CONTROL OF BUSH ENCROACHMENT WITH FIRE IN THE ARID SAVANNAS OF SOUTHEASTERN AFRICA

Winston Smuts Watts Trollope

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DECLARATION

This thesis is the result of the author's original work, unless specifically indicated to the contrary in the text.

W. S. W. Trollope

W.S.W. Trollope

The Author

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CHAPTER 1

INTRODUCTION

In this study the term savanna has been used in its widest context and includes bushveld, thornveld, lowveld, woodland and scrub. Its overall structure is that of a wooded grassland where the woody vegetation comprises mature trees and shrubs. The herbaceous vegetation is dominated by perennial grasses, some species of which occur in the open spaces between the trees and shrubs and others occur underneath the trees (Walker & Noy-Meir, 1982). With the exception of the savannas of the southeastern seaboard and river valleys many of the grass species occurring in the open areas between the trees (e.g. Cymbopogon plurinodis) are less palatable than the species underneath the trees (e.g. Panicum maximum).

The arid savannas of southeastern Africa comprise the thornveld and valley bushveld areas of the eastern Cape Province, Ciskei and Transkei that receive less than 650mm of rain per annum. Attention was focussed on this area because it is one of the premier livestock producing areas of South Africa. Here livestock production is wholly dependent upon the veld which is currently threatened by a serious bush encroachment problem. However, before considering the problem of bush encroachment in this region it is appropriate to briefly describe the distribution and condition of the savannas as a whole in South Africa. This will assist in viewing the problem of bush encroachment in its correct perspective in this important livestock producing area.

Savanna constitutes one of the major biomes of South Africa. Its distribution is illustrated in Figure 1.1. It occurs along the southeastern seaboard as a narrow strip of thornveld and includes the valley bushveld of the dry river valleys. Further north it broadens out into the lowveld and bushveld of Natal and the eastern and northern Transvaal and finally merges into the Kalahari thornveld of the southwestern Transvaal, western Orange Free State and northern Cape Province.

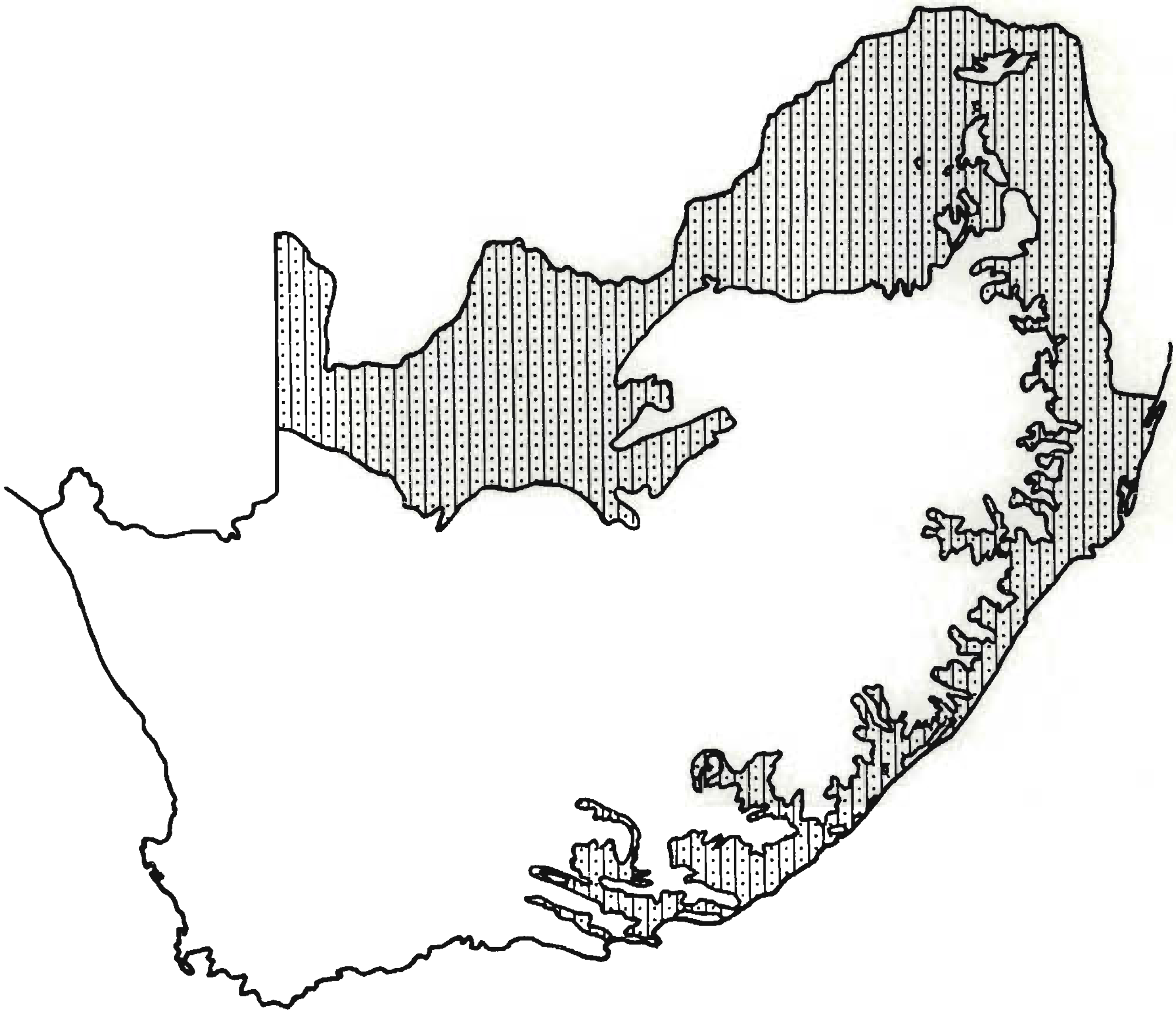

FIGURE 1.1. The savanna areas of South Africa. Adapted from Acocks (1953).

The climatic environment of the savannas varies widely and Huntley (1982) has divided this biome into two broad types viz. moist and arid savanna. In general the arid savannas are found in areas receving less than 650mm of rain per annum. The majority of the rain falls during the summer but severe mid-summer droughts occur frequently and frost is a common phenomenon. Conversely the moist savannas generally receive more than 650mm of rain per annum. However, there are the exceptions that moist savannas sometimes occur on sandy latosols in areas subject to frequent drought and which receive less than 600mm of rain per annum. Mid-summer droughts are also a feature of moist savannas at the lower limit of their moisture range. Frost is not a common phenomenon but can occur in response to physiographic features of the landscape (Huntley, 1982).

The distribution of moist and arid savannas is closely related to the base status of the major soil types in southern Africa. Generally, moist savannas occur on leached acid soils while arid savannas occupy soils with a high base status. This pattern is consistent over a wide range of soil textures and is illustrated by the dominance of bush species of arid savannas on the relatively base-rich sands of the southern Kalahari. This is in contrast to the moist savanna species occurring on the highly leached acidic sands of the northern extension of the Kalahari system. This phenomenon also results in bush species typical of arid savannas extending into moist savannas on the base-rich substrates provided by termitaria. Conversely moist savanna species occur in arid savannas on leached acidic sands overlying crystalline rocks or sandstone (Huntley, 1982).

In discussing the present condition of the veld in the savannas it is essential to recognise that the major part of this type of veld is used for cattle ranching. Commercial goat farming is important only in the Valley Bushveld of the Eastern Cape where mohair from Angora goats and meat from Boer goats are important livestock products. Consequently the condition of the veld is generally assessed in relation to its ability to produce forage for grazing rather than browsing animals and so the balance (ratio) between grass and bush and the basal cover and botanical composition of the grass sward assume major significance. Bush encroachment is regarded as one of the most serious veld management problems in the savannas and comprises the thickening up of trees and shrubs to form dense impenetrable thickets to the severe detriment of the grazing capacity of the veld.

Donaldson (1969) quotes van der Schijff (1964) as estimating that at least 13 million hectares of savanna are in various stages of encroachment in South Africa. Bush encroachment is more of a problem in the arid than in the moist savannas and van der Schijff (1957) has estimated that practically the entire sweet bushveld of the Transvaal is seriously encroached with bush. In the semi-arid Kalahari Thornveld of the Molopo area in the northern Cape Province, in excess of a million hectares have been encroached by *Acacia mellifera* subsp. *detinens*, resulting in the grazing capacity of the veld being reduced by 50 per cent or more

(Donaldson, 1969). In the dry thornveld areas of the Eastern Cape *Acacia karroo* is the most important encroaching species (du Toit, 1972a) and poses a serious threat to the livestock industry.

In the arid savannas bush encroachment has been accompanied by an overall reduction in the basal cover and changes in the botanical composition of the grass sward. Desirable perennial grass species have been replaced by inferior biennial and annual species. Productive and highly acceptable genera like *Panicum*, *Setaria*, *Digitaria*, *Brachiaria*, *Stipagrostis*, *Cenchrus* and *Themeda* have largely given way to the less productive and/or less acceptable species like *Eragrostis*, *Aristida*, *Chloris*, *Tragus*, *Schmidtia*, *Enneapogon*, and *Perotis*. In the more westerly and southern savannas the destruction of the grass sward has also resulted in the encroachment of karroid species like *Chrysocoma tenuifolia* (bitter karroo) and *Felicia filifolia* (draaibossie). This has led to the development of the False Karroid Broken Veld in large areas of the Fish River valley in the Eastern Cape and the Kalahari Thornveld invaded by Karroo in the northern Cape Province (Acocks, 1953).

