common but the frequency varies with region.

DISCUSSION

Climatic variables affecting fire behaviour

(i) Wind speed is probably the single most important factor determining fire behaviour. Unfortunately wind is the factor most difficult to forecast accurately and it causes most problems

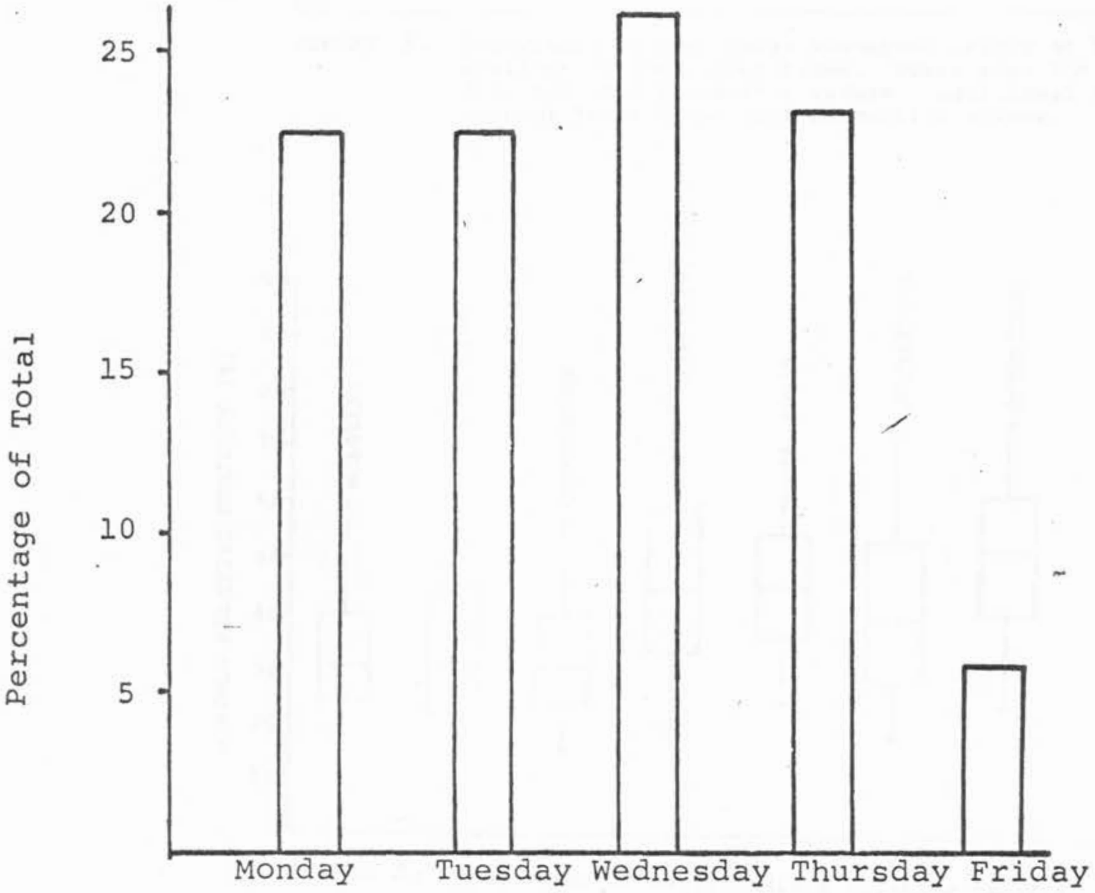


FIGURE 2 : Selection of days of the week for burning operations. The number of burns carried out on each day of the week is expressed as a percentage of the total number of burns examined (h = 114)
No burning was done over weekends

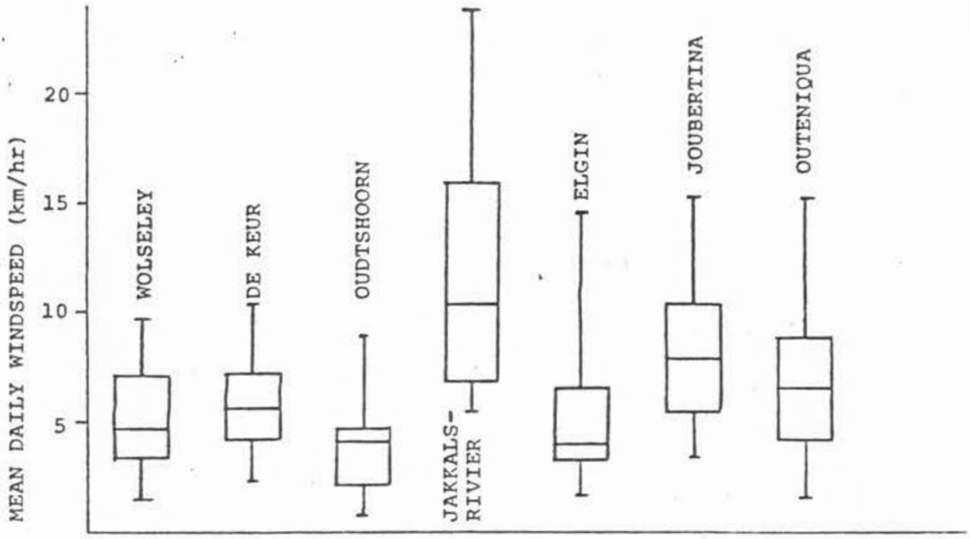


FIGURE 3: Occurrence of mean daily windspeed values at 7 weather stations in the fynbos biome. Boxes show the median, 25th and 75th percentile values. Additional lines connect the 5th and 95th percentile values.

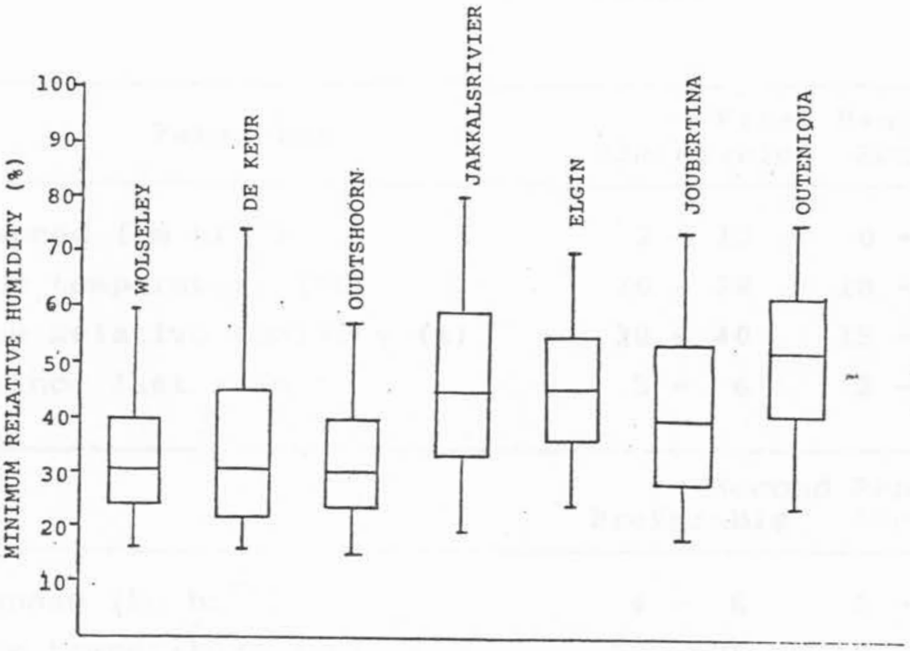


FIGURE 4: Occurrence of daily minimum relative humidity values at 7 weather stations in the fynbos biome. Boxes show the median, 25th and 75th percentile values. Additional lines connect the 5th and 95th percentile values.

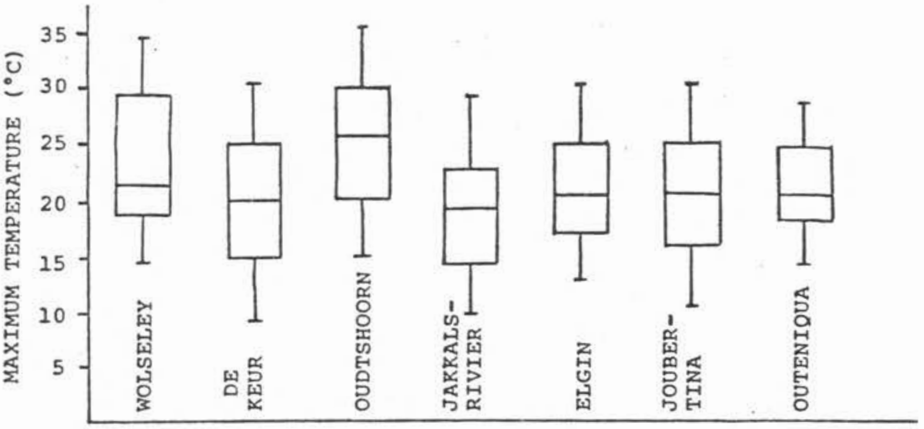


FIGURE 5: Occurrence of daily maximum temperature values at 7 weather stations in the fynbos biome. Boxes show the median, 25th and 75th percentile values. Additional lines connect the 5th and 95th percentile values.

TABLE 4 : Ranges of preferable and acceptable burning conditions used in data analysis

Parameter	First Range	
	Preferable	Acceptable
Wind speed (km hr^{-1})	2 - 12	0 - 14
Maximum temperature (°C)	20 - 28	18 - 28
Minimum Relative Humidity (%)	20 - 40	15 - 45
Days since last rain	3 - 6	2 - 8
	Second Range	
	Preferable	Acceptable
Wind speed (km hr^{-1})	4 - 6	0 - 8
Maximum temperature (°C)	20 - 26	18 - 28
Minimum Relative Humidity (%)	33 - 40	25 - 45

TABLE 5 : Percentage occurrence of rainy days and days since last rainfall at seven weather stations in the Fynbos Biome

Station	Rainy days	Days since last rain							Longest rainless period (days)
		1	2	3	4	5	6	7	
Wolseley	16.0	9.2	8.1	7.2	6.4	5.3	4.9	42.9	64
De Keur	16.7	9.1	8.4	7.5	6.5	5.6	5.0	41.2	56
Oudtshoorn	10.9	6.7	6.0	5.6	5.2	4.8	4.5	56.3	78
Jakkals-rivier	27.1	14.4	12.1	9.9	7.9	6.2	4.7	17.7	33
Elgin	21.7	13.2	11.2	9.2	7.8	6.2	5.3	25.4	35
Joubertina	19.1	13.0	11.2	9.7	8.2	6.8	5.4	26.6	34
Outeniqua	22.9	14.5	12.3	10.1	7.9	6.3	5.1	20.9	35