In the moist savannas of the Transvaal, Natal and the Eastern Cape, bush encroachment is a serious problem but there has not been quite the same deterioration in the basal cover of the grass sward as has occurred in the arid savannas. Nevertheless the botanical composition of the grass sward has retrogressed and, for example, in the Sour Bushveld of the Transvaal Acocks (1953) refers to the grass component as being "peculiarly useless" because of the decrease in the desirable grass species like *Themeda triandra* (rooigras). In the Coastal Forest and Thornveld of the southeastern seaboard extensive areas have become dominated by *Aristida junciformis* (ngongoni) (Acocks, 1953).

Turning to the arid savannas of southeastern Africa, Story (1952), Acocks (1953), du Toit (1968; 1972a; 1972b) and Scott (1970) have all referred to the serious bush encroachment problem that exists in the thornveld areas of the Eastern Cape. A similar problem, albeit on a more limited scale, has also developed in the thornveld regions of the Ciskei and Transkei since the introduction of veld rehabilitation schemes in the location farming areas (Trollope, 1976). The affected veld types in the Eastern Cape, Ciskei and Transkei are the False Thornveld of the Eastern Cape and the Invasion of Grassveld by Acacia karroo. The distribution of these veld types is illustrated in Figure 1.2.

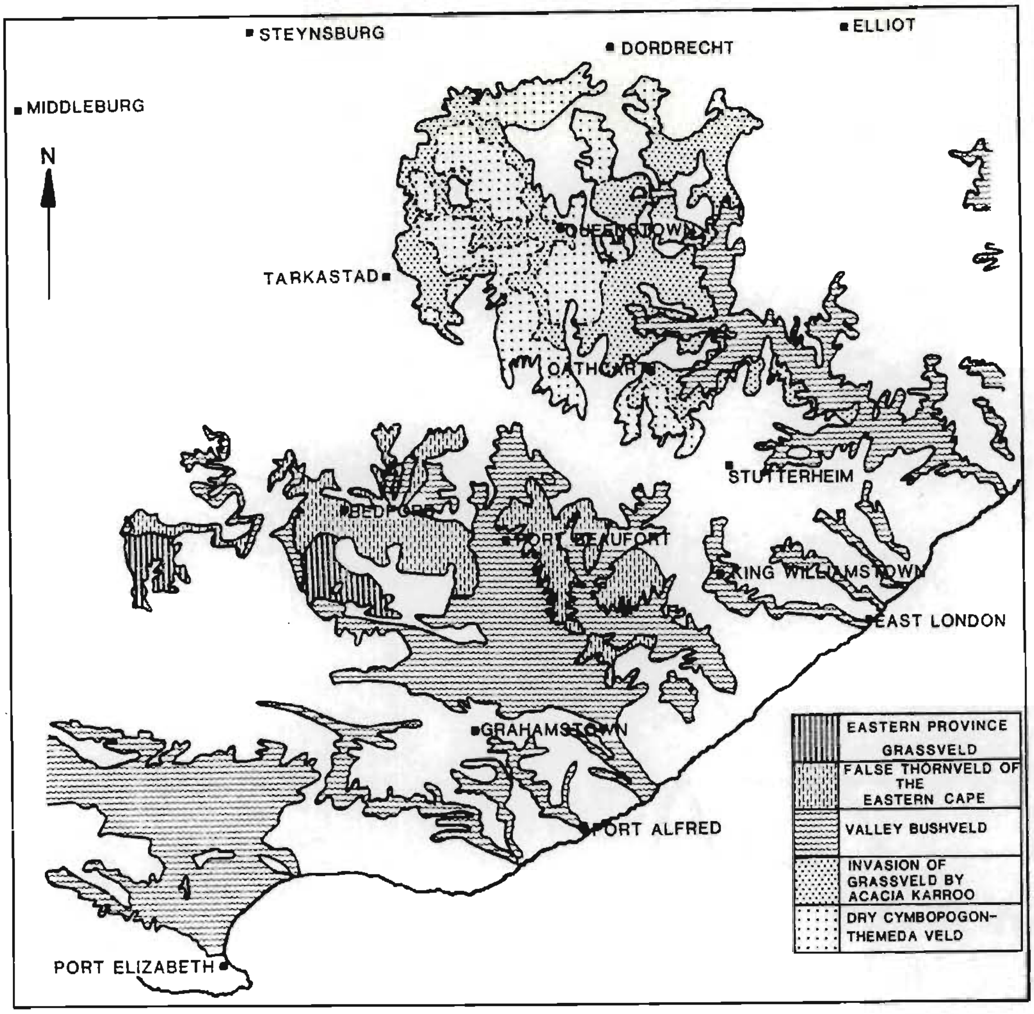

FIGURE 1.2. The arid savannas of southeastern Africa and related veld types (adapted from Acocks, 1953).

The principal encroaching species is Acacia karroo but other important associated species are Scutia myrtina, Maytenus heterophylla, Rhus spp., Diospyros lycioides, Xeromphis rudis, Azima tetracantha and Ziziphus mucronata. The encroachment has involved the invasion of grassland by these species from the adjacent scrub forest that is marginal to the high forest of the Winterberg, Katberg and Amatole mountain ranges. Encroachment has also occurred from the Valley Bushveld of the dissecting river valleys. The encroachment in the False Thornveld of the Eastern Cape constitutes a natural progression in the plant succession from the grassland stage to a higher scrub forest stage because Acocks (1953) suspected that the climatic climax vegetation of these areas was temperate scrub forest. The events leading to the encroachment of A. karroo into the veld type referred to by Acocks (1953) as the invasion of Grassveld by Acacia karroo is somewhat different from the pattern of encroachment in the False Thornveld. This veld was previously part of the southeastern variation of the Dry Cymbopogon Themeda Veld and was considered by Acocks (1953) as a pure grassveld because grassland is the climatic climax community. In these areas the encroachment of bush has been a process of invasion into an area where it previously did not occur and was not therefore a natural component of the vegetation. However, du Toit, (1972b) concluded that bush can be regarded as a permanent component of these areas for the foreseeable future, because of the large reservoir of seed that has been built up in the soil in recent times.

The seriousness of the bush encroachment problem is illustrated by the results obtained by du Toit (1972b) in the encroached portions of the Dry Cymbopogon Themeda Veld where over a six-year period the seasonal production of grass was reduced on average by 46 per cent in veld severely encroached by A. karroo. Further research in the Eastern Cape by Aucamp, Danckwerts, Teague & Venter (1983) supports these results but it was found that the production of grass did not decline linearly with increasing densities of A. karroo. The results showed that at bush densities of 1000, 1500 and 2000 tree equivalents (definition - page 38) per hectare the grazing capacity of the veld can be expected to be 90, 67 and 32 per cent respectively of its potential. In situations where encroachment has developed to a multi-species bush community the deleterious effect of this encroachment on the productivity of the grass sward is manifested primarily via its adverse effect on the botanical composition of the herbaceous layer rather than only through a yield reduction resulting from competition per se. (Teague, Trollope & Aucamp, 1981). Results obtained in the False Thornveld of the Eastern Cape showed that in veld with different densities of a multi-species bush component the estimated mean grazing capacity of unencroached veld was 3,1 hectares per animal unit while that of encroached veld was only 6,1 hectares per animal unit (Trollope, 1983a).

The two most important factors that must be considered when formulating a program for controlling bush encroachment are the ecological and economic consequences of applying the methods of control. The species composition and cover of the veld must not be impaired and lead to a deterioration in the condition of the natural resources of the area. Secondly the economics of the program must be such that it is within the financial grasp of the land user to apply the control methods in practice.

Results + discuss

(+) With these two factors in mind it was decided to investigate the use of fire as a means of controlling bush encroachment in the arid savannas of southeastern Africa. From the ecological point of view fire is recognised as being a natural factor of the environment in the savanna areas of Africa and has been occurring since time immemorial (see chapter 2). Experience has shown that if the ecological role of fire is clearly understood then it can be used as an important tool in the management of different ecosystems. An example of this is the use of fire in maintaining grassland in areas prone to the encroachment of macchia in the Amatole mountains of the Eastern Cape and Ciskei (Trollope, 1970).

Comparing Methods

(+) ow costs of burning

From the economic point of view fire has the very important advantage of being a non-capital intensive technique. Burning results in the loss of potential grazing and so the cost of a burning program must be assessed in terms of lost profits. Direct costs are involved when using fire, such as machinery and labour, but these are usually low. Field experience in the Eastern Cape indicates that the direct costs of burning veld do not exceed approximately R2 ha^{-1}. It is therefore believed that burning provides an attractive economic alternative to direct-cost techniques, for example chemical and mechanical methods, that are normally used in controlling bush encroachment. This point is well illustrated by the minimal use that has been made of mechanical and/or chemical methods of controlling bush encroachment in South Africa despite the existence for decades of experimentally proven technology. Generally the costs are too high in relation to the potential returns. For example in severly encroached thornveld areas of the Eastern Cape the current mean grazing capacity of the veld is approximately 10 ha AU^{-1}. The mean gross margin for beef ranching in this area was estimated by the Department of Agriculture and Fisheries in the Eastern Cape Region to be R108 AU^{-1} for the period 1981 to 1982. This means that the gross margin for bush encroached veld was R10,80 ha^{-1}. Experience gained on the research farm of the University of Fort Hare indicates that it would cost at least R200 ha^{-1} to control this type of encroachment by chopping down the bush and treating the stumps with weedicide. At the current rate of 14 per cent charged by the Land Bank the interest on R200 would be R28 ha^{-1}. Clearly an initial return of R10,80 ha^{-1} would not justify such an investment in controlling bush encroachment. Even if the grazing capacity increased to 4 ha AU^{-1} this approach would still be economically suspect. The aforementioned discussion also assumes that mechanical and/or chemical control methods involve a single operation that is completely effective. Practical experience gained in the Eastern Cape indicates that this is not so and that follow-up treatments are necessary to control the regeneration of bush from seedlings and coppice growth that survived the original treatment.

It is therefore firmly believed that the economic principle of using non - capital intensive techniques has great applicability in controlling bush encroachment in the arid savannas. The low economic potential of the veld demands that methods must be compatible with the financial capabilities of the land user.