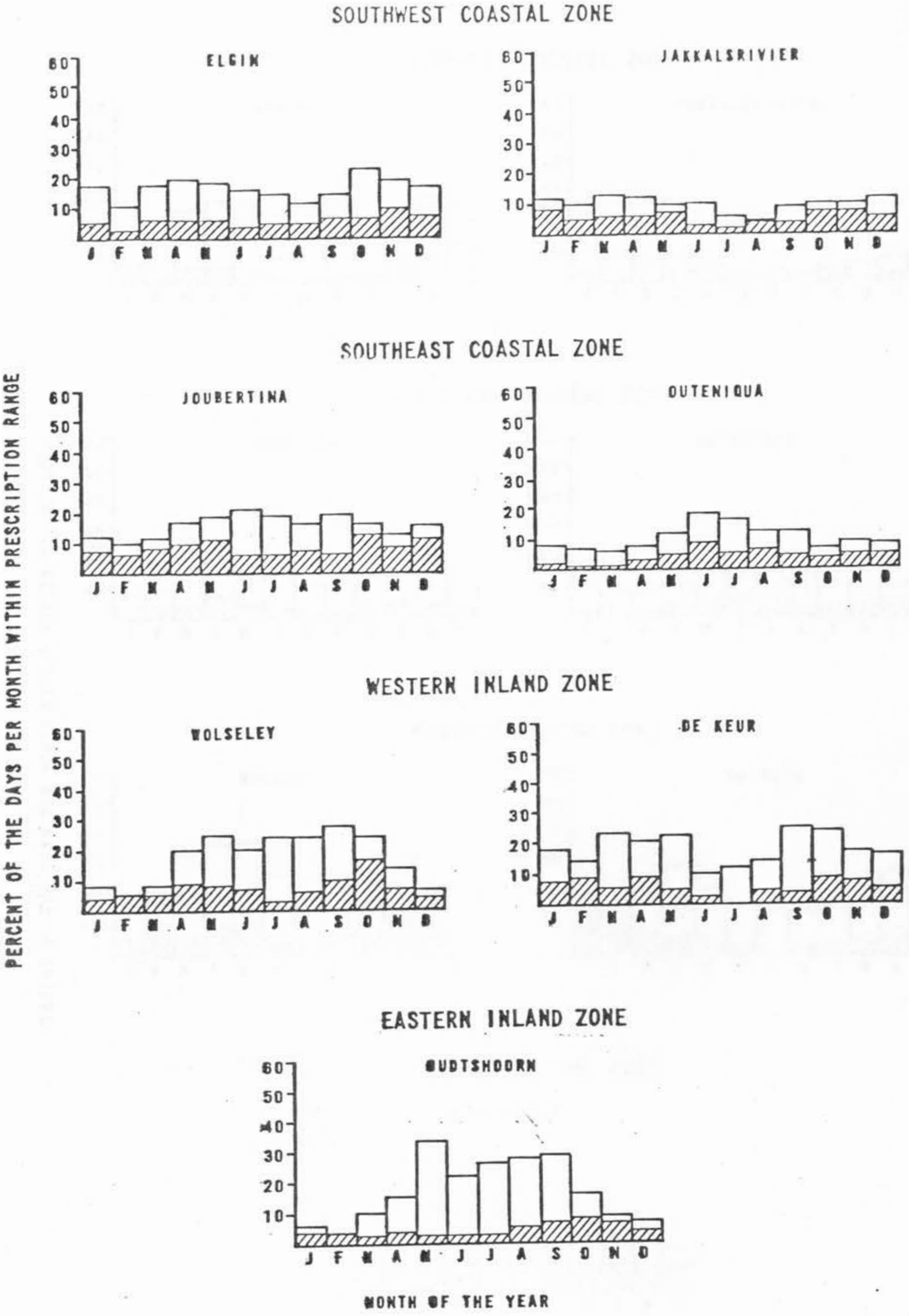


FIGURE 6: Percentage monthly occurrence of suitable burning days at seven weather stations in four fire climate zones using four prescription factors (first range) Table 4). Shaded portions represent preferable days; unshaded parts represented acceptable days.

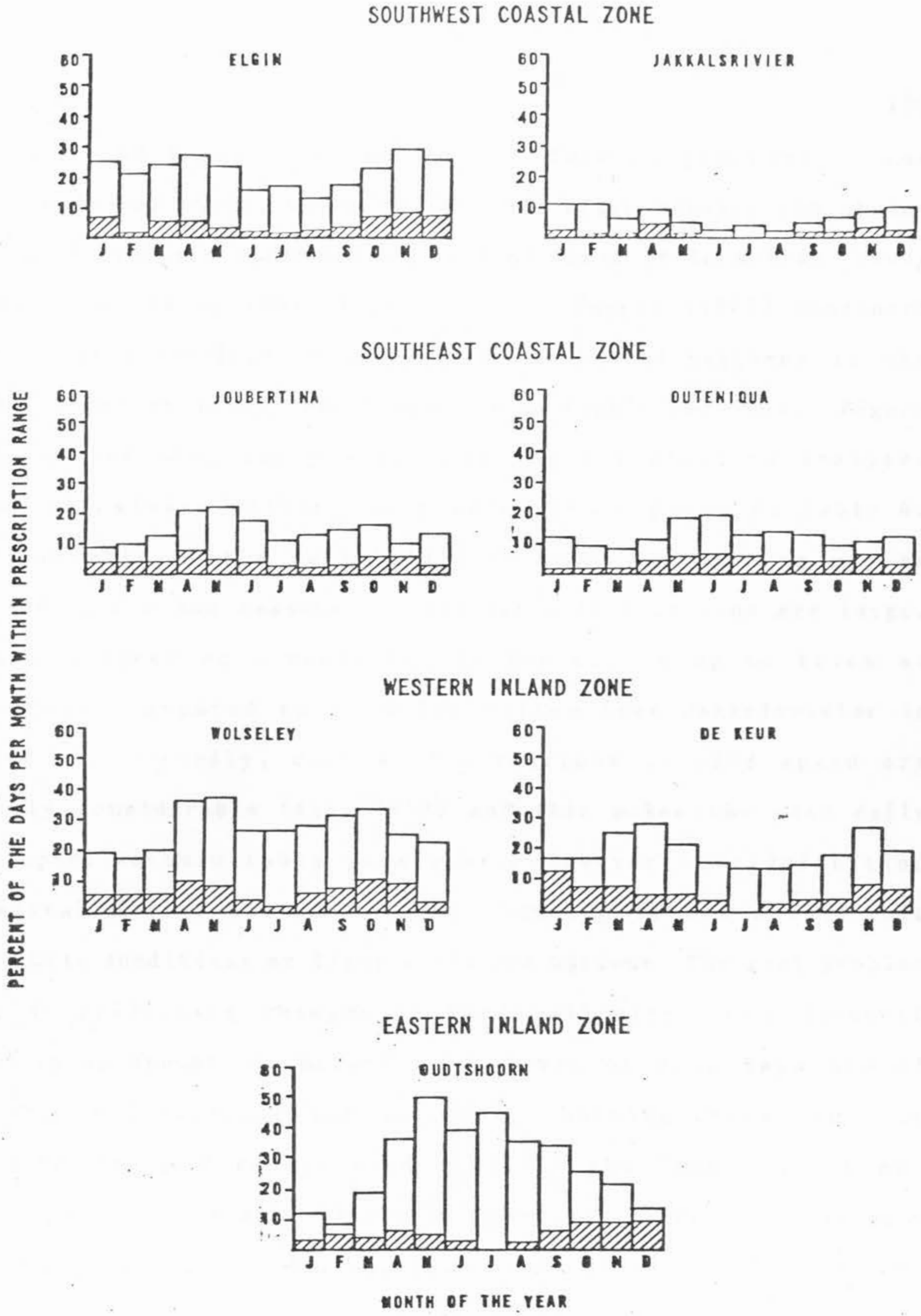


FIGURE 7 : Percentage monthly occurrence of suitable burning days at seven weather stations in four fire climate zones using three prescription factors (second range, Table 4). Shaded portions represent preferable days; unshaded parts represent acceptable days.

in prescribed burning (Green 1981). This is especially true for the fynbos biome, where local winds often enhance the channelling of synoptic scale winds, so that zones of localised strong winds occur (King 1957, Fuggle 1981). Fuggle (1981) concluded that it is impossible to generalise about wind patterns in the fynbos biome as local conditions are so highly variable. Figure 3 shows that mean daily wind speed at the stations analysed is almost always within the prescriptions given in Table 4. This analysis of the suitability of days for burning may be misleading for two reasons. Local variations in wind are large. Mean wind speed at a mountain station can be up to twice as great when compared to a valley bottom (see Jakkalsrivier in Figure 2). Secondly, diurnal fluctuations in wind speed are usually considerable (King 1957) and this makes the mean daily wind speed an unsuitable parameter. However, the definition of suitable wind speeds for safe burning is not a difficult task. Calm conditions or light winds are optimum. The real problem lies in predicting changes in wind following commencement of the burning operation. Accurate forecasts of calm days are of the utmost importance for successful burning operations. It is difficult to forecast wind speed in the Cape, but it may be easier to forecast relatively calm conditions, and managers should concentrate on this aspect.

(ii) Relative humidity affects fire behaviour through its effect on the moisture content of fine fuels. Relative humidity, although found to be important in governing the decision to burn, is not measured by managers and a wide range was noted at burns (Figure 1). Unlike wind or temperature, relative humidity is impossible to assess without measurement. By measuring this parameter, the selection of suitable burning days could be much improved.

Weather forecasts usually give predicted maximum temperatures but not predicted minimum humidity. In order to use minimum relative humidity as a prescription factor, a predicted value should be calculated. Figure 8 shows the relationship between temperature and relative humidity (Gedzelman 1980). These relationships can be preprogrammed into hand-held calculators. If the current temperature and relative humidity are known, a predicted minimum relative humidity for the day can easily be estimated using the forecast maximum temperature. This will establish whether conditions will be within prescription assuming that the air mass will not change (for example through the movement of fronts) causing a change in the amount of moisture in the atmosphere.

Minimum relative humidity is generally lower in inland regions than in coastal regions (Figure 4). The median minimum relative humidity at both De Keur and Oudtshoorn is 31%, while at Elgin it is 46% and at Outeniqua it is 52%. This means that many days in the coastal zones will fall outside the prescribed range

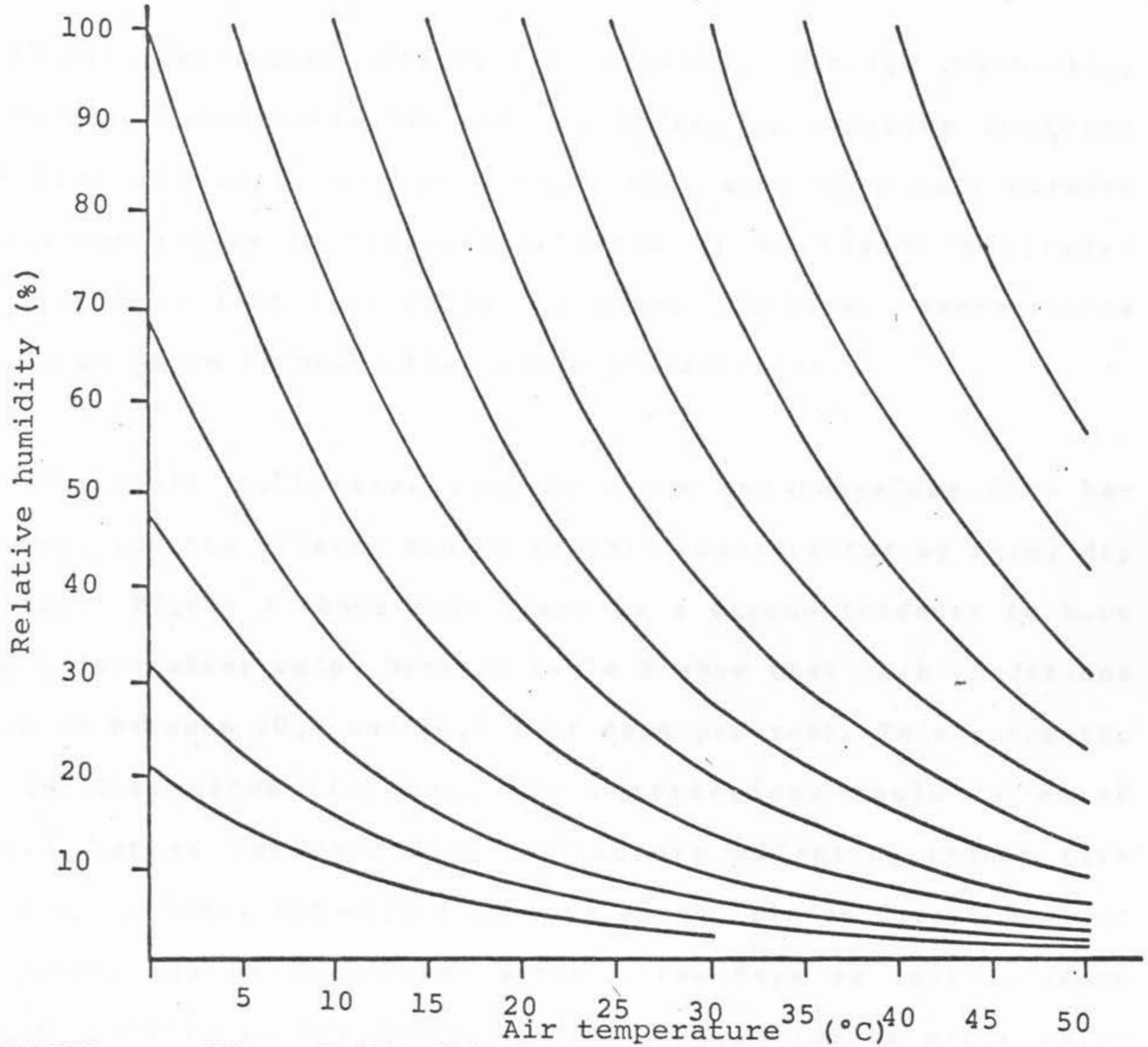


FIGURE 8: The relationship between air temperature and relative humidity for a parcel of air at 1000mb pressure

due to humid conditions, while relative humidity will be less limiting inland.