Consequently it was decided to conduct a research program directed at controlling bush encroachment with fire in the arid savannas of south-eastern Africa. In considering such an approach the key question that required investigation was what is the role fire can play in controlling bush encroachment in the arid savannas?

The research program was conducted mainly on the research farm of the University of Fort Hare at Alice in the Ciskei but certain aspects were also investigated elsewhere in the arid savannas of the Eastern Cape.

CHAPTER 2

A REVIEW OF FIRE AND ITS EFFECTS IN THE SAVANNA AREAS OF SOUTH AFRICA.

2.1 INTRODUCTION

In the savanna areas of Africa fire is recognised as having an important ecological role in the development and maintenance of productive savanna communities (Lemon, 1968; Phillips, 1965; West, 1971; van Wyk, 1971; Vesey Fitzgerald, 1971; Austen, 1971; Gillon, 1971). Nevertheless, except for the wildlife areas, the general attitude regarding its practical use tends to be negative and veld burning is applied only as a last resort. This attitude has arisen through the deleterious effects burning has on veld when used injudiciously and has resulted in a significant reduction in the occurrence of veld fires in the savanna areas of South Africa. This reduction in the frequency of fires began in about 1946 with the proclamation of the Soil Conservation Act. Strict procedures governing the use of fire were laid down and controlled burning was virtually eliminated in practice in the arid savannas. Scott (1970) drew attention to this trend when discussing the pros and cons of eliminating veld burning in South Africa and the question arises whether an important or even essential factor is not being inadvertantly eliminated or drastically reduced, to the detriment of the sustainable productivity of the savanna ecosystems of South Africa. This point emphasises the necessity for studying and assesing the effects of fire in the savanna in order to establish the the manner in which fire can be used to sustain forage production in this ecosystem. Unfortunately this is a difficult task because a review of the literature shows that there is a distinct lack of quantitative information on the effect of fire in the savanna areas, particularly the arid savannas which constitute the major portion of this ecosystem in southern Africa (West, 1965; Scott, 1970; Scott, 1971; van Wyk, 1971; Trollope, 1974; Trollope, 1978).

2.2 TERMINOLOGY USED IN FIRE ECOLOGY

In South Africa there is no well developed nomenclature available for describing the various aspects of burning that are pertinent to the field of fire ecology. A set of terms and definitions based on a review of the world literature and adapted where necessary, are proposed in an effort to overcome this problem. The terms have been grouped into those that describe general aspects of fire ecology and those that relate to fire behaviour and related parameters.

2.2.1 Terms describing general aspects of fire ecology

Fire ecology is an all embracing term that Komarek (1962) defined as "the study of fire as it affects the environment and the interrelationships of plant and animals therein". However, it is felt that this definition is not comprehensive and specific enough to convey adequately the concept of fire ecology which is itself defined as the study of the interaction of the biotic and abiotic components of the ecosystem with the season, frequency, type and intensity of fire. Each of these functions does, however, need to be defined.

2.2.1.1 Types of fire

Three broad types of fires are recognised, based on the layers in which the vegetation burns:

A ground fire is a fire that burns below the surface of the ground in deep layers of organic material, (Brown & Davis, 1973; Luke & McArthur, 1978) and plant debris;

A surface fire is a fire that burns in the herbaceous surface vegetation (Brown & Davis, 1973; Luke & McArthur, 1978);

A crown fire is a fire that burns in the canopies of trees and shrubs (Brown & Davis, 1973; Luke & McArthur,1978).

Besides the aforementioned broad types of fires a further subdivision can be made into fires burning with the wind and against the wind.

A head fire is a surface or crown fire burning with the wind.

A back fire is a surface fire burning against the wind.

2.2.1.2 Spotting

Spotting is the initiation of a new fire ahead of a main fire by an airborne firebrand or ember (Luke & McArthur, 1978).

Fires arising from spotting are sometimes referred to as spot fires (Brown & Davis, 1973; Luke & McArthur, 1978) but it is felt that this is an unnecessary distinction because such fires develop into one or more of the three broad types of fires, viz. ground, surface or crown fires. Spotting refers to a process and is one of the ways in which new fires are initiated.

2.2.1.3 Fire regime

Fire regime is another all embracing term used to describe different aspects of burning. Gill (1974) and Huntley (1978) state that the term fire regime comprises the three components of season, frequency and intensity of a fire. The author is of the opinion that this is an incomplete description of the term and that it should also include the type of fire. This is because results to be presented later showed that back fires burning in grassland had a significantly greater depressive effect on the recovery growth rate of grass than head fires burning under the same environmental conditions. Conversely, head fires had a more detrimental effect on trees and shrubs than did back fires.

Therefore it is essential when describing the fire regime to also include the type of fire that has occurred or is envisaged or expected. The following definition is proposed to describe the term fire regime.

Fire regime refers to the season and frequency of burning and the type and intensity of the fire.

2.2.2 Terms describing fire behaviour and related parameters

There are very few definitions of the term fire behaviour in the literature. Brown & Davis (1973) defined it as "a general descriptive term to designate what a fire does". Luke & McArthur (1978) defined it as "the manner in which fuel ignites, flame develops and fire spreads and exhibits other phenomena".

It is believed that, from the ecological point of view, these definitions are inadequate because the central and essential concept of the release of heat energy during combustion is not mentioned. It is proposed therefore the term fire behaviour be used to define the release of heat energy during combustion as described by fire intensity, rate of spread of the fire front, flame characteristics and other related phenomena.

Numerous parameters have been developed to quantitatively describe the behaviour of a fire but in this paper only those parameters that are pertinent to the effect of fire on the biotic and abiotic components of the ecosystem need be considered. The pertinent parameters are those that describe the amount, rate and the vertical level at which heat energy is released during the fire.

2.2.2.1 Available heat energy

Factors that are used to describe and calculate the amount of heat energy released during a fire are fuel load, heat of combustion and heat yield:

Fuel load is the mass of plant material per unit area that is available for combustion during a fire. Units are kilograms per square metre - DMkg m^{-1} (Luke & McArthur, 1978).

Heat of combustion is the total amount of heat energy contained per unit mass of fuel. Units are kilojoules per kilogram - kJ kg^{-1} (Luke & McArthur, 1978)

Heat yield is the amount of heat energy available for release per unit mass of fuel. Units are kilojoules per kilogram - kJ kg^{-1} (Luke & McArthur, 1978).

Refer to section 4.2.1 for details of heat combustion and heat yield.

2.2.2.2 Rate of heat energy release

Fire intensity is the term used for describing the rate at which heat energy is released during a fire. The most widely accepted and used definition of fire intensity is that of Byram, (1959).

Fire intensity is the release of heat energy per unit time per unit length of fire front.

Units There is a conceptual difficulty with the units that are used to express fire intensity. In the U.S.A. fire intensity is expressed as British thermal units per second per foot (Byram, 1959; Brown & Davis, 1973; Albini, 1976) but in Australia, where the metric system is used, it is expressed as kilowatts per metre (Luke & McArthur, 1978). This is because the basic units in terms of the definition are kilojoules per second per metre, but a kilojoule per second is equal to a kilowatt, hence the unit kilowatt per metre. Herein lies the conceptual difficulty because, in the opinion of the author, expressing fire intensity in terms of power i.e. kilowatts, is not very meaningful. This is so because the effect of the fire on living organisms depends upon the release of heat energy and it is therefore felt that the units should be compatible with this concept. The incompatibility of the unit of power to express fire intensity is best illustrated by visualising the intensity of a fire in terms of the imperial unit, horse power! Therefore it is strongly recommended that fire intensity be expressed in units that are in accordance with the concept as originally conceived by Byram (1959) i.e. kilojoules per second per metre - kJ $s^{-1}m^{-1}$. This recommendation is made while fully realising the desirability of having standard units to describe physical objects and phenomena. However, it is also believed that units must be conceptually meaningful and that a system such as the International Metric System (S.I.) should be flexible enough to satisfy this requirement. It is worthwile to note that in the guide to the use of the S.I. metric system in South Africa published by the South African Bureau of Standards (annonymous, 1973) certain exceptions to the S.I. metric system are recognised. Therefore the precedent does exist to deviate from the S.I. metric system if it is considered advisable to do so.

An important parameter that is used in the calculation of fire intensity is the rate of spread of a fire. Brown & Davis (1973) defined the rate of spread as "a general term to describe the rate at which a fire increases either its area or linear dimensions".

Conversely Albini (1976) stated that rate of spread has the dimension of velocity and includes the forward rate, the rate of spread against a flank or a backing rate. Luke & McArthur (1978) did not define rate of spread but imply that it is the forward rate of spread of a fire and express it in terms of distance per unit time. Cheney & Vines (undated) make a distinction between rate of forward spread and rate of area spread.

Despite the ill-defined use of the term rate of spread in the international literature, the most widely used interpretation of this expression is to describe the forward rate of movement of a fire. Therefore it is recommended that the term rate of spread be defined and used in the following context.

Rate of spread is the forward movement of the fire front per unit time. Units In the U.S.A. non-metric units are generally used and will therefore not be considered. In Australia the following metric units are used (Cheney & Vines, undated).

Unit	Abbreviations	Remarks
metre/second	$m\ s^{-1}$	Research
metre/hour	$m\ h^{-1}$	Prescribed burning
kilometre/hour	$km\ h^{-1}$	Public information and forecasting

It is recommended that in South Africa the following units be used:

Unit	Abbreviations	Remarks
metre/second	$m\ s^{-1}$	Research
kilometre/hour	$km\ h^{-1}$	Prescribed burning, public information and forecasting

2.2.2.3 Vertical distribution of heat energy

Results presented in chapter 4 show that flame height is a reliable indicator of the vertical distribution of heat energy released during a fire.

Flame height is the perpendicular height of the flames from ground level (Luke & McArthur, 1978). It is in most cases expressed as a mean value and does not take into account occasional flame flashes which rise above the general level of flames. Units are metres - m (Luke & McArthur, 1978).

The interrelationships between the main components of fire ecology, fire regime and fire behaviour are illustrated in Figure 2.1.

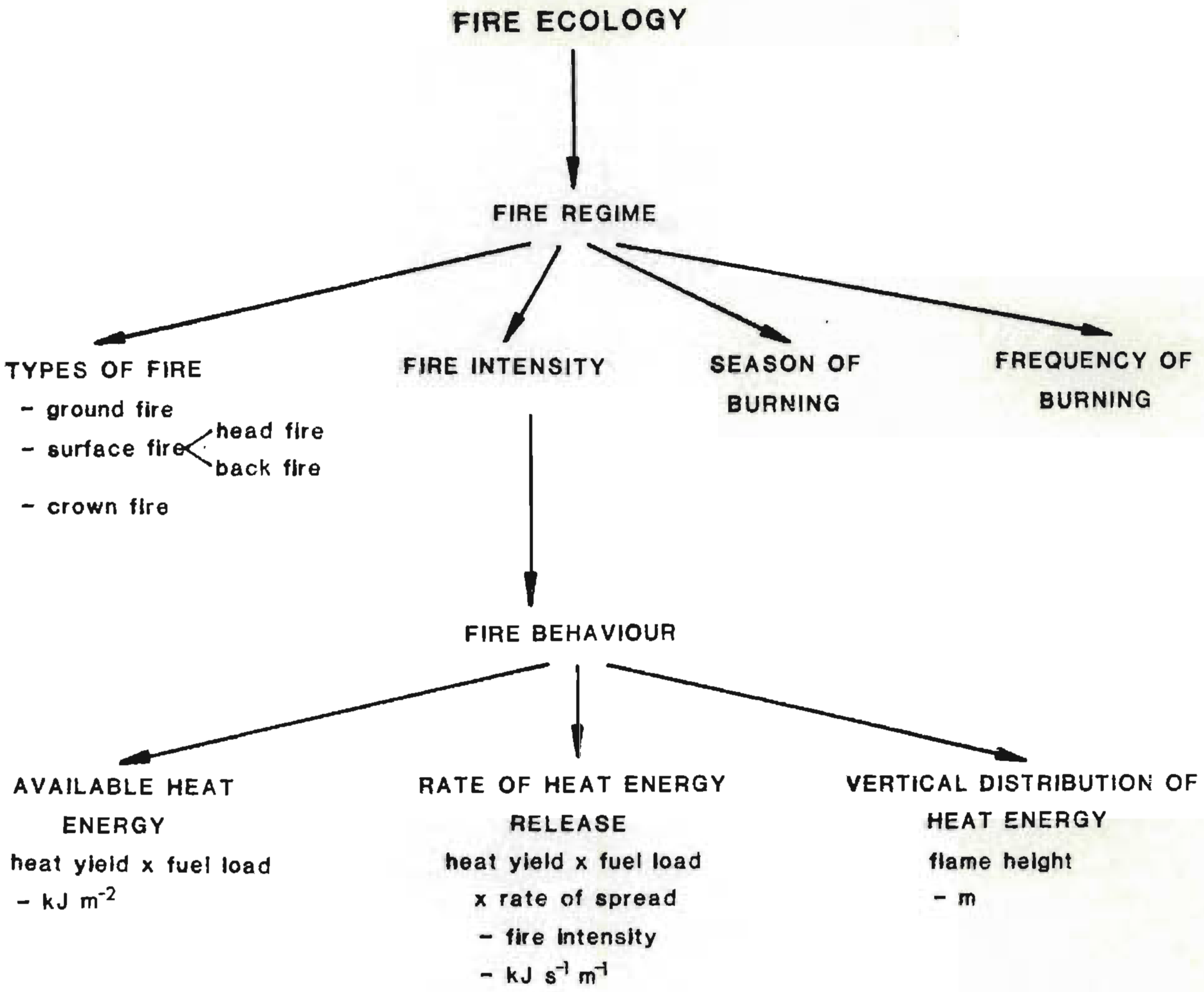

FIGURE 2.1. The interrelationships between fire ecology, fire regime and fire behaviour.

2.3 NATURAL FIRE REGIME

A study of the literature shows that there is virtually no information available on the ancient fire regime that existed prior to the advent of man or before his presence had a significant effect in the savanna areas of South Africa. Nevertheless, based on a knowledge of fire behaviour it is logical to expect that the factors that played the greatest role in determining the season, frequency and intensity of natural fires in the savanna were fuel load, fuel moisture and the incidence of lightning. The savanna areas of South Africa are largely confined to the summer rainfall region which is characterised by a dry season extending from approximately May to October, at the end of which the herbaceous/grass fuel layer is very dry. Komarek (1971) stated that Africa has a unique fire climate that accentuates the probability and occurrence of lightning fires because at the end of the dry period dry lightning storms frequently occur and ignite many fires. The importance of lightning as an ignition source is illustrated by Siegfried (1980) who reported that in the Etosha National Park, where a policy of fire exclusion is applied, at least 54 per cent (30 fires) and probably 73 per cent (41 fires) of all fires that occurred during the period 1970 to 1979 were caused by lightning. In the Kruger National Park Gertenbach & Potgieter (1979) recorded found that lightning caused 45 per cent of all unscheduled fires during the 1977/78 season.

2.3.1 Types of fire

In the savanna areas both crown and surface fires occur but the most common are surface fires burning with or against the wind as head or back fires. Crown fires develop only under very dry conditions when the fuel moisture is low and the prevailing weather is characterised by high winds, high air temperatures and low relative humidities. Surface fires are generally more frequent than crown fires in the savanna because the foliage of tropical and sub-tropical trees and shrubs is relatively non-flammable and will ignite only under extreme atmospheric conditions. This is in contrast to temperate vegetation, like macchia, where the leaves are very inflammable due to the presence of terpenes, and crown fires normally develop in this type of vegetation. The exception to this general rule of the non-flammability of savanna trees and shrubs is the Mopane Veld of the northern and north eastern Transvaal dominated by *Colophospermum mopane* (mopane). This species has highly inflammable foliage because of the presence of volatile oils which lead to the development of crown fires even under mild atmospheric conditions.

A very interesting and pertinent aspect of fire behaviour in savanna is that bush clumps are generally very resistant to fire even under extreme burning conditions. Fires generally skirt around the edges of the bush clumps, leaving the centre unburnt. Observations indicate that this phenomenon is caused either by a lack of grass fuel under the trees and shrubs of the bush clump or by relatively non-flammable grass species growing under the trees and shrubs of the bush clump. In the Eastern Cape two common grass species occurring in bush clumps are Panicum maximum and Karrochloa curva, both of which generally have higher moisture contents than the grasses growing between the bush clumps. The practical significance of this phenomenon is that once bush encroachment has progressed to the bush clump stage then fire is a far less effective management tool than during the initial stages of encroachment.

2.3.2 Fire intensity

Considering the intensities of fires occurring during the natural fire regime, it is reasonable to assume that fire intensities were far greater in the past than at present. This is because Acocks (1953) has presented widely accepted botanical evidence indicating that the grass component of the veld in South Africa has been drastically altered and reduced in all veld types, including the savanna, since settled agricultural conditions came into being. The effect of a drastic reversal in the grassland succession to a more pioneer stage on the production of grass fuel is illustrated by data presented by Dankwerts (1981). He found that in the False Thornveld of the Eastern Cape the phytomass of grass produced per unit area by pioneer veld dominated by species like Aristida congesta, was only 13 per cent of that produced by climax veld dominated by Themeda triandra. Bearing in mind that grass constitutes the major component of the fuel load in savanna fires and is the most important factor influencing fire intensity, it clearly indicates why the fires of the natural fire regime were probably far more intense. Another factor that contributed to higher intensities was that the fires were able to burn under more extreme conditions in contrast to controlled burning as applied at present. Obviously intense wild fires do occur during present times but are the exception rather than the rule.

The intensity of the fires of the natural fire regime was probably higher in the moist savannas than in the arid savannas because of greater fuel loads. However, fire behaviour data would reveal that the moist savannas of the southeastern seaboard experienced cooler fires than the northern and western savannas of the interior because the grass fuel moisture and the relative humidity are generally higher along the coastal areas than inland.

2.3.3 Season of burning

Concerning the season of burning that occurred in the natural fire regime Komarek (1971) quotes the Secretary of Forestry in South Africa (1967) who stated that most of the fires of any consequence that are initiated by lightning occur during the early summer months, October and November, before the summer rains have commenced or set in properly. This evidence would reveal that the burning season under the natural fire regime occurred most frequently at the end of the dry season and just prior to the first spring rains. Obviously fires also occurred at other times of the year in response to unseasonal drought periods and other ignition sources like rock falls.

2.3.4 Frequency of burning

The frequency of burning in the natural fire regime would have been largely influenced by the rate of accumulation of sufficient grass fuel to support a fire and the availability of an ignition source. Rainfall is the most important factor affecting the productivity of the grass sward under veld conditions and therefore also the accumulation of grass fuel. Thus, assuming equivalent ignition probabilities, fires were undoubtedly more frequent in the moist savannas (> 650mm per annum) than in the arid savannas because of the more rapid accumulation of grass fuel in response to higher rainfall and the loss in acceptability of the grass herbage to herbivores on reaching maturity.