(iii) Air temperature affects fire behaviour through pre-heating of fuel and indirectly through its effect on relative humidity and fuel moisture. Figure 5 shows that many days fall outside prescribed ranges in the coastal zones or at higher altitudes (De Keur) so that this factor is often limiting. Temperatures will more often be below than above prescription.

(iv) Rainfall influences fuel moisture and therefore fire behaviour, but the effects can be quickly counteracted by warm, dry weather. Figure 1 shows that there is a strong tendency to burn 3 to 4 days after rain. Data in Table 5 show that such conditions occur on between 10,8 and 18,0 % of days per year. This parameter is therefore often limiting, but restrictions could be eased when a better understanding of factors affecting fynbos fire behaviour exists. The effect of days since rain on fire behaviour in fynbos may be irrelevant after a few days as fuel moisture adjusts quickly to dry conditions when these follow after rain. Days since last rain is a concept more appropriate to silvicultural burns, such as those conducted to remove debris while preserving the humus layer. It is nonetheless the only parameter currently accepted as a prescription for conducting fires in natural vegetation.

Occurrence of suitable burning days

(i) Western inland zone. Figure 6 shows the occurrence of suitable days where a restriction has been placed on days since last rain. The highest percentage of acceptable days occurs in spring and autumn. The chance of encountering a suitable day is increased if the restriction on rainfall is done away with and replaced by more stringent restrictions on the remaining factors (Figure 7). This approach should therefore be encouraged. For this zone, fire is preferable in late summer - early autumn (van Wilgen and Viviers 1985). More than 20% of the days in March and April are generally suitable for burning in this zone. This should be sufficient to allow the burning programme to be completed as approximately five burns will be carried out at each station per year. Spring burning should be discouraged because of its adverse effects on fynbos plant species.

(ii) Southwest coastal zone. This zone has fewer suitable days than the western inland zone because of relatively cool, humid conditions. Fires in this zone can be scheduled for the period November to April however, as fire hazard in the summer months is not as extreme as that in inland areas (van Wilgen and Burgan 1984). Although suitable days are rarer, the extended permissable season should allow for completion of work programmes.

(iii) Eastern inland zone. Preferable burning days are very rare, but acceptable days are sometimes frequent. Bond et al's (1984) study on the response of Proteaceae indicates that fires in late summer - early autumn (March and April) result in maximum regeneration in this zone, while fires in spring result in very poor regeneration. There should be sufficient suitable days in these two months to allow for completion of the burning programme provided that the suitable weather is efficiently utilised. Although a higher frequency of suitable days occurs in the late autumn and winter, poor regeneration of Proteaceae makes prescribed burning in this period undesireable. Burning in midsummer would probably be impractical.

(iv) Southeast coastal zone. As is the case in the southwest coastal zone, suitable days are rare and seasonal fluctuations are not marked. Attempts to burn vegetation in the Outeniqua mountains in summer often fail as conditions are too humid. Natural fires in this zone would have occurred in summer during dry years or occasionally in winter following bergwinds. Fires should be concentrated in dry years, when they would probably have occurred before man altered the fire regime. Burning could feasibly take place in summer or winter. By selecting conditions which will lead to fairly intense fires, effective fuel reduction will also be achieved. The effects of fire season on the vegetation in the southeast coastal zone require investigation in order to refine seasonal burning prescriptions.

CONCLUSIONS

For all areas in the fynbos biome, suitable burning days are rare. Finding enough suitable days to burn is thus a major problem and practical solutions to this problem need to be found. When planning prescribed burns, it is important to assess the suitability of weather from day to day. As successful fires depend on suitable weather conditions, they cannot be planned far in advance. Other management operations should be scheduled so that when conditions are within the prescribed range, highest priority can be given to burning. A future policy may require that burns should be carried out during favourable weather conditions even if these occur over weekends or on public holidays. No burning is done on weekends and managers are reluctant to burn on Fridays (Figure 2). This means that many suitable days are lost. Enhanced utilization of available burning days will greatly improve the feasibility of burning in the correct season. Burning operations in mountain catchment areas can be divided into large scale compartment burns and firebreak burns. Further savings of suitable days could be made by sheduling firebreak burns for seasons not suitable for compartment burns. The aim of burning firebreaks is to reduce biomass; the maintenance of species diversity is not an issue. If firebreaks were burned under suitable weather conditions outside the recommended season, then suitable burning days could be better utilised for compartment burns in the recommended seasons.

Conservation objectives will only be achieved if burning operations are conducted in the ecologically acceptable seasons. The seasonal restrictions on burning operations adopted by most authorities up to now have been based on safety considerations and have not considered ecological consequences, as these were poorly understood. The need for caution is understandable but policies should be revised to accommodate recent advances in the understanding of the seasonal effects of fire. Burning conditions should not be prescribed solely, or predominantly, in relation to ease of control. If this is done, objectives for which burning is carried out in the first place will be forfeited. The seasonal distribution of prescribed burns in the western Cape forestry region is shown in Figure 9. This distribution results from selection of relatively cool moist days for burning operations. In exceptional cases where burning has been prescribed in periods such as March or November for research purposes (van der Zel and Plathe 1969, van Wilgen and Kruger 1981), burns were carried out safely, indicating that a less strict seasonal approach is feasible.

The ranges of conditions presented here are not meant to be used as fixed prescriptions. They should rather be seen as a starting point from which prescriptions can be developed through continual updating as experience accumulates. However, the greatest problem the fire manager has to cope with relates to changes

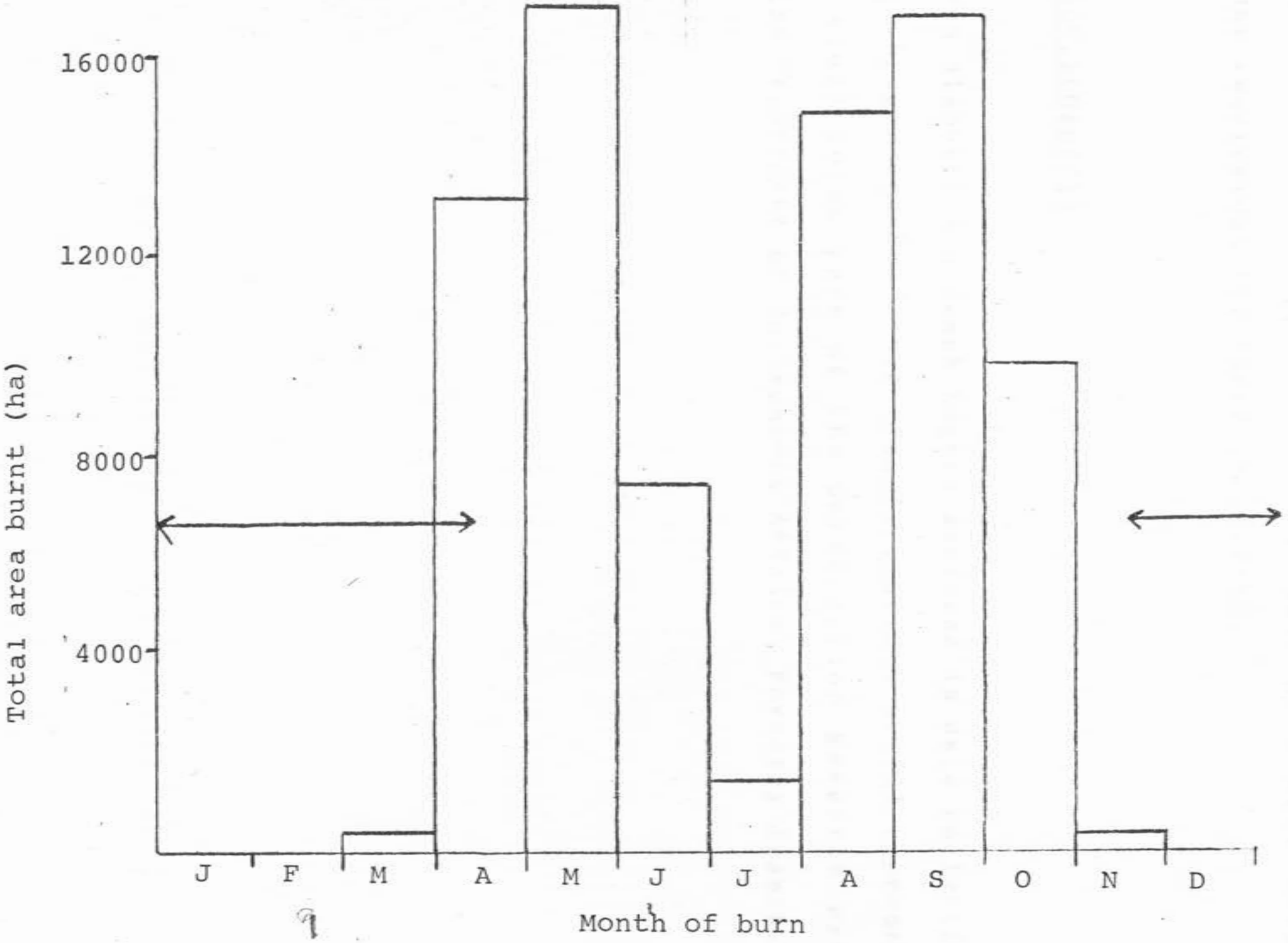


FIGURE 9: Seasonal distribution of the area burnt in burning operations in the western inland zone between 1978 and 1983. Arrows show the ecologically desireable burning period.

in weather. Careful documentation of experience in this field is required to assess the possibility of anticipating changes in local fire weather. The establishment of a data base is an urgent requirement for sound management.

ACKNOWLEDGEMENTS

Gideon Slabbert and Frank Rogers assisted in data collection. Mr. F.J. Kruger and Prof. R.F. Fuggle provided useful comments.
The study forms part of the Conservation Research Programme of the Department of Environment Affairs, Forestry Branch.

REFERENCES

Bands, D.P. (1977). Prescribed burning in Cape Fynbos Catchments. Proceedings of the Symposium on the Environmental Consequences of Fire and Fuel Management in Mediterranean Ecosystems (ed. by M.A. Mooney and C.E. Conrad), pp. 245 - 256. USDA Forest Service, Technical Report W03.

Bond, W.J. (1984). Fire survival of Cape Proteaceae - influence of fire season and seed predators Vegetatio.56, 65-74.

Bond, W.J., Vlok, J., and Viviers, M. (1984). Variation in seedling recruitment of Cape Proteaceae and its causes. Journal of Ecology 72, 209 - 221.

Bradshaw, L.S. and Fisher, W.C., (1981). A Computer system for scheduling fire use. USDA Forest Service, Technical Report INT-91.

Fuggle, R.F., (1981). Macro-climatic patterns within the fynbos biome. Unpublished report, Fynbos Biome Project.

Gedzelman, S.D., (1980). The science and wonders of the atmosphere. John Wiley and Sons, New York.

Green, L.R., (1981). Burning by prescription in chaparral. USDA Forest Service, Gen. Tech. Rep. PSW-51.

King, N.L., (1957). Meteorological aspects of forest fire danger rating South African Forestry Journal 29, 31 - 38.

Kruger, F.J. (1982). Use and management of mediterranean ecosystems in South Africa - current problems. In: Conrad,C.E. and Oechel, W.C. (Eds.) Dynamics and management of mediterranean-type ecosystems. USDA Forest Service, General Technical Report PSW-58.

Ray, A.A. (1982). (Editor) SAS User´s Guide : Statistics. SAS Institute, Cary, North Carolina. 584 pp.

Rothermel, R.C.(1972) A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service, Research Paper INT-115.