Present day research indicates that the natural frequency of fires in the moist savannas must have ranged between annual and biennial, depending upon the seasonal rainfall and the degree of utilization of the vegetation by wild ungulates. Evidence for this fire frequency is provided by Scott (1971) who found that in the Southern Tall Grassveld (720mm per annum) of Natal, which Acocks (1953) described as open savanna, complete protection of the grass sward for three years caused it to become moribund and die out. Conversely annual and biennial burning maintained a vigorous grass sward with a far superior basal cover. Furthermore, in the Kruger National Park, where fire is an important component of the veld management strategy, it has been concluded from burning experiments initiated in 1954 that the most desirable burning frequency under grazing conditions in the moist savanna areas is annual or biennial, depending upon grazing and grass fuel conditions (Gertenbach, 1979).

In the arid savannas the frequency of fire must have been far lower than in the moist savannas because the rainfall is both less and highly erratic and the grass sward remains acceptable to grazing animals even when mature, thus reducing the rate of accumulation of grass fuel. The frequency of fires would have been determined by the occurrence of exceptionally wet seasons. Studies by Tyson & Dyer (1975) showed that periods of above and below average rainfall occur at cyclic intervals of approximately ten years. Thus the frequency of fire in the arid savannas would have varied according to the prevailing stage in the rainfall cycle. Results presented by Gertenbach & Potgieter (1979) for the mopane shrubveld in the Kruger National Park, showed that under grazing conditions annual and biennial burning significantly reduced the basal cover of the grass sward and resulted in an increase of pioneer grass species when applied during a dry rainfall cycle. Bearing these results in mind and considering the period 1910 to 1980, Gertenbach & Potgeiter (1979) concluded that annual and biennial burning were the appropriate burning frequencies during the above average rainfall periods. Conversely, burning once every three to five years and at times, complete fire exclusion, was applicable during the dry rainfall periods. Thus in the arid savannas no definite burning frequency apparently occurred other than it being less frequent than in the moist savannas and that it largely depended on the rate of accumulation of grass fuel in response to the amount of rainfall and the stocking rate of grazing animals.

In conclusion, the natural fire regime in the savanna areas undoubtedly resulted in a fire mosaic of areas burnt by different types and intensities of fire occurring at various times and frequencies, all of which maintained a diversity of vegetation types and so provided ideal habitats for a wide range of animals.

2.4 EFFECT OF FIRE ON THE GRASS/BUSH BALANCE

Considerable attention has been given to the effect of fire on the balance (ratio) between grass and trees and shrubs in the savanna areas (Scott, 1947, 1952, 1955, 1970, 1971; West, 1955, 1969; Donaldson, 1969; Roux, 1969) because of the economic significance of the grass layer to domestic livestock production. The general conclusion is drawn that fire _per se_ favours the development and maintenance of a predominantly grassland vegetation by destroying the juvenile trees and shrubs and preventing the development of the more mature plants to a taller fire resistant stage. However, once the bush has become dominant and is suppressing the grass, fire is no longer effective because of insufficient grass fuel being present to support an intense fire.

Conversely van der Schijff (1957) quoted observations made in the Kruger National Park and at Mara Research Station in the northern Transvaal which suggested that the development of a dense vigorous grass cover and the withdrawal of fire resulted in the significant dying-off of _Dichrostachys cinerea_ and _Acacia_ species. He concluded that, in the drier areas of South Africa, it was probably possible to restore a desirable grass/bush balance by resting an area for an indefinite period and protecting it from fire. Pienaar (1959) supported these observations and reported that at the Towoomba and Soutpan Research Stations and in the Pietersburg district of the northern Transvaal, _D. cinerea_, _Acacia karroo_, _A. nilotica_ and _A. tortilis_ were successfully being reduced in density by excluding fire and resting the veld. Both van der Schijff (1957) and Pienaar (1959) stated that burning often merely destroys the aerial portions of trees and shrubs causing them to coppice and produce numerous stems. However, Pienaar (1959) felt that in situations where the increase in bush was still in the initial stages it may be possible to control it with veld burning.

Van Wyk (1971) refutes the observation that D. cinerea is fire dependent and susceptible to competition from a dense grass cover. He concluded from quantitative data obtained in the Kruger National Park that D. cinerea increased in density with the exclusion of fire and showed no increase in numbers on burnt plots. However, Gertenbach (1979) is of the opinion that the anomaly concerning D. cinerea is due to there being two subspecies of Dichrostachys that react differently to fire. The subspecies africana occurs in the moist savannas and is as van Wyk (1971) maintains, not encouraged by fire and does not succumb to increased grass competition. Conversely the subspecies nyassana occurs in the arid savannas and is as van der Schijff (1957) and Pienaar (1959) claim, stimulated to coppice and develop profusely after a fire but is susceptible to increased grass competition.

The author has also observed the depressive effect of the exclusion of fire and increased grass competition on D. cinerea and Acacia karroo in the Mixed Bushveld and Sourish Mixed Bushveld in the Thabazimbi district of the north western Transvaal. This phenomenon, is though, of a localised nature in that area and is apparently associated with deep heavy soils. It does not apply to other bush species in the area like Acacia tortilis, A. erubesceus, Grewia flava and Ziziphus mucronata.

2.5 EFFECT OF FIRE REGIME ON THE VEGETATION

2.5.1 Type of fire

Apparently no published data are available on the effect of type of fire on the vegetation in the savanna areas of South Africa.

2.5.2 Fire intensity

Similarly apparently no published data are available on the effect of fire intensity on the vegetation in the savanna areas of South Africa.

2.5.3 Season of burning

Very little published quantitative information is available on the effect of season of burning on the grass sward in the savanna. The results from burning experiments in the Kruger National Park are confounded with grazing and van Wyk (1971) drew attention to the cumulative effect of grazing after burning, particularly in the annual spring burns and to a lesser extent the biennial burns applied in April and August. These effects of grazing make it very difficult to identify the effect of the season of burning per se on the herbaceous grass layer.

West (1965), reporting on the effect of season of burning on the grass sward in the savanna areas of Zimbabwe, stressed the importance of burning when the grass is dormant and advocated burning just prior to the spring rains when fire is used to control bush encroachment. This is in conflict with Scott (1971) who stated that burning in winter damages the grass and, when using fire to control bush encroachment, recommended burning after the first spring rains. However, Scott (1971) quoted data from the Southern Tall Grassveld of Natal, where the mean grass basal cover of plots burnt in autumn, late winter and after the first spring rains for a period exceeding 20 years as 12,8, 13,0 and 14,4 per cent respectively. The absence of large differences in the mean grass basal cover obtained with these different seasons of burning would reveal that for all practical purposes burning when the grass sward is dormant in late winter or immediately after the first spring rains has very little difference in effect on the grass sward. This conclusion is supported by Tainton, Groves and Nash (1977) and Dillon (1980) who also found that burning before or immediately after the first spring rains in the Tall Grassveld of Natal had essentially the same effect on the recovery of the burnt veld. Conversely if the veld is burnt later in the season when it is actively growing, it causes a high mortality of tillers of Themeda triandra, resulting in a significant reduction in the abundance of this species (Dillon, 1980).

It is difficult to ascertain the effect of season of burning on trees and shrubs in savanna because generally it is confounded with fire intensity. Van Wyk (1971) stated that in the Kruger National Park burning during late winter and early summer (end of dry season) resulted in very hot fires, whereas burning during summer (wet season) resulted in much cooler fires. Therefore it is difficult to ascertain the true effect of season of burning *per se* on trees and shrubs because it is confounded with fire intensity.

Suffice it to say that West (1965) postulated that trees and shrubs are probably more susceptible to fire at the end of the dry season than at the beginning of the dry season for the following reasons:

- The initial temperature of the plant tissue is high and is therefore closer to the lethal temperature for plant tissue.

- Most of the trees have produced new leaves, probably resulting in the plant reserves being depleted.

- Less protection is provided by the bark because there is a probable increase in the moisture content and therefore an increase in the thermal conductivity of the bark with the resumption in active growth.

- New leaves are very susceptible to heat damage. Therefore the trees are more readily defoliated and are forced to again draw from already depleted plant reserves to produce new leaves.

Kennan (1971) supported this view and stated that at the Matopos Research Station in Zimbabwe damage to trees was greatest when burnt in spring after the trees had flushed. He found it difficult however, to test this hypothesis because the mortality of plants was generally low.

The effect of burning on the production of seed was recorded in an experiment at the University of Fort Hare where a T. triandra dominant sward produced significantly more T. triandra seed when burnt during a drought in midsummer than when burnt immediately after the rains a month later. Burning after the first spring rains virtually prevented any seed from being produced (Trollope, 1983).

In an experiment investigating the effect of burning or mowing on the seeding of Anthephora pubescens, an important grass species in the savanna areas of the northern Cape Province, Nursey and Kruger (1973) found that grassland which was burnt at the beginning of the growing season produced 19 per cent more seed than areas mown at this time. They also found that both treatments significantly depressed the production of seed when applied later in the season at the early piping stage.

The effect of fire on seed germination has not been studied on a seasonal basis but only from the point of view of a heat treatment per se. West (1951) found that the germination of fresh T. triandra seed was significantly increased by a heat treatment involving pre-drying at temperatures of 30° to 40°C. Trollope (1983) conducted an investigation in the savanna areas of the Eastern Cape which indicated that fire may stimulate the germination of T. triandra. In a survey conducted on burnt and unburnt veld dominated by T. triandra 18 days after a wild-fire burnt an extensive area, the density of T. triandra seedlings in the burnt area was $190{,}5\text{m}^{-2}$ and that in the unburnt area $0{,}2\text{m}^{-2}$. Germination tests on seed collected from the soil surface in the burnt and unburnt areas showed that only the seed from the unburnt area germinated (2,7 per cent germination). Mowing the unburnt veld to expose the soil surface failed to stimulate any germination of T. triandra seed. These results reveal that in the burnt area only seed that was embedded in the ground germinated. This seed would have been protected by the insulating effect of the soil against the damaging effect of the fire but could still have been subjected to a stimulatory heat treatment. Cresswell and Nelson (1972) showed that the physiological dormancy of T. triandra seed can be broken using biochemical manipulations, a result which lends support to the possibility that the heat treatment may have the same effect on dormant T. triandra seed.

The effect of fire on the germination of seed of trees and shrubs was investigated by Story (1952). He quoted Sim (1907) as stating that the germination of seeds of Acacia karroo is greatly enhanced by a severe heat treatment. He also found experimentally that treating A. karroo seed with either boiling water or a ground fire stimulated germination very significantly. He concluded that the stimulation of germination was due to the breaking of the hard seed testas, making it more permeable and thus enhancing the germination process. However, observations by the author after numerous fires in the savanna areas of the Eastern Cape indicate that the seeds of A. karroo are not necessarily stimulated to germinate after a fire. MacDonald (1980) reported similar findings in the Hluhluwe Game Reserve in Zululand where single fires did not give rise to any significant establishment of seedlings of A. karroo, A. davyi and Euclea divinorum during the first post-fire season. These results reveal that the stimulation of germination occurs only when conditions are very dry, fire intensities very high and the burn is followed by favourable moisture conditions.

2.5.4 Frequency of burning

When considering the effect of frequency of burning on vegetation a clear distinction must be made between the effect of burning at a particular frequency, the number of times that the treatment has been applied and the type of management that is used during the interval between the fires. All three factors have a significant influence on the vegetation and must be borne in mind when interpreting burning frequency results. For example Kennan (1971) at Matopos Research Station in Zimbabwe found that initially, annual burning had the most deleterious effect on trees and shrubs but that as the grass sward deteriorated with the application of this treatment, so fire became progressively less damaging to the bush. Therefore the effect of annual burning varied according to the number of times that the treatment was applied.

The effect of the management that is applied during the interval between burns is very important and in most of the experiments in South Africa and Zimbabwe it would appear that this factor is confounded with the frequency of burning. For example, van Wyk (1971) stated that in the Kruger National Park overgrazing of the grass sward was a very serious problem in many of the experimentally burnt plots and was correlated with the frequency of burning, the most apparent effect being manifested on the annual and to a lesser extent, biennial burning treatments. He drew the general conclusion that factors such as overgrazing, drought and frost complicate the interpretation of the results to such an extent that it is difficult to ascribe the response of the vegetation to a particular burning treatment.

Further evidence of the confounding effect of the type of management during the interval between burns is provided by Robinson, Gibbs Russel, Trollope and Downing (1979) who found that in the absence of grazing in the Eastern Cape, annual burning resulted in a high rooted frequency of grasses but a low rooted frequency of forbs. Conversely, quadrennial burning caused a significant decrease in the grasses and a significant increase in the forbs. However, complete protection for five years also resulted in a reduction in the rooted frequency of grasses and an increase in the rooted frequency of forbs. Therefore it would appear that the effect of burning once every four years is confounded with the effect of resting for four years and that the grasses decreased due to their becoming moribund through a lack of defoliation and not because of being burnt once every four years.

Another confounding effect in burning frequency treatments applied under conditions of no grazing are different fire intensities resulting from different fuel loads accumulating during the interval between fires. Generally the longer the interval the greater the fuel load and therefore the higher the fire intensity.

On the basis of the aforegoing discussion it would appear that only limited conclusions can be drawn from the published research data on the effect of frequency of burning in savanna areas. Van Wyk (1971) presented long term data (15 years) on the effect of annual, biennial and triennial burning treatments on the grass component in the Kruger National Park but as already mentioned the effects are confounded with the grazing that occurs after the fire. At Matopos Research Station, Kennan (1971) found after 14 years, that under conditions of no grazing the effect of fire was greatest in the thornveld which occurs on heavier soils than in the sandveld which has lighter soils. In the former, annual burning resulted in a very poor basal cover with perennial grass species being replaced by annual grass species. Less frequent burning resulted in an improved basal cover and dominance of perennial grass species with triennial burning being the most desirable treatment. Apparently in the dry climate of Matopos the extended period without defoliation between fires had no significant effect in itself as shown in the data presented by Robinson *et al* (1979).

Robinson *et al* (1979) found at the University of Fort Hare that frequent burning favoured the dominance of *Themeda triandra*. Similar results were obtained by Scott (1971) and Dillon (1980) in the Tall Grassveld of Natal where annual burning in late winter and spring favoured the dominance of *T. triandra*. Conversely *Tristachya leucothrix* became dominant with complete protection and with less frequent burning.

Considering the effect of frequency of burning on the tree and shrub component, Kennan (1971) found that provided there was sufficient grass fuel to ensure an intense enough fire, all frequencies of burning resulted in a topkill of smaller trees and shrubs, the majority of which coppiced again. The only effect of frequency of burning was the degree to which the plants recovered during the interval between fires. After a period of 15 years no significant changes had occured in the densities of trees and shrubs. Similar conclusions can be drawn from data presented by van Wyk (1971) from the Kruger National Park where in moist savanna after 15 years there were no biologically meaningful changes in the bush density in response to different burning frequencies.

Conversely Sweet (1982) showed that after 22 years, annual and biennial burning resulted in a significantly lower density of bush (38,9 per cent) than burning every third, fourth and fifth year in arid savanna in Botswana. Similarly, Boultwood & Rodel (1981) found in moist savanna in Zimbabwe that after 14 years, annual burning resulted in a significantly greater reduction in the density of bush than biennial and triennial burning.

It is difficult to draw any general conclusions from these results except to note that in all cases significant numbers of bushes remained even in the areas burnt annually. Therefore burning cannot be regarded as a means of bush eradication in the savanna areas but rather as a method of control.

2.6 EFFECT OF FIRE ON HERBAGE PRODUCTION AND QUALITY

2.6.1 Effect on herbage production

There is very limited quantitative information available on the effect of the fire regime on the production of herbage in the savanna areas.

Studies in the Tall Grassveld of Natal have shown very little if any difference in the pattern of recovery growth of veld burnt either late winter or early spring when the grass sward is dormant (Tainton *et al*, 1977; Dillon, 1980). Conversely burning when the grass sward is actively growing during late spring and early summer caused a significant reduction in the yield during the following season. This was caused by the high mortality of actively growing tillers in response to the fire (Dillon, 1980). No published information is available on the effect of type and intensity of fire and frequency of burning on grass production in the savanna areas.

There is also no published information available on the effect of the fire regime on the production of browse by trees and shrubs in the savanna areas.

2.6.2 Effect on the herbage quality

West (1965) stated that the fresh green shoots of new growth on burnt grassland are very high in protein and that the new herbage is much sought after by grazing animals. He reported also that Plowes (1957) found that the average crude protein content of recovery growth of 20 common grass species growing on three soil types at the Matopos Research Station in Zimbabwe, was 19 per cent after burning. Tainton et al (1977) found in the Tall Grassveld of Natal that initially the protein content of new leaves of grass burnt shortly before (September) and after the first spring rain (October) was approximately 2,6 per cent higher than for grass mown at the same times. Conversely, there was no difference in the protein content of new regrowth in grasses that were burnt or mown in late winter (August).

No information is apparently available on the effect of burning on the chemical content of the browseable material of savanna trees and shrubs.

CHAPTER 3

ROLE OF FIRE IN CONTROLLING BUSH ENCROACHMENT IN THE ARID SAVANNAS

3.1 INTRODUCTION

It is clear from the review of literature presented in Chapter 2 that a rather contradictory situation exists regarding the effect of fire on the balance of grass and bush. Nevertheless personal observations made during extensive travels through the savanna areas of Southern Africa have led to the conclusion that the effect of fire on the grass/bush balance can be summarised as follows. Generally the tree and shrub species of the savanna areas are very resistant to fire alone since many of them coppice from dormant buds situated at the base of the stem. In the moist savannas it is possible to control bush encroachment with fire alone, because even though the bush species coppice, the rainfall is sufficient and reliable enough to enable adequate amounts of grass material to accumulate under grazing conditions to support frequent enough fires to burn down the coppice growth and to control bush seedlings. In the arid savannas which constitute the major portion of the South African savannas, the rainfall is too low and erratic to support frequent enough fires under grazing conditions to prevent the regeneration of bush from coppice and seedling growth. Support for this is provided by Kennan (1971) who states that at the Tuli Experiment Station in south western Zimbabwe, a burning trial was abandoned because it was impossible to apply regular burning treatments. The area has a very low and erratic rainfall (450mm per annum) which causes marked fluctuations in the seasonal production of grass material and therefore insufficient fuel loads to support a fire.

These conclusions led to the postulation of a hypothesis that the role fire can play in controlling bush encroachment in the arid savannas is to maintain bush at an available height and in an acceptable state for browsing animals. This hypothesis is based on the assumption that in the past fires were initiated by lightning and/or primitive man after abnormally high rainfall seasons when there was an exceptional accumulation of inflammable grass material. The resultant fierce fires destroyed the aerial growth of encroaching bush species, thus providing coppice growth at an available height and in an highly acceptable state for browsing by wild ungulate species. This browsing treatment controlled or at least decreased the recovery rate of the coppicing bush. The author has observed these interacting effects of burning and browsing on the recovery of bush after intense fires in the Mkuze Game Reserve in northern Natal and in the Kruger National Park in the eastern Transvaal.

This hypothesis was tested in an experiment conducted on the research farm of the University of Fort Hare in the Ciskei.

3.2 PROCEDURE

The experiment was conducted on the research farm of the University of Fort Hare situated in the False Thornveld of the Eastern Cape (Acocks, 1953) in an area of sweet grassveld moderately encroached with Acacia karroo and other bush species. The grass sward had a total basal cover of 16,8 per cent, the dominant species being Themeda triandra (42,2 per cent of the basal cover). Other important grasses were Panicum stapfianum, Digitaria eriantha, Cymbopogon plurinodis, and Sporobolus fimbriatus.