Van der Zel, D.W., and Plathe, D.J.R., (1969). `n Veldbrand eksperiment op meervoudige opvanggebiede in Jakkalsrivier, Lebanon. Forestry in South Africa 10, 63 - 69.

Van Wilgen, B.W., and Kruger, F.J., (1981). Observations on the effects of fire in mountain fynbos at Zachariashoek, Paarl. Journal of South African Botany 47, 195 - 212.

Van Wilgen, B.W. (1984). Fire climates in the southern and western Cape Province and their potential use in fire control and management. South African Journal of Science 80, 358-362.

Van Wilgen, B.W., and Burgan, R.E., (1984). Adaptation of the United States Fire Danger Rating System to fynbos conditions. II. Historic fire danger in the fynbos biome. South African Forestry Journal 129, 66-78.

Van Wilgen, B.W., and Viviers, M., (1985). The effect of season of fire on serotinous Proteaceae in the western Cape and the implications for fynbos management. South African Forestry Journal 133

Paper 8. The effect of alien shrub invasions on vegetation structure and fire behaviour in South African fynbos shrublands: a simulation study. <u>Journal of Applied Ecology</u> 22 (3) (in press).

Journal of Applied Ecology (1985) **22,** 000–000

THE EFFECTS OF ALIEN SHRUB INVASIONS ON VEGETATION STRUCTURE AND FIRE BEHAVIOUR IN SOUTH AFRICAN FYNBOS SHRUBLANDS: A SIMULATION STUDY

BY B. W. VAN WILGEN AND D. M. RICHARDSON

South African Forestry Research Institute, Jonkershoek Forestry Research Centre, Private Bag 5011, Stellenbosch 7600, South Africa

SUMMARY

(1) South African fynbos vegetation is fire-prone and susceptible to invasion by alien shrubs. Alien shrubs change the nature of the fuel bed and thus affect fire behaviour.

(2) Changes in biomass, size and distribution of plant parts as fuel and plant moisture and energy contents were determined at two sites invaded by the important alien shrubs *Hakea sericea* Schrad. and *Acacia saligna* (Labill.) Wendl.

(3) The data were used to define fuel models and to simulate fire behaviour using Rothermel's fire model. This simulation was used to test the hypothesis that invasion increases fire hazard through increasing fuel loads.

(4) Invasion by *H. sericea* resulted in a 60% increase in fuel load and lowered the moisture content of live foliage from 155 to 110%. Simulated rates of fire spread and intensity were nonetheless lower than in fynbos due to a densely-packed fuel bed.

(5) Invasion by *A. saligna* resulted in a 50% increase in fuel load. The high moisture content of foliage of this shrub (about 270%) effectively reduce the fuel load and fuel bed depth, resulting in low rates of fire spread and intensity in the simulation.

(6) Shortcomings in Rothermel's model prevented the accurate simulation of high intensity fires which have occurred in invaded areas under extreme weather conditions. Such fires vigorously consume the increased biomass of shrub crowns, are difficult to control and are potentially more damaging to ecosystems than fires in natural vegetation. Under such conditions, the fire hazard will be increased by invasion.

INTRODUCTION

The sclerophyllous shrubland vegetation of the south-western Cape Province of South Africa is known locally as fynbos. The name is derived from the Afrikaans term for 'fine' and 'bush', reflecting the finely-divided and bushy nature of the vegetation. Most remaining fynbos vegetation occurs in mountain areas which are managed as water catchments and for nature conservation. Fires occur in fynbos vegetation at intervals of between 6 and 40 years (Kruger & Bigalke 1984). Fynbos vegetation is fire-adapted (Bond 1980; van Wilgen 1982) and fire is necessary for species survival, but fires also cause control problems in semi-developed areas.

Alien woody weed species invade fynbos with remarkable success in many areas. They often form dense and impenetrable stands which dominate the vegetation and replace native shrubs entirely. Kruger (1979) lists the major disadvantages of such invasions as: (i) drastic changes in natural community structure, including reduction in species diversity; (ii) increase in fire hazard through increased fuel loads and decreased accessibility; (iii) reductions in surface water resources; and (iv) reduction in aesthetic, recreational and scientific values of fynbos communities. Macdonald & Jarman (1984) list thirty-three species of invasive plants which pose a threat to fynbos ecosystems. These were ranked according to the extent of current infestation and their potential as invasive species. The small Australian tree *Acacia saligna* (Labill.) Wendl. (Fabaceae) is listed as posing the greatest threat to fynbos ecosystems, while the Australian shrub *Hakea sericea* Schrad. (Proteaceae) has invaded the largest area. The management of fynbos consists largely of controlling and applying fire, and of controlling invasions of woody weed species.

The changes in vegetation structure brought about by invasion need to be quantified in order to assess their effect on fire hazard. The term 'fire hazard' is concerned with the condition of fuel and takes into consideration such factors as quantity, arrangement, current or potential flammability and the difficulty of suppression if fuel should be ignited (Luke & McArthur 1977). Potential fire behaviour is central to the fire hazard rating problem and it will be changed by changes in vegetation structure. Some data on fire behaviour in fynbos are given by Van Wilgen, Le Maitre & Kruger (1985), who obtained reasonable estimates of fynbos fire behaviour using Rothermel's (1972) fire model. A review of the development of this model, its uses and limitations is given by Albini (1984). The model requires estimates of the physical and chemical makeup of the fuel, and the environmental conditions under which it burns. Fuel characteristics are summarized in fuel models, which are sets of values that quantify vegetation stands as fuel beds. The following data are required to define a fuel model (Deeming & Brown 1975): (i) Fuel loads (biomass) divided into dead and live components. Dead fuel is further divided into size classes and live fuel into herbaceous or woody (leaves and twigs < 6 mm diameter only) components. Dead fuel size classes are based on the time their moisture content takes to adjust to changes in atmospheric conditions, and are 1 h timelag fuels (0–6 mm), 10 h timelag fuels (6–25 mm), 100 h timelag fuels (25–75 mm) and 1000 h timelag fuels (>75 mm); (ii) Surface area to volume ratios of the above fuel components; (iii) The fuel bed depth; (iv) A mean fuel energy content for the combined fuel mass. Structural changes due to invasion can be incorporated into fuel models and comparisons can be made by estimating fire behaviour for different structural categories of vegetation under identical weather conditions.

This study was aimed at quantifying changes in above-ground biomass, stratification, height, the size of plant parts as fuel and plant moisture and energy contents brought about by converting pristine fynbos vegetation to vegetation dominated by *H. sericea* or *A. saligna*. The data are used to define fuel models for the invaded sites. Estimates of fire behaviour in invaded areas are compared to estimates using a fynbos fuel model (van Wilgen 1984), to test Kruger's (1979) hypothesis that fire hazard is increased through increased fuel loads brought about by invasion.

THE STUDY AREAS

Biomass and structure of invaded areas were determined at two 50 × 50 sites. The first is situated on the Vergelegen Estate, where there was a heavy infestation of *H. sericea* (*c.* 8900 stems ha^{-1}). The presence of scattered individuals of the native shrubs *Protea repens* (L.) L. and *P. neriifolia* R. Br. and comparison with adjacent uninvaded areas indicated that the original vegetation was a tall shrubland dominated by these two species. The second site was situated on a rocky slope above the town of Muizenberg. The original fynbos vegetation in the area had been replaced through invasion by *A. saligna* (*c.* 9800 stems ha^{-1}). The data from invaded sites were compared to data from two pristine fynbos sites in the Kogelberg and Cederberg Forest Reserves. Previous studies on these sites include the development of a fynbos fuel model (van Wilgen 1984) and the measurement of fire behaviour (van Wilgen, Le Maitre & Kruger 1985). Salient features of these four sites are given in Table 1.

TABLE 1. Principal features of four sites used to determine fuel models in pristine and invaded fynbos vegetation

Site	Vegetation	Position	Geology	Mean annual rainfall (mm)	Altitude (m)	Slope (%)	Aspect	Vegetation post-fire age (years)
Vergelegen Estate	*Hakea*-invaded fynbos	34°02'S 18°56'E	Sandstone-granite mixtures	1200	375	0	—	9
Muizenberg	*Acacia*-invaded fynbos	34°04'S 18°27'E	Sandstone	1000	120	23	N.E.	20
Kogelberg	Fynbos	34°16'S 19°00'E	Sandstone	1020	110	0	—	18
Cederberg	Fynbos	32°20'S 19°03'E	Sandstone	660	470	17	E.	18

METHODS

Biomass and fuel loads of invaded areas

Biomass was determined by collecting all plant material, except for dominant alien shrubs, from a random sample of ten plots (2 × 2 m). Clipped material was divided into the following categories: (i) woody shrubs other than dominant shrubs; (ii) herbaceous (non-woody) plants; and (iii) litter (all dead material including standing dead). These categories were separated into pieces with diameters of less than and greater than 6 mm. This division followed the convention used in estimating available fuel in fuel models (Countryman & Philpot 1970; Deeming & Brown 1975; van Wilgen 1982). Estimation of the biomass of dominant alien shrubs was done by regression analysis. Twenty shrubs, selected to cover a representative range of diameters, were harvested outside the sites after measuring their diameters 10 cm above the ground. Each shrub was divided into potential fuel (pieces with diameters <6 mm) and larger pieces, weighed and then subsampled for moisture content to estimate the dry weight of the original material. Linear, power and exponential regressions of stem diameter on dry weight were fitted. In all cases power curves gave the highest r^2 values. The resultant equations for *H. sericea*, where x is the diameter (cm) and y the mass (g) were

(i) diameter and total dry weight:

$$y = 100{\cdot}76\, x^{2{\cdot}30},\ r^2 = 0{\cdot}95 \tag{1}$$

(ii) diameter and dry weight of fuel:

$$y = 80{\cdot}48\, x^{1{\cdot}83},\ r^2 = 0{\cdot}94 \tag{2}$$

A similar allometric model for *A. saligna* gave

(i) diameter and total dry weight:

$$y = 58{\cdot}67\, x^{2{\cdot}49},\ r^2 = 0{\cdot}99 \tag{3}$$

(ii) diameter and dry weight of fuel:

$$y = 19{\cdot}30\, x^{2{\cdot}00},\ r^2 = 0{\cdot}93 \tag{4}$$

The stem diameter of each *H. sericea* shrub occurring on two random transects of 50 × 2 m was measured and the dry mass of the shrubs calculated from eqns (1) and (2). The same procedure was followed on the second site for *A. saligna* using eqns (3) and (4).

Size of plant parts as fuel

Surface area to volume ratios were determined for the fuel component of the two invasive species. The diameter of twenty leaves of *H. sericea* were measured in two places using callipers, and a mean diameter was calculated. The leaves were regarded as cylinders for the purposes of calculating surface areas and volumes. The area of each of a sample of twenty leaves of *A. saligna* was calculated using a surface area meter. Leaf thickness was measured using callipers. Surface areas and volumes were calculated using these estimates.

Vegetation height and stratification

Data on vegetation height and stratification were obtained from a transect (1 × 10 m) at each of the invaded sites and from the Kogelberg site. The transects were positioned in an area with vegetation judged to be representative of the site. The following data were recorded on each transect: (i) Mean depth of the litter layer at 0·5 m intervals across the transect; and (ii) The height, crown diameter and height of the lowest leaves of each plant on the transect. Plants were recorded as either dominant shrubs (*A. saligna*, *H. sericea* or other microphyllous shrubs similar to the indigenous genus *Protea*), other microphyllous shrubs, picophyllous shrubs similar to the indigenous genus *Erica*, evergreen herbaceous plants similar to the indigenous genus *Restio* and standing dead plants. The data were used to draw profile diagrams and to define fuel bed depths.

Fuel moisture contents

The moisture content of foliage of *H. sericea* and *A. saligna* shrubs was compared to that of the indigenous shrub *Protea repens*. *Protea repens* is widespread and often dominant in fynbos vegetation, and it was used in defining the fynbos fuel model (van Wilgen 1984). A site where all three species grew within 20 m of each other was located in the Jonkershoek valley (33°57′ S, 18°55′ E). Five samples of the foliage of each species were taken on five different days in December 1984. Samples were sealed in air-tight bottles to prevent moisture loss, weighed and oven dried. The percentage moisture content was calculated on a dry weight basis.