The density of the bush in the area, as estimated using a concentric circle survey of 53 circles (du Toit, 1973) was 1625 ± 119 plants per hectare and 89,5 per cent of the bushes present were Acacia karroo. Other associated species included Ehretia rigida, Diospyros lycioides, Rhus lucida, Grewia occidentalis and Scutia myrtina.

The experiment was situated at an altitude of 580m in an area which received an annual rainfall of 539mm with a coefficient of variation of 25,6 per cent during the period 1909 to 1982. The soil type in the experimental area is a sandy loam of the Glenrosa form.

3.2.1 Treatments

The treatments fall into two catagories. Firstly the entire experimental area of 2,2 hectares was burnt during September, 1972 and the effect of fire on the bush was assessed. Thereafter follow-up treatments were superimposed on the burnt area to determine the effect of browsing and burning on the vegetation.

3.2.1.1 Initial burning treatment

The experimental area was burnt with a surface head fire on the 11th September, 1972, seven days after 56mm of rain had fallen. The details of the initial burning treatment are presented in Table 3.1.

TABLE 3.1. The details of the initial burning treatment applied to the experimental area.

Variable	Value
Fuel load	0,6352 kg m^{-2} (6,4 t ha^{-1})
Fuel moisture	25,1% 1000 ^ 10 000
Soil moisture (0 - 20cm depth)	17,6%
Relative humidity	21%
Air temperature	28°C
Wind speed (estimated)	±5 m s^{-1} (±18 km h^{-1})
Fire intensity (estimated)	3875 kJ s^{-1} m^{-1}

The fuel load mentioned in Table 3,1, comprised almost exclusively of grass had accumulated over two years i.e. 1/9/70 to 11/9/72. The fire intensity was estimated using the prediction equation presented on page 88.

3.2.1.2 Follow-up treatments

Three months after the application of the initial burning treatment, the experimental area was subdivided into three plots to which follow-up treatments were applied. The follow-up treatments comprised stocking with goats, annual spring burning, and a control treatment (K1). A second control treatment (K2) was introduced on the 1st September, 1976 and was adjacent to the original experimental area. The layout of the plots are presented in sketch form in Figure 3.1.

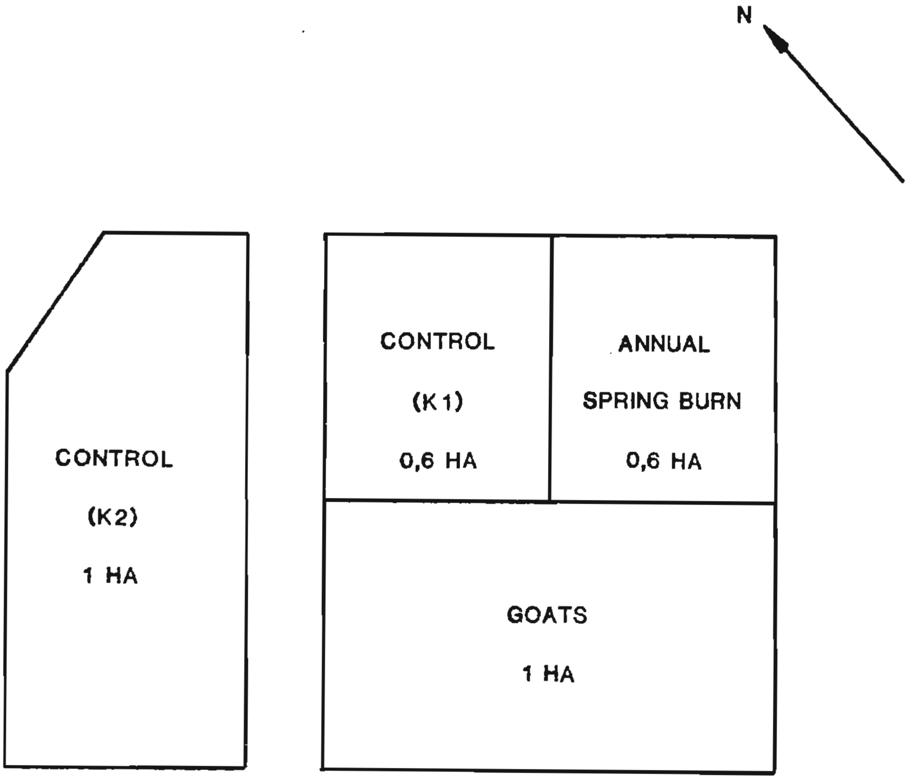

FIGURE 3.1. A sketch plan of the experimental area indicating the different follow-up treatments.

(i) <u>Goat treatment</u>

This treatment comprised stocking an area, one hectare in size, with mature goats at a stocking rate of approximately one goat per hectare. However, because goats are gregarious animals the treatment was applied by stocking the plot with three goats for three days per week from sunrise to sunset. Stocking was commenced as soon as the coppice growth of the bush had grown to a height of 150 to 300mm after the initial burn. This simulated continuous stocking was applied provided the grass sward was 50mm or more in height, the object being to keep the coppice growth of the bush under control but not at the expense of the grass sward.

(ii) Annual spring burn treatment

Annual spring burning was applied to a plot 0,6 ha in size provided at least 2 500 kg ha^{-1} of grass had accumulated during the previous season. Initially the burns were applied after the first spring rains of at least 13mm. However, in latter years the fires were applied before the first spring rains because with repeated annual burning the fires would not carry when applied after the rains. The object of this treatment was to determine the effect of frequent fires on the recovery of bush.

(iii) Control treatments

The initial control treatment (K1) comprised an area of 0,6 ha which was not stocked with goats after the initial burning treatment. The object of this treatment was to determine the recovery of the bush after a single intense fire in the absence of browsing.

A second control treatment (K2) was included in 1976 to determine the extent to which goats were utilizing the grass in the goat plot. This treatment had become necessary because the goats had suppressed the bush to a very significant degree by this stage and were being forced to supplement their diet with grass. This treatment comprised eradicating all the bush from an area one hectare in size and allowing the grass sward to grow uninterrupted for the entire growing season.

Finally, in the case of the goat and two control treatments, the grass was grazed off short immediately after the first frost at the end of autumn (April/May) each year. Non-protein nitrogen blocks were provided in each plot and the stocking density of cattle approximated that which would occur in a 12 camp one herd system with a stocking rate of three hectares per animal unit. The object of this treatment was to maintain the grass in a vigorous and productive state.

3.2.2 Measurements

Parameters pertinent to the reaction of the bush and the grass to the treatments were recorded during the course of the experiment. These are discussed below.

3.2.2.1 Fire behaviour

Measurements pertinent to fire behaviour were recorded before and during the application of the burns. The pre-burn measurements comprised estimating the fuel load and fuel moisture content of the standing grass crop prior to burning. The fuel load was initially estimated by cutting 20 square metre quadrats but from 1978 onwards all estimates of the standing crop of grass were made using the disc pasture meter developed by Bransby and Tainton (1977). Furthermore, all estimates of the standing crop of grass recorded with the square metre quadrat have been adjusted so as to be compatible with those determined with the disc pasture meter. The fuel load was expressed in kg/m^{-2}.

The fuel moisture was recorded by taking ten stratified, random grass samples immediately before burning. These were dried at 80°C for 96 hours. The moisture content was expressed as a percentage of dry mass.

The soil moisture was recorded by taking ten samples on a stratified random basis to a depth of approximately 20cm. The samples were oven dried at 80°C for 96 hours and the moisture content was expressed as a percentage of dry mass.

During the fire the temperature and relative humidity of the general atmosphere was recorded with a whirling psychrometer and was expressed in degrees Celsius and as a percentage, respectively. The wind speed was recorded with a digital cup annemometer and was expressed in metres per second. The rate of spread of the fire front was recorded using the procedure described on page 66. The rate of spread, used for calculating the intensity of a fire, was expressed in metres per second. Initially the rate of spread was not recorded because of the absence of suitable procedures for measuring it. However, in 1974 a technique was developed for estimating the rate of spread and as mentioned, is described later.

3.2.2.2 Bush surveys

(i) After the initial burn

A survey was conducted ten weeks after the initial burn to determine the effect of the fire on the bush. The survey comprised recording the response of all bush species occurring in the experimental area, except for a border area 10m wide around the perimeter. The reaction of the bush was classified into the following categories:

(a) dead;
(b) top growth killed; coppicing from the base of the stem;
(c) top growth not killed; coppicing from the base of the stem and shooting from the branches;
(d) top growth not killed; shooting from the branches.

During the first season after the burn a photographic point technique (Aucamp, 1973) was used to an estimate the amount of coppice growth of Acacia karroo that was not browsed by goats. Thirty stratified, random, coppicing bushes were photographed from the same distance in each treated plot using colour positive film. The resultant slide photograph of each coppicing bush was projected on to metric graph paper from a fixed distance and the number of strikes were recorded at one centimetre intervals along the widest horizontal axis of the coppice growth. A strike was defined as any living plant material coming in contact with the centimetre grid intersections on the graph paper. The results were expressed as the percentage strikes of living plant material. The difference between the mean percentage strikes of living plant material in the control and goat plots indicated the degree to which the goats had browsed the coppice growth in the goat plot.

(ii) After the follow-up treatments

The effect of the follow-up treatments on the bush were recorded in annual surveys of the control (K1), goat and annual spring burn plots. Each bush was identified to species and its height measured during early summer (November/December) of each year, commencing in 1976. These data were used for calculating the density of the bush, and expressed as plants per hectare, and also to develop an index of the phytomass of the bush. Phytomass was expressed in tree equivalents (Teague, Trollope & Aucamp, 1981), a tree equivalent being defined as a tree or shrub 1,5m tall. The number of tree equivalents per hectare was calculated by dividing the total height of the bush recorded in the surveys by 1,5m and adjusting for the size of the sample area. This parameter proved most useful because it provided some quantitative measure of the volume of bush canopy in an area.