Fuel energy contents

The energy contents of three samples of the foliage of both *H. sericea* and *A. saligna* were determined using standard bomb calorimetry.

Simulation of fire behaviour

Biomass and other structural data were used to define fuel models for each site. Fire behaviour predictions were made using a Texas Instruments TI-59 programmable calculator, equipped with a special module preprogrammed with Rothermel's fire spread model. Fuel models were entered on magnetic strips. Weather parameters and fuel moisture contents were then entered manually to produce fire behaviour estimates. The method is described by Burgan (1979).

RESULTS

Biomass and fuel mass of invaded areas

Biomass estimates for the two invaded sites and a mean biomass estimate for pristine fynbos from the Kogelberg and Cederberg sites are presented in Table 2. There was a marked increase in the biomass of the dominant shrub component following invasion. The *H. sericea* site had 4·4 times the dominant shrub biomass of the mean for fynbos sites, while that of the *A. saligna* site was 6·2 times that of fynbos. Estimates of the fuel component (<6 mm) of dominant shrubs were 5·2 and 2·4 times greater than fynbos for *H. sericea* and *A. saligna* respectively. The herbaceous component, normally considered to be potential fuel (Kruger 1977), was reduced to about one third of the amount found in pristine fynbos following invasion by *H. sericea*, and was almost eliminated following invasion by *A. saligna*. Similarly, understorey shrubs ('other shrubs' in Table 2) were reduced following invasion by *A. saligna* to less than half the biomass in fynbos, and to less than one third by invasions of *H. sericea*. Dead material increased 1·4 times following invasion by *H. sericea*, and 3·2 times with invasion by *A. saligna*. Overall, invasion of fynbos by *H. sericea* or *A. saligna* increased the fuel mass (all biomass with diameters <6 mm) by a factor of 1·6 and 1·5, respectively. Some of these differences may be attributed to site factors, but these figures support the general observation (Kruger 1979) that invasion by vigorous alien shrubs increases biomass and fuel mass.

Table 2. Above-ground biomass of vegetation components (g m^{-2}) in pristine and invaded fynbos

Vegetation	Pristine* fynbos	*Hakea*-invaded fynbos	*Acacia*-invaded fynbos
Dominant shrubs†			
>6 mm	445	1808	3532
<6 mm	210	1099	498
Other shrubs			
>6 mm	46	118	130
<6 mm	232	83	145
Herbaceous plants	376	130	9
Dead material			
>6 mm	71	50	358
<6 mm	404	639	1144
Total biomass	1784	3927	5816
Total fuel (<6 mm)	1222	1951	1796

* Mean of fourteen sites (van Wilgen, Le Maitre & Kruger 1985).
† Indigenous Proteaceae, *Hakea* or *Acacia*.

Size of plant parts as fuel

The mean surface area to volume ratios for the foliage of the two alien species are given in Table 3, together with a value for *P. repens* (van Wilgen 1984). The foliage of the three species is depicted in Plate 1. The surface area to volume ratio for *H. sericea* leaves was almost double that of *P. repens*, while that of *A. saligna* was about 1·4 times that of *P. repens*. Fine fuel particles (with larger surface area to volume ratios) will increase fire behaviour parameters such as rate of spread when compared to coarser fuel particles.

Vegetation height and stratification

Profile diagrams showing the height and stratification of vegetation at the three sites are given in Fig. 2. The increase in height following invasion by *A. saligna*, the increase in

TABLE 3. Mean surface area to volume ratios and energy contents of the foliage of one indigenous and two alien invasive shrubs. The figure in parentheses is the standard deviation of the mean ($n = 20$ for surface area to volume ratios, $n = 3$ for energy contents)

Species	Surface area to volume ratio ($m^2 m^{-3}$)	Energy content ($J g^{-1}$)
Hakea sericea	8456 (735)	18 302 (525)
Acacia saligna	6460 (862)	18 198 (883)
*Protea repens**	4523 (571)	21 984 (100)

* After van Wilgen (1984).

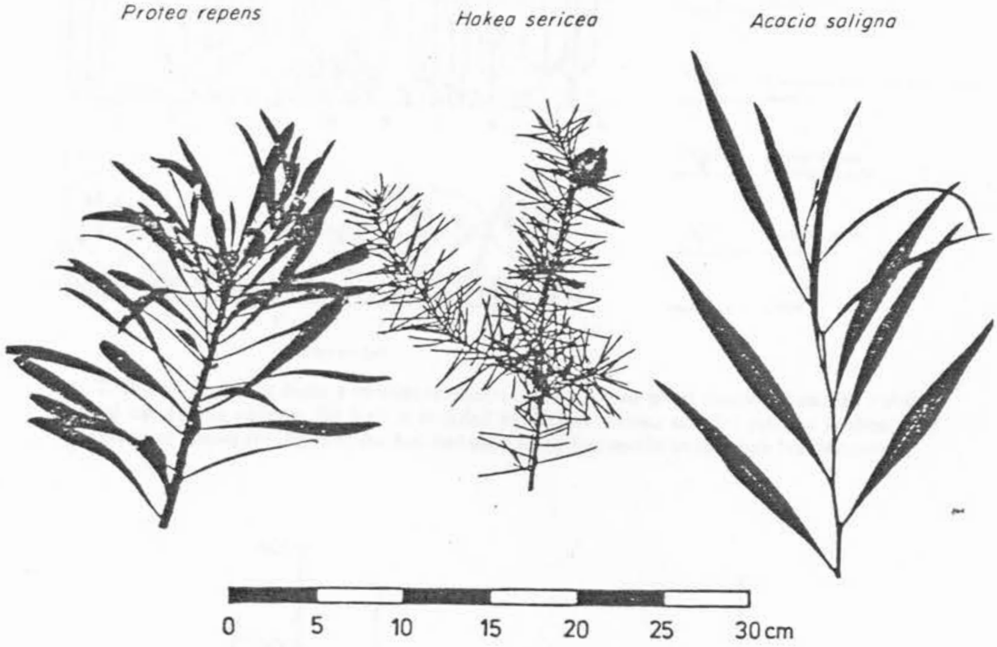


FIG. 1. Foliage of one indigenous and two alien invasive shrubs used to represent dominant species in pristine and invaded fynbos. The fruits of *Hakea sericea* were included in particles >6 mm in the biomass analysis.

foliage density following invasion by *H. sericea* and the reduction in the understorey component in both cases can clearly be seen.

Fuel moisture contents

Fluctuations in fuel moisture content of the three species sampled are depicted in Fig. 3. The moisture content of the three species differed significantly ($P < 0{\cdot}05$) on all days sampled. The moisture content of *H. sericea* remained at about 110%, while that of *P. repens* was about 155% and *A. saligna* about 270%. Differences in fuel moisture content should be taken into account when simulating fire behaviour.

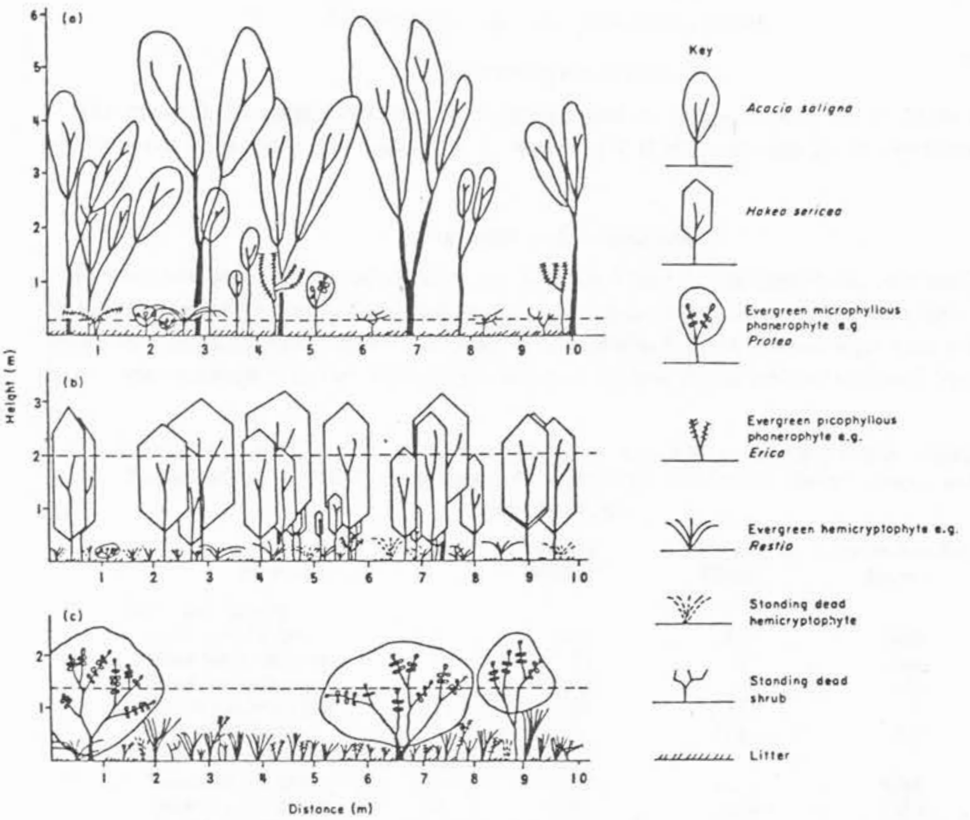


FIG. 2. Profile diagrams from 1 m-wide transects through three plant communities. (a) Fynbos invaded by *Acacia saligna*, (b) fynbos invaded by *Hakea sericea* and (c) pristine fynbos. The dashed line shows the depth of the fuel bed used in the fuel model to simulate fire behaviour.

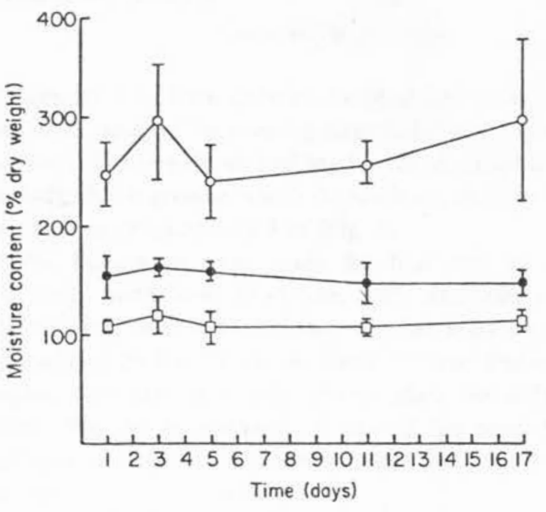


FIG. 3. Fluctuations in the moisture content of the foliage of three species growing on the same site. The species are *Acacia saligna* (○), *Protea repens* (●) and *Hakea sericea* (□). Bars are the 95% confidence intervals of the mean. The first sample was taken on 17 December 1984.

Fuel energy contents

The mean fuel energy contents of *H. sericea* and *A. saligna* are given in Table 3. These values were lower than the value for *P. repens* and fynbos species generally (van Wilgen 1984).

Simulation of fire behaviour

Parameters used in the fuel models are given in Table 4. The fuel loads and surface area to volume ratios in the fynbos fuel model have been changed to reflect changes brought about by invasion. The moisture content of *A. saligna* foliage was so high that it does not burn under average weather conditions. Most of the live shrub fuel is held aloft in stands of *A. saligna*, and fires tend to burn only in the litter layer below the canopy. Attempts to clear infestations of *A. saligna* by burning have failed for this reason (D. M. Richardson personal observation). The live shrub fuel load in the *A. saligna* fuel model was reduced to 145 $g\ m^{-2}$ to exclude shrub crowns which do not burn, and the fuel bed depth estimate for the *A. saligna* model was reduced to 0·3 m (Fig. 2).

TABLE 4. Details of three fuel models used to simulate fire behaviour (using Rothermel's fire model) in pristine fynbos and sites invaded by *Hakea sericea* and *Acacia saligna*

Parameter	Pristine fynbos*	*Hakea*-invaded fynbos	*Acacia*-invaded fynbos
Fuel loads (gm^{-2})			
Dead fuel <6 mm	400	625	1150
Dead fuel 6–25 mm	95	45	314
Dead fuel >25 mm	12	12	45
Live herbaceous fuel	500	130	9
Live shrub fuel	224	1180	145
Surface area to volume ratios ($m^2\ m^{-3}$)			
Dead fuel <6 mm	7215	7215	6460
Dead fuel 6–25 mm	357	357	357
Dead fuel >25 mm	98	98	98
Live herbaceous fuel	5900	5900	5900
Live shrub fuel	4920	8450	6460
Heat content ($J\ g^{-1}$)	20 000	18 500	18 700
Fuel bed depth (m)	1·4	2·0	0·3
Extinction moisture (%)	34	34	34
Midflame wind conversion factor	0·6	0·6	0·6

* After van Wilgen (1984).

Estimates of fire behaviour were made for four sets of weather conditions which represent typical days with low, moderate, high and extreme fire hazard (Table 5). Estimates of fuel moisture used in simulations are also shown in Table 5. The estimates for dead fuel were simulated by the TI-59 calculator routine. Estimates for live fuel are based on observed means, and have been adjusted to allow for differences between alien and indigenous species (Fig. 3). Simulations of rate of fire spread and Byram's (1973) fire intensity were calculated for each fuel model under the different conditions. Byram's fire intensity was estimated using the formula:

$$I = Hwr$$

where I is the fire intensity ($kW\ m^{-1}$), H is the heat yield of the fuel($kJ\ g^{-1}$), w is the mass of available fuel ($g\ m^{-2}$), and r is the rate of fire spread ($m\ s^{-1}$). Results are shown in Figs 4

TABLE 5. Weather parameters and fuel moisture contents used in simulating fire behaviour

Degree of fire hazard	Low	Moderate	High	Extreme
Degree of cloudiness*	2	1	0	0
Air temperature (°C)	15	20	30	40
Relative humidity (%)	50	40	25	15
Windspeed (m s^{-1})	0·5	2	5	7
Slope (degrees)	0	0	0	0
Dead fuel moisture content (%)	9	8	6	4
Live fuel moisture content (%)				
(i) Pristine fynbos	180	150	140	130
(ii) *Hakea*-invaded site	130	120	110	100
(iii) *Acacia*-invaded site	180	150	140	130

* The figures for cloudiness are as follows: 0 = 0·1 cloud cover; 1 = 0·1–0·5 cloud cover; 2 = 0·6–0·9 cloud cover.

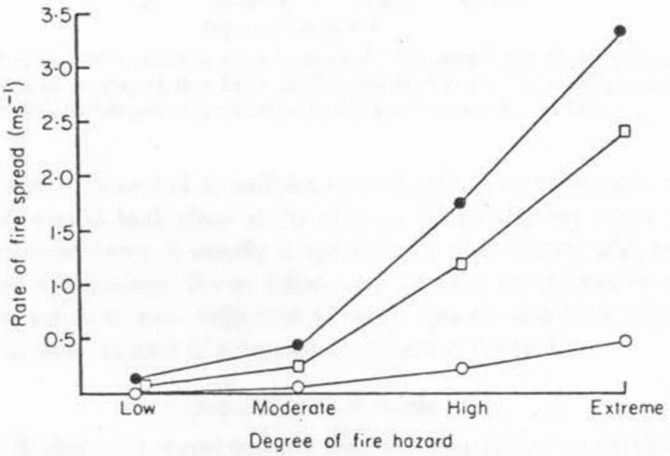


FIG 4. Simulated rates of fire spread using Rothermel's fire model and three different fuel models at four levels of fire hazard (see Table 5). The fuel models are *Acacia saligna*-invaded fynbos (○), *Hakea sericea*-invaded fynbos (□) and pristine fynbos (●).

and 5. Simulated rate of fire spread was highest in fynbos vegetation. *Hakea*-invaded areas show similar but lower rates of spread, with differences becoming larger with increasing fire hazard. Fire intensity (Fig. 5) was also slightly lower in *Hakea*-invaded sites. *Acacia*-invaded areas show low rates of fire spread ($<0·5$ m s^{-1}) and fire intensity ($<11\,000$ kW m^{-1}) under all conditions.

DISCUSSION

Invasions and fynbos vegetation structure

Invasion results in considerable changes in the natural community structure of fynbos. The mean density of dominant shrubs on the Kogelberg site was 1895 stems ha^{-1}, with a mean dominant shrub height of 1·78 m (Le Maitre 1984). The density of dominant *Protea* shrubs in fynbos at Jonkershoek was 1384 stems ha^{-1} at 21 years after fire (van Wilgen 1982). Shrub density was estimated at 8900 stems ha^{-1} for *H. sericea* and 9800 stems ha^{-1} for *A. saligna* from biomass transects. Data from stratification transects gave mean heights

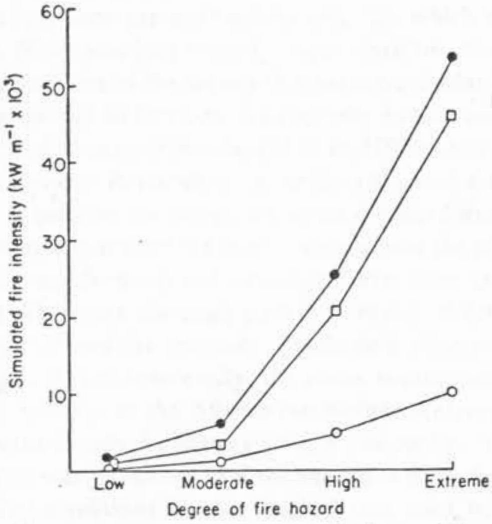


FIG. 5. Simulated rates of fire intensity using Rothermel's fire model and three different fuel models at four levels of fire hazard (see Table 5). The fuel models are *Acacia saligna*-invaded fynbos (○), *Hakea sericea* -invaded fynbos (□) and pristine fynbos (●).

of 2·6 and 3·9 m for *H. sericea* and *A. saligna*, respectively. This increase in the number and size of dominant shrubs took place at the expense of understorey herbs and shrubs (Fig. 2). The fynbos understorey is usually a species-rich assemblage, with many of the species having limited distributions. Severe infestations of alien shrubs can be expected to lead to the drastic reduction or local extinction of many species, and such infestations are therefore incompatible with the aims of nature conservation in the fynbos.

Invasions and fire behaviour

Simulations using Rothermel's model indicate that invasion of fynbos shrublands by *H. sericea* will not change potential fire behaviour markedly. Invasion should therefore not significantly increase fire hazard as was postulated by Kruger (1979), despite an increase in fuel loads, an increase in surface area to volume ratio and a decrease in live fuel moisture content of the dominant species. The major reason for this (in terms of Rothermel's model) is the increased packing density of fuel particles in the fuel bed, which effectively reduces the simulated rate of fire spread. The lower fuel energy content also contributes to the lower fire intensity. However, a large number of wildland fire phenomena still elude theoretical description (Albini 1984): 'For example, dead grass will seldom support a spreading fire when the moisture content is above 15–20%, nor will forest litter if it contains more than about 30% moisture. Yet stands of chaparral (Californian shrublands) composed predominantly of live foliage and stems, and timber stands with virtually all live foliage, can burn with great vigour at a foliar moisture content of 100%' (Albini 1984). Understorey plants in fynbos are finely divided and are important in determining fire behaviour. They are, together with dead material, responsible for carrying fires which in turn ignite the dominant shrubs. The drastic reduction of understorey plants after invasion means that fires will be more dependent on the crowns of dominant shrubs for fuel. As understorey plants have been largely eliminated, fuel in the crowns of invasive species is only ignited under extreme conditions. Fire behaviour in the elevated crowns of old *H. sericea* stands can be quite different from that in fynbos (F. J. Kruger personnal communication). These differences are not simulated by Rothermel's model. The dense foliage of the shrubs will also reduce (and in many places prevent) access (Fig. 2), which complicates the task of firefighters. In addition, *H. sericea* has recently succumbed to attacks by a fungal disease which rapidly kills large numbers of the shrubs (Richardson & Manders 1985). Fire hazard in these stands can be expected to increase dramatically as the moisture content of partly or completely dead shrubs decreases from about 110 to 10% or less.

Simulations of fire behaviour in stands of *A. saligna* showed a reduction in fire spread rate and intensity. This is because the dominant shrub did not form part of the fuel model, due to the high proportion of particles >6 mm diameter and the high moisture content of the foliage. The fuel bed was effectively reduced to the litter layer and remaining vegetation below the canopy (Fig. 2), where the high packing density of fuel particles reduces the simulated rate of fire spread and fire intensity. While field observations have shown that sites invaded by *A. saligna* do not burn easily, the above assumptions do not hold under all conditions. In a recent wildfire in the Silvermine Nature Reserve (34°10'S, 18°25'E), thickets of *A. saligna* burnt cleanly, indicating a fairly intense fire. To simulate fires in such stands, the fuel bed depth was increased to 4 m, and the woody fuel load to 650 g m^{-2} in the *Acacia* fuel model. The conditions listed in Table 5 were used, but live fuel moisture was increased by 60% to allow for observed differences (Fig. 3). Simulated rates of fire spread and intensity were slightly higher than for fynbos (3·27 m s^{-1} and 64 400 kW m^{-1} under extreme weather conditions). This fuel model will probably only apply under extreme conditions when fires burn in the shrub crowns.

The hypothesis that invasion results in increased fire hazard should be seen in the light of the above discussion. Fires will be more easily ignited in pristine fynbos, where there is an abundance of fine material in the herbaceous layers. Under moderate weather conditions, fires in fynbos will spread faster, and burn with greater intensity, than in invaded vegetation. However, under extreme weather conditions, fire intensity in invaded sites would be much higher than in pristine fynbos, although this cannot be simulated as the processes governing fire behaviour in such stands are not clearly understood. The increase in fire intensity under extreme conditions will mean that fires will be more difficult to contain and potentially more damaging to ecosystems than fires in natural vegetation. Under such conditions, the observation that invasion increases fire hazard would be valid.

ACKNOWLEDGMENTS

We thank G. M. Bailey, M. P. Brink, P. J. Brown and A. Simmers for assistance with field work, D. C. Le Maitre for some estimates of fynbos fuel mass, and the Department of Poultry Science, University of Stellenbosch for the use of a bomb calorimeter. F. J. Kruger, I. A. W. Macdonald and W. R. Siegfried provided useful comment on the manuscript. This work forms part of the conservation research programme of the Forestry Branch of the South African Department of Environment Affairs and is published by permission of the Deputy Director General.

REFERENCES

Albini, F. A. (1984). Wildland fires. *American Scientist*, 72, 590–597.

Bond, W. J. (1980). Fire and senescent fynbos in the Swartberg. *South African Forestry Journal*, 114, 68–71.

Burgan, R. E. (1979). *Fire Danger/Fire Behaviour Computations with the Texas Instruments TI-59 Calculator: Users Manual.* USDA Forest Service, General Technical Report INT-61.

Byram, G. M. (1973). Combustion of forest fuels. *Forest Fire: Control and Use.* (Ed by A. A. Brown and K. P. Davis) pp 155–182. McGraw-Hill, New York.

Countryman, C. M. & Philpot, C. W. (1970). *Physical Characteristics of Chamise as a Wildland Fuel.* U.S.D.A. Forest Service Research Paper PSW-66.

Deeming, J. E. & Brown, J. K. (1975). Fuel models in the National Fire Danger Rating System. *Journal of Forestry,* **73,** 347–350.

Kruger, F. J. (1977). A preliminary account of aerial plant biomass in fynbos communities of the mediterranean-type climate zone of the Cape Province. *Bothalia,* **12,** 301–307.

Kruger, F. J. (1979). Conservation: South African heathlands. *Heathlands and Related Shrublands of the World. B. Analytical Studies.* (Ed. by R. L. Specht), pp. 231–234. Elsevier, Amsterdam.

Kruger, F. J. & Bigalke, R. C. (1984). Fire in fynbos. *Ecological Effects of Fire in South African Ecosystems.* (Ed. by P. de V. Booysen & N. M. Tainton), pp. 67–114. Springer, Berlin.

Le Maitre, D. C. (1984). *Aspects of the phenology and structure of two fynbos communities.* M.Sc. thesis, University of Cape Town.

Luke, R. H. & McArthur, A. G. (1977). *Bushfires in Australia.* Australian Government Publishing Service, Canberra.

Macdonald, I. A. W. & Jarman, M. L. (1984). *Invasive Alien Organisms in the Terrestrial Ecosystems of the Fynbos Biome, South Africa.* South African National Scientific Programmes Report 85, CSIR, Pretoria.

Richardson, D. M. & Manders, P. T. (1985). Predicting pathogen-induced mortality in *Hakea sericea* (Proteaceae), an aggressive alien plant invader in South Africa. *Annals of Applied Biology,* **106,** (in press).

Rothermel, R. C. (1972). *A Mathematical Model for Predicting Fire Spread in Wildland Fuels.* U.S.D.A. Forest Service Research Paper INT-115.

Van Wilgen, B. W. (1982). Some effects of post-fire age on the above-ground plant biomass of fynbos (macchia) vegetation in South Africa. *Journal of Ecology,* **70,** 217–225.

Van Wilgen, B. W. (1984). Adaptation of the United States Fire Danger Rating System to fynbos conditions. I. A fuel model for fire danger rating in the fynbos biome. *South African Forestry Journal,* **129,** 61–65.

Van Wilgen, B. W., Le Maitre, D. C. & Kruger, F. J. (1985). Fire behaviour in South African fynbos (macchia) vegetation and predictions from Rothermel's fire model. *Journal of Applied Ecology,* **22,** 207–216.

(*Received 27 February 1985; revision received 7 June 1985*)

APPENDIX 1

MEAN MONTHLY FIRE DANGER INDICES FOR 40 WEATHER STATIONS IN THE FYNBOS BIOME

Data presented here are based on climatic records analysed by the United States Fire Danger Rating System used in conjunction with a fynbos fuel model, as described in papers 1 and 3. Salient features of the weather stations are presented in Table 1 of paper 5 (page 123). The indices presented here are mean monthly values for the period analysed. The indices are the spread component (SC), energy release component (ERC), burning index (BI) and ignition component (IC). The spread component is a rating of the forward rate of spread of a head fire. The energy release component is related to the available energy per unit area within the flaming front at the head of a fire (fire intensity). The burning index combines the spread and energy release components into a number related to the contribution of fire behaviour to the effort of containing a fire. In practical terms, it is related to flame length. The ignition component is an index of fire occurrence; it rates the probability that a firebrand will cause a fire requiring suppression action. The long-term seasonal means of these indices form useful reference points for fire managers using the United States National Fire Danger Rating System.

		MONTH											
STATION	INDEX	JAN.	FEB.	MARCH	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
BIEN DONNE	SC	152.1	155.7	118.8	53.5	14.4	9.1	14.7	15.6	26.2	43.6	92.7	125.4
	ERC	25.8	26.4	23.9	15.5	9.9	9.3	9.8	10.0	10.4	12.0	17.5	22.6
	BI	124.7	126.4	104.9	56.0	24.0	18.8	23.4	26.0	33.4	46.7	81.7	106.4
	IC	38.3	38.3	31.5	17.1	7.4	5.9	6.8	7.8	10.0	17.3	28.8	34.8
CALITZDORP	SC	52.6	44.7	32.8	20.2	23.2	18.7	25.8	27.8	35.6	38.0	48.0	47.4
	ERC	23.8	22.2	20.4	15.9	13.2	11.8	12.7	13.8	15.5	20.6	23.9	21.8
	BI	78.0	70.2	58.3	40.9	38.1	32.2	29.1	43.0	50.8	61.2	74.3	71.4
	IC	25.1	22.2	19.1	13.2	13.6	11.8	14.3	15.2	18.4	21.2	24.1	23.2
CITRUSDAL	SC	166.9	137.8	109.6	69.7	29.3	14.2	12.8	18.3	31.4	64.8	114.0	144.2
	ERC	32.5	31.4	29.8	26.0	16.7	11.4	11.3	10.7	13.0	19.7	27.4	29.7
	BI	152.5	136.8	120.0	89.0	46.8	27.7	26.5	29.8	44.8	77.4	116.9	135.7
	IC	52.3	46.6	37.9	26.6	14.4	8.5	8.0	9.4	15.1	26.1	40.3	45.9
DE DOORNS	SC	92.7	76.3	60.9	42.8	33.9	27.2	34.0	44.1	56.9	77.8	90.6	93.3
	ERC	28.2	27.1	24.0	19.7	16.9	14.1	15.6	16.1	18.2	24.1	27.7	28.0
	BI	109.8	98.2	83.1	63.7	52.0	41.7	19.1	56.4	69.9	93.0	106.6	109.1
	IC	41.0	35.1	29.2	21.9	19.3	16.0	18.3	20.8	25.6	34.6	39.9	40.8
DE KEUR	SC	81.7	90.8	82.6	52.8	35.1	24.2	26.4	27.6	32.2	43.5	69.2	75.5
	ERC	25.9	29.8	28.7	21.7	13.9	10.0	10.5	10.6	11.5	16.1	22.3	23.6
	BI	96.3	109.6	102.9	71.7	47.4	33.4	36.3	36.7	41.4	57.4	83.0	89.2
	IC	34.8	40.8	37.0	23.5	14.9	10.1	10.8	11.1	12.2	18.2	28.4	32.7
ELGIN	SC	38.8	33.2	26.9	17.1	11.8	13.6	13.2	11.9	13.2	18.1	29.4	38.7
	ERC	15.0	13.6	12.4	10.7	9.3	9.1	9.1	8.9	9.3	10.2	11.6	13.8
	BI	53.4	47.4	40.8	30.1	21.5	22.4	22.1	21.0	23.7	29.9	40.8	50.4
	IC	18.0	16.2	13.6	9.8	7.0	7.4	7.2	6.1	7.2	10.0	14.4	16.9

		MONTH											
STATION	INDEX	JAN.	FEB.	MARCH	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
ELSENBURG	SC	93.8	88.7	77.1	38.5	25.0	18.4	18.7	22.4	31.7	45.6	66.6	89.5
	ERC	21.1	21.4	20.3	12.1	10.2	9.2	9.4	9.3	10.8	13.0	16.0	21.2
	BI	92.8	92.8	85.8	46.8	34.6	28.8	28.7	30.3	39.8	52.6	69.5	95.4
	IC	32.9	34.2	33.6	17.0	11.2	9.4	8.7	9.1	13.5	19.6	26.5	34.0
FRANSCHHOEK	SC	73.6	73.4	65.2	50.9	31.6	18.7	18.2	34.5	42.6	52.4	68.6	81.3
	ERC	22.6	24.4	23.4	19.9	14.8	11.4	10.7	10.8	14.3	19.1	21.6	23.5
	BI	86.3	89.2	83.9	66.7	45.0	31.6	30.3	40.8	51.9	66.1	80.4	89.3
	IC	29.3	29.4	25.6	21.0	14.1	10.1	9.8	13.0	16.9	21.3	26.2	29.9
GRAAFWATER	SC	71.8	62.8	53.5	42.8	36.0	38.9	31.3	14.1	33.2	49.4	66.6	66.7
	ERC	27.3	27.5	26.7	32.1	18.8	17.3	15.9	14.0	17.7	23.8	27.7	28.0
	BI	95.3	90.2	81.6	67.5	55.4	54.1	46.8	40.2	53.7	74.5	92.3	92.0
	IC	34.1	31.3	27.7	22.3	19.0	19.6	16.7	14.6	18.8	26.2	32.0	32.1
GROOT CONSTANTIA	SC	37.2	42.3	32.0	18.0	9.4	9.7	10.5	11.2	12.8	16.5	29.8	33.5
	ERC	13.3	14.9	13.2	10.6	8.6	8.3	8.5	8.4	8.7	9.3	11.3	12.2
	BI	49.6	55.6	45.9	30.7	19.3	18.9	20.1	20.6	23.2	27.7	40.9	44.8
	IC	13.3	14.9	11.6	8.2	5.2	5.2	5.0	5.1	5.9	7.8	11.6	12.2
GYDO	SC	109.9	100.7	77.9	39.3	24.7	11.4	9.3	16.6	22.0	37.6	68.0	97.0
	ERC	27.3	28.4	26.7	17.8	12.7	11.0	10.0	9.9	11.3	13.1	19.0	25.5
	BI	115.0	112.6	97.2	57.7	38.2	25.1	21.1	27.9	34.5	49.2	76.8	106.5
	IC	39.4	39.1	32.5	18.8	12.6	8.2	6.1	8.3	11.7	18.3	28.7	36.7
HOLLAAGTE	SC	78.9	58.7	38.4	27.6	26.7	22.1	26.9	21.6	26.6	38.5	53.5	68.0
	ERC	14.4	11.4	10.1	9.6	9.5	9.2	9.6	8.6	9.0	9.6	10.5	12.4
	BI	72.6	56.8	44.0	34.5	35.5	31.8	36.2	30.3	35.1	43.3	52.0	64.0
	IC	21.4	15.3	12.5	11.1	10.8	9.3	10.9	7.7	10.0	12.6	15.4	19.8

		MONTH											
STATION	INDEX	JAN.	FEB.	MARCH	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
JAKKALSRIVIER	SC	94.1	88.6	68.5	62.8	44.8	49.0	53.8	33.5	34.8	43.2	64.6	78.6
	ERC	13.0	11.6	10.7	10.3	9.3	9.7	9.6	8.9	8.8	9.5	10.3	11.4
	BI	73.0	66.6	56.5	52.4	41.5	44.2	45.6	34.1	36.1	42.6	53.4	62.1
	IC	26.0	23.9	19.1	17.6	13.2	15.5	15.5	11.4	11.1	14.3	19.0	22.5
JOUBERTINA	SC	79.9	63.5	46.4	34.9	38.7	48.5	64.4	55.4	42.2	49.9	55.3	71.0
	ERC	15.8	14.4	12.6	11.9	12.2	13.4	14.7	13.5	11.6	12.1	12.4	14.5
	BI	75.3	64.3	51.4	44.0	46.3	54.1	65.4	57.7	47.4	52.8	56.3	68.8
	IC	25.3	21.9	18.0	14.7	15.0	17.0	20.4	18.9	15.9	18.9	19.5	24.1
JONASKRAAL	SC	160.4	123.0	90.6	48.4	33.5	25.8	22.9	25.5	26.2	69.1	122.8	164.1
	ERC	21.4	17.6	14.7	11.9	10.3	10.2	9.9	9.1	9.4	12.4	16.8	20.5
	BI	121.1	94.9	77.0	49.9	37.9	33.6	31.3	31.7	33.0	62.2	93.7	119.9
	IC	38.8	29.4	23.8	16.3	11.0	9.3	8.1	8.5	9.7	22.1	30.7	37.5
KARRINGMELKRIVIER	SC	138.5	110.3	75.4	53.0	46.6	55.2	50.5	41.4	38.3	68.6	120.0	148.1
	ERC	19.0	16.4	13.2	11.4	11.2	11.6	10.8	9.8	9.9	12.5	15.4	18.8
	BI	104.4	86.8	66.8	51.0	45.6	50.4	47.3	41.2	40.7	61.0	88.2	108.9
	IC	34.5	28.6	22.0	16.8	14.6	16.3	14.6	12.3	12.6	21.5	30.0	36.0
KLAWER	SC	153.0	114.8	134.1	102.8	96.1	73.5	70.4	99.1	107.7	143.4	144.6	147.5
	ERC	30.0	27.8	28.5	26.3	23.6	21.9	19.9	19.2	23.5	28.2	31.0	29.9
	BI	138.0	120.0	127.0	102.9	91.4	78.9	75.0	85.3	102.7	130.7	139.4	138.1
	IC	49.5	44.0	44.1	35.0	30.5	27.9	25.4	28.5	35.4	44.6	49.0	48.6
KOO	SC	69.6	62.2	42.2	35.9	36.8	41.8	41.6	43.4	41.0	57.0	74.1	69.7
	ERC	10.3	18.6	15.9	13.9	14.0	15.5	14.1	13.9	13.3	17.4	19.4	18.7
	BI	80.2	72.6	57.5	47.2	47.9	53.6	50.6	51.2	50.9	67.6	78.4	77.7
	IC	25.8	23.7	18.7	15.2	14.6	15.1	13.6	14.1	14.9	21.8	23.5	25.5

		MONTH											
STATION	INDEX	JAN.	FEB.	MARCH	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC
KORINGBERG	SC	201.7	200.9	193.1	82.9	41.6	20.8	14.3	21.3	44.9	80.5	118.7	158.0
	ERC	31.8	32.9	32.6	23.7	14.8	9.4	8.7	9.8	13.0	19.1	24.0	27.2
	BI	163.8	167.0	162.3	91.4	51.6	29.0	24.5	30.8	51.6	83.7	112.4	137.0
	IC	56.3	56.4	53.2	29.1	15.3	7.3	6.0	9.2	17.0	32.4	42.1	52.8
LANDAU	SC	197.8	157.1	137.1	76.0	43.5	26.4	31.1	32.9	53.0	91.7	158.0	183.8
	ERC	28.4	26.8	25.6	20.4	14.2	11.6	11.7	11.4	14.0	19.0	25.8	26.7
	BI	151.1	130.2	121.9	81.1	51.5	37.1	39.7	40.4	57.8	87.5	130.8	143.4
	IC	55.2	47.7	44.5	30.7	18.7	13.2	13.9	14.7	21.7	34.0	48.9	51.8
LANGGEWENS	SC	219.5	226.6	198.0	129.5	93.0	61.7	50.9	53.8	68.4	107.8	157.5	190.7
	ERC	34.0	34.1	32.9	25.0	17.5	13.3	12.5	11.7	15.6	21.5	28.2	31.5
	BI	171.6	176.2	162.9	113.8	80.9	58.8	50.3	49.6	66.8	98.8	133.8	157.5
	IC	57.7	59.8	54.6	36.9	24.5	18.7	15.2	15.2	23.2	35.6	47.0	54.7
LANGKLOOF	SC	71.9	73.1	36.8	20.1	22.6	19.3	33.0	32.4	19.7	33.4	48.4	57.9
	ERC	25.3	27.2	18.4	14.2	13.1	13.0	14.8	15.0	11.9	15.0	17.6	19.6
	BI	93.7	97.1	56.8	37.0	37.1	34.4	49.0	45.7	35.3	48.5	63.8	73.5
	IC	27.3	27.5	17.5	13.1	12.9	11.2	16.9	14.2	12.9	16.7	20.1	23.3
MALMESBURY	SC	115.3	108.4	78.9	52.4	29.9	20.4	16.8	14.3	19.3	41.8	82.3	109.4
	ERC	27.0	28.0	24.9	20.5	14.1	11.1	11.8	9.9	10.4	14.4	21.2	25.3
	BI	117.2	116.1	94.1	69.4	43.4	32.0	30.2	24.9	31.7	54.3	88.2	110.1
	IC	40.3	38.3	29.7	21.7	12.7	8.9	8.3	6.8	9.7	19.7	30.4	38.1
MOREESBURG	SC	156.9	150.9	128.1	79.6	42.8	24.4	20.9	26.3	33.3	74.8	119.7	143.9
	ERC	28.3	29.4	27.4	21.5	13.9	10.3	10.0	9.6	12.2	17.7	24.1	26.9
	BI	136.3	138.0	121.4	85.1	50.8	34.3	30.7	32.9	46.1	77.6	110.9	128.5
	IC	45.3	45.5	38.6	25.3	14.6	10.1	8.5	9.4	14.9	26.6	36.7	42.9

		MONTH											
STATION	INDEX	JAN.	FEB.	MARCH	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
NIETVOORBIJ	SC	121.0	118.0	81.8	43.7	18.0	18.3	16.1	28.0	37.0	67.1	106.3	117.2
	ERC	20.3	20.2	18.4	13.0	9.5	9.2	8.9	9.4	10.9	12.9	17.4	19.4
	BI	101.5	98.6	78.4	47.6	27.1	26.6	24.6	32.3	41.9	60.2	87.9	98.5
	IC	32.2	31.4	24.7	14.5	8.2	7.8	6.9	9.4	13.4	20.3	30.0	31.3
OUDTSHOORN	SC	77.5	67.7	45.0	29.1	16.6	12.1	15.2	20.7	24.3	55.2	73.0	86.7
	ERC	27.1	26.0	22.7	18.4	13.5	11.8	12.3	13.2	14.1	22.4	26.0	28.9
	BI	95.6	87.7	69.1	51.4	33.7	27.2	30.9	36.6	41.3	75.8	91.8	105.8
	IC	33.0	29.9	23.2	17.5	11.1	9.1	11.1	14.0	15.1	28.2	32.7	35.9
OUTENIQUA	SC	36.8	27.3	19.3	17.1	24.2	30.9	29.6	31.6	21.8	22.4	24.2	33.1
	ERC	11.0	9.9	9.5	9.5	9.9	10.6	10.4	10.3	9.8	9.0	9.1	10.1
	BI	43.5	35.7	29.9	28.3	32.3	37.5	36.9	37.6	31.9	31.3	32.8	39.6
	IC	13.4	11.1	9.0	8.8	11.0	14.4	12.7	13.7	10.2	8.8	9.1	11.3
PHILEDELPHIA	SC	83.5	77.5	65.0	30.8	15.8	10.0	9.2	11.0	16.8	32.0	60.0	74.2
	ERC	26.1	26.7	23.8	16.0	10.7	9.2	9.0	9.4	10.5	14.2	19.4	23.1
	BI	97.7	96.2	83.1	47.5	27.7	21.1	19.9	21.9	29.2	47.1	71.9	86.9
	IC	32.6	31.2	26.7	14.4	8.5	5.7	4.8	5.8	8.7	16.9	25.6	30.3
PORTERVILLE	SC	80.4	70.3	53.1	35.7	21.7	15.1	13.4	14.7	19.6	36.6	60.6	74.7
	ERC	27.2	27.4	23.0	17.0	12.6	10.5	10.4	10.2	11.6	15.6	22.8	26.8
	BI	101.6	94.1	74.5	52.0	35.1	27.1	25.5	26.0	32.8	50.9	79.3	94.9
	IC	35.4	31.3	24.2	18.3	12.6	9.7	8.7	9.2	12.6	20.5	29.4	23.9
PRINSKRAAL	SC	110.9	87.4	63.0	35.8	20.2	16.9	17.1	22.3	31.8	59.2	94.5	131.4
	ERC	13.7	10.9	9.7	8.8	8.5	8.4	8.2	8.5	8.7	10.0	11.3	13.9
	BI	80.4	64.5	52.6	37.4	28.5	25.7	25.5	29.5	35.9	51.8	69.3	89.7
	IC	22.7	17.4	13.9	9.9	7.0	6.1	5.6	6.8	9.0	15.6	20.6	25.2

		MONTH											
STATION	INDEX	JAN.	FEB.	MARCH	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
PROTEM	SC	139.1	119.8	86.5	69.2	43.8	45.3	50.8	42.4	51.4	86.2	128.8	140.3
	ERC	19.0	16.3	13.1	12.6	10.8	10.6	10.8	10.0	10.3	13.8	16.5	17.6
	BI	104.3	89.6	70.7	62.0	47.0	46.6	48.8	43.7	48.8	72.5	94.9	102.9
	IC	33.6	27.8	22.8	20.0	14.0	14.0	13.8	11.6	13.8	23.8	29.3	33.3
RIEBEECK WEST	SC	136.0	133.3	107.2	65.4	33.7	21.4	21.0	22.6	41.4	68.6	106.5	135.4
	ERC	30.0	31.4	29.4	22.4	14.5	11.1	11.0	10.1	13.2	19.1	25.5	28.5
	BI	129.3	133.1	115.3	77.2	44.9	31.8	31.0	30.7	47.9	75.0	105.8	127.1
	IC	43.9	44.5	36.9	23.3	13.2	9.2	8.1	8.8	15.2	25.2	35.6	42.7
RIVERSDALE	SC	58.3	56.2	36.0	24.9	19.9	18.5	22.1	21.1	23.6	39.6	56.4	63.5
	ERC	18.2	16.4	14.0	12.8	11.8	11.6	11.3	11.5	11.8	14.0	16.7	18.3
	BI	69.6	62.5	48.8	39.4	33.4	32.2	34.1	34.2	37.0	51.9	66.0	71.3
	IC	23.9	20.9	17.1	14.5	12.2	11.6	12.8	12.7	13.5	19.5	23.2	24.8
RIVERSIDE	SC	29.8	29.4	24.8	13.5	19.1	11.9	10.5	14.7	16.5	22.1	30.3	16.3
	ERC	17.9	19.0	18.7	14.3	14.6	12.9	12.9	13.6	14.4	14.6	18.9	12.5
	BI	53.2	54.5	50.0	32.3	36.7	26.6	26.4	31.6	35.8	41.1	51.7	31.8
	IC	31.3	31.9	29.2	16.7	19.2	14.3	13.5	17.0	18.3	16.2	18.9	13.5
ROBERTSON	SC	56.4	44.7	35.8	23.9	19.3	14.1	15.3	21.1	28.5	43.0	53.3	63.0
	ERC	24.0	22.0	18.1	13.7	11.0	9.8	10.1	10.3	11.6	15.0	19.0	22.5
	BI	78.9	68.1	55.7	39.4	30.2	24.7	26.4	30.1	38.0	53.7	67.4	79.3
	IC	26.0	21.9	18.0	13.2	9.8	7.4	7.8	9.5	12.2	18.2	22.9	25.7
TYGERHOEK	SC	110.2	90.0	75.4	28.2	18.6	14.5	20.8	21.7	28.9	58.1	90.0	105.8
	ERC	19.6	17.3	13.9	11.0	9.4	8.9	9.0	9.4	9.9	12.7	15.6	17.7
	BI	98.2	83.3	61.1	38.0	29.1	25.0	28.7	31.6	36.9	58.8	79.2	90.0
	IC	32.6	27.0	19.6	12.4	8.5	6.5	8.2	8.6	10.9	20.0	26.4	33.4

		MONTH											
STATION	INDEX	JAN.	FEB.	MARCH	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
VREDENBURG	SC	168.2	154.0	124.7	81.7	60.4	54.2	47.7	41.2	64.4	111.8	153.1	163.6
	ERC	18.3	18.4	17.4	15.2	12.6	11.4	10.9	9.5	11.2	14.6	17.1	18.1
	BI	116.8	112.9	99.3	76.5	57.8	52.3	47.8	41.8	58.4	86.8	107.2	114.7
	IC	35.3	34.1	30.7	24.0	17.2	15.5	13.1	11.9	17.2	26.8	31.5	34.3
WELGEVALLEN	SC	69.5	77.4	57.3	38.6	23.8	22.7	20.8	23.4	28.6	36.4	63.5	64.6
	ERC	19.4	20.7	17.2	14.3	11.0	10.2	10.1	10.1	11.0	12.9	16.2	16.7
	BI	78.6	83.8	66.4	50.3	34.0	31.4	30.6	31.6	37.3	47.2	67.7	70.1
	IC	28.4	30.9	24.1	18.7	13.1	12.6	11.8	12.1	14.7	17.1	23.9	23.8
WELTEVREDEN	SC	67.8	51.4	39.0	25.6	19.7	13.7	13.6	16.6	22.6	36.8	52.4	56.8
	ERC	28.2	25.8	23.0	17.8	15.2	12.7	12.7	12.8	14.4	18.7	23.3	25.5
	BI	94.3	77.7	66.7	47.6	38.9	30.4	30.9	32.6	40.7	58.4	76.1	84.4
	IC	33.9	27.4	23.8	17.5	14.1	10.9	11.1	11.9	15.1	22.1	28.0	30.8
WOLSELEY	SC	109.5	103.8	82.1	45.7	32.4	23.1	24.5	25.6	37.9	55.1	84.3	99.0
	ERC	31.7	31.2	28.6	21.8	15.7	12.9	13.0	12.3	14.9	20.0	26.5	29.2
	BI	122.5	119.5	102.9	67.3	48.5	37.1	38.8	38.1	51.5	71.3	100.0	112.4
	IC	45.3	42.9	36.3	23.6	17.2	13.7	14.1	14.0	19.0	26.4	36.2	40.8