3.2.2.3 Grass surveys

A detailed botanical grass survey comprising a point quadrat analysis of 1 678 points was conducted in the experimental area during the autumn following the application of the inital burn. Similar surveys were conducted in the follow-up treatment plots during 1976, 1977, 1979 and 1981.

The seasonal production of grass was recorded in all the plots every year after the first frost in winter (April/May). Initially this was done by cutting 30 square metre quadrats per plot but fom 1978 onwards the disc pasture meter, as described by Bransby & Tainton (1977), was used. In both cases stratified random sampling was applied. The disc pasture meter estimate was based on the mean of 100 disc height readings and the standing crop of grass was estimated using the regression equation presented on page 78.

3.2.2.4 Climatic data

A rain gauge was erected at the experimental site and daily precipitation was recorded.

Other climatic data were recorded at the University of Fort Hare weather station approximately 5km from the experimental site.

3.3 RESULTS AND DISCUSSION

The results will be presented and discussed in terms of the immediate and long term effects of the treatments on the vegetation.

3.3.1 Immediate treatment effects

The initial burning treatment comprised a high intensity fire (3875 $kJ\ s^{-1}\ m^{-1}$) which had a marked effect on the bush in the experiment. The majority of the bushes suffered a kill of stems and branches (80,8%) and most of them coppiced from the base of the stem (71,5%). Only a small proportion of the bushes were killed (9,3%). The bushes that did not suffer a complete kill of stems and branches were, nevertheless, adversely affected by the fire because considerable dieback occurred from the extremities of the branches. The overall size of these bushes was significantly reduced by the fire in the majority of cases. The only specimens that recovered fully after the burn were the large multi-stemmed plants of Rhus lucida which were up to 6m in height.

The detailed effects of the fire on the bush are presented only for Acacia karroo because this was the dominant species in the experimental area and the only one that was adequately represented in most of the height and stem diameter classes. Visual observations were made of the response of the other bush species to the fire.The effect of the fire on plants of A. karroo of different heights is presented in Table 3.2.

TABLE 3.2 The effect of the initial burning treatments on plants of Acacia karroo in different height classes expressed as number of plants and as a percentage.

Height class	Top Growth Killed						Top Growth Not Killed						Total	
	Dead		Coppicing		Total		Coppicing & Shooting		Shooting		Total		No	%
	No	%	No	%	No	%	No	%	No	%	No	%		
0 - 0,50m	-	-	14	100,0	14	100,0	-	-	-	-	-	-	14	2,5
0,51 - 1,00m	7	6,0	110	94,0	117	100,0	-	-	-	-	-	-	117	21,5
1,01 - 1,50m	14	10,9	110	85,9	124	96,8	2	1,6	2	1,6	4	3,2	128	23,0
1,51 - 2,00m	18	13,6	92	69,7	110	83,3	16	12,1	6	4,6	22	16,7	132	23,8
2,01 - 2,50m	11	11,1	51	51,5	62	62,6	23	23,3	14	14,1	37	37,4	99	17,8
2,51 - 3,00m	5	8,5	19	32,2	24	40,7	21	35,6	14	23,7	35	59,3	59	10,6
3,01 - 3,50m	-	-	2	50,0	2	50,0	-	-	2	50,0	2	50,0	4	0,7
3,51 - 4,00m	-	-	-	-	-	-	-	-	1	100,0	1	100,0	1	0,2
4,01 - 4,51m	-	-	-	-	-	-	2	100,0	-	-	2	100,0	2	0,4
Total number and mean %.	55	9,9	398	71,6	453	81,5	64	11,5	39	7,0	103	18,5	556	100,0

The results indicate that the bushes became more resistant to the fire as their height increased. The vast majority of bushes up to a height of 2m were killed above ground level while bushes in the height class 2,01 to 3,00m still suffered a significant kill of stems and branches. The results also show that the majority of bushes 2m tall and less coppiced from the base of the stem and only a small proportion of the bushes in this height class were killed by the fire. In fact the mortality of Acacia karroo in all height classes was very low (9,9 per cent on average), indicating that this bush species is extremely resistant to fire alone. The effect of the fire on the other bush species of different heights show a similar trend to that of Acacia karroo.

The effect of the fire on Acacia karroo plants in different basal stem diameter classes is presented in Table 3.3.

TABLE 3.3. The effect of the initial burning treatment on plants of Acacia karroo in different basal stem diameter classes expressed as number of plants and as a percentage.

Stem Diameter Class	Top Growth Killed						Top Growth Not Killed						Total	
	Dead		Coppicing		Total		Coppicing & Shooting		Shooting		Total		No	%
	No	%	No	%	No	%	No	%	No	%	No	%		
0 - 2,00cm	7	6,0	109	93,2	116	99,1	1	0,9	-	-	1	0,9	117	21,0
2,01 - 4,00cm	16	8,1	172	87,3	188	95,4	7	3,6	2	1,0	9	4,6	197	35.4
4,01 - 6,00cm	11	12,5	59	67,0	70	79,5	10	11,4	8	9,1	18	20,5	88	15,8
6,01 - 8,00cm	9	12,2	36	48,6	45	60,8	19	25,7	10	13,5	29	39,2	74	13,3
8,01 - 10,00cm	5	15,6	10	31,3	15	46,9	11	34,4	6	18,8	17	53,1	32	5,8
10,01 - 12,00cm	3	18,8	1	6,2	4	25,0	8	50,0	4	25,0	12	75,0	16	2,9
12,01 - 14,00cm	4	22,2	6	33,3	10	55,5	5	27.8	3	16,7	8	44,5	18	3,2
14,01 - 16,00cm	-	-	-	-	-	-	-	-	1	100,0	1	100,0	1	0,2
16,01 - 18,00cm	-	-	3	27,3	3	27,3	3	27,3	5	45,4	8	72,7	11	2,0
18,01 - 20,00cm	-	-	2	100,0	2	100,0	-	-	-	-	-	-	2	0,4
Total number and mean %	55	9,9	398	71,6	453	81,5	64	11,5	39	7,0	103	18,5	556	100,0

Several distinct trends are evident. Firstly, stems and branches of bushes with a small basal diameter were more susceptible to a topkill than bushes with thicker stems. Bushes with a basal stem diameter of up to 6cm were very susceptible but thereafter resistance increased to the damaging effects of the fire. This is probably because as the diameter of the stem increases, the outer layer of the dead bark also increases thus providing greater insulation to the vulnerable phloem, cambium and xylem cells.

The other clear trend in Table 3.3 is that although only a small proportion of the Acacia karroo bushes were killed by the fire, they became more susceptible to a total kill as the basal stem diameter increased. This was probably due to the fact that as the stem diameter of a plant increases with age, the viability of the dormant buds in the collar region of the stem decreases, resulting in a reduced ability to produce coppice growth.

Regarding the effect of the goat treatment on the regrowth of the bush measurements showed that there was significantly less browse material on the coppice growth in the goat plot than in the control plot. The mean percentage strikes of living plant material of Acacia karroo was 15,7 per cent in the goat plot and 34,8 per cent in the control plot ($P \lesssim 0{,}01$). This confirms the observation that the goats had severely browsed the coppice growth. Observations showed that Rhus lucida, Grewia occidentalis and Ehretia rigida, which were the only other bush species present in the goat plot, were also very acceptable to the goats and had been severely browsed. The goats also utilised the available new shoot growth that had developed on the stems and branches of all the bush species that had not been killed by the fire.

The mean yields of grass expressed on a dry matter basis in the control (K1) plot and after browsing in the goat plot at the end of the 1972/73 growing season were 4 330 ± 753 kg ha^{-1} and 4 085 ± 665 kg ha^{-1} respectively. These yields were not significantly different from one another, confirming a visual assessment that there was no apparent difference in the grass yield between the two plots before they were grazed off by cattle at the beginning of winter. This result supports the conclusion by du Toit (1972a) that the inclusion of goats in the farming system in savanna areas will not be to the detriment of associated grazers. This is provided that the stocking rate of goats is based on the browsing capacity of the bush.

3.3.2 Long term treatment effects

The long term effects of the follow-up treatments will be discussed separately for the bush and the grass sward. The data for the bush includes all the different bush species in the plots.

3.3.2.1 Effect on bush

The effect of the treatments on the bush are presented in Table 3.4.

TABLE 3.4. The effect of the control (K1), goat and annual spring burn treatments on the bush as represented by tree equivalents per hectare (TE ha^{-1}) and plants per hectare (P ha^{-1}).

Season	Control (K1)		Goat		Annual Spring Burn	
	TE ha^{-1}	P ha^{-1}	TE ha^{-1}	P ha^{-1}	TE ha^{-1}	P ha^{-1}
1972/73 - pre-burn	385	403	925	836	605	580
1972/73 - post-burn	242	366	509	758	438	526
1973/74	-	-	-	-	-	-
1974/75	-	-	-	-	-	-
1975/76	-	369	-	370	-	297
1976/77	640	588	110	206	76	454
1977/78	1 456	1 661	66	92	222	907
1978/79	1 212	2 173	32	155	183	954
1979/80	1 524	2 165	68	265	231	882
1980/81	1 529	2 173	65	301	194	848
1981/82	1 465	1 921	64	341	243	742

Considering firstly the above-ground phytomass of bush as represented by tree equivalents per hectare (TE ha^{-1}), the results in Table 3.4 indicate that the initial burn applied during 1972 significantly reduced the amount of bush. However, the follow-up treatments had vastly differing effects on the structure of the bush communities in the different plots. Both the goat and annual spring burn treatments resulted in a drastic decrease in the overall phytomass of bush, with the goat treatment having the greater effect. Conversely, the control (K1) treatment resulted in an initial decrease immediately after the fire but thereafter the bush recovered and greatly surpassed its original phytomass.

The changes caused by the follow-up treatments are illustrated graphically in Figure 3.2.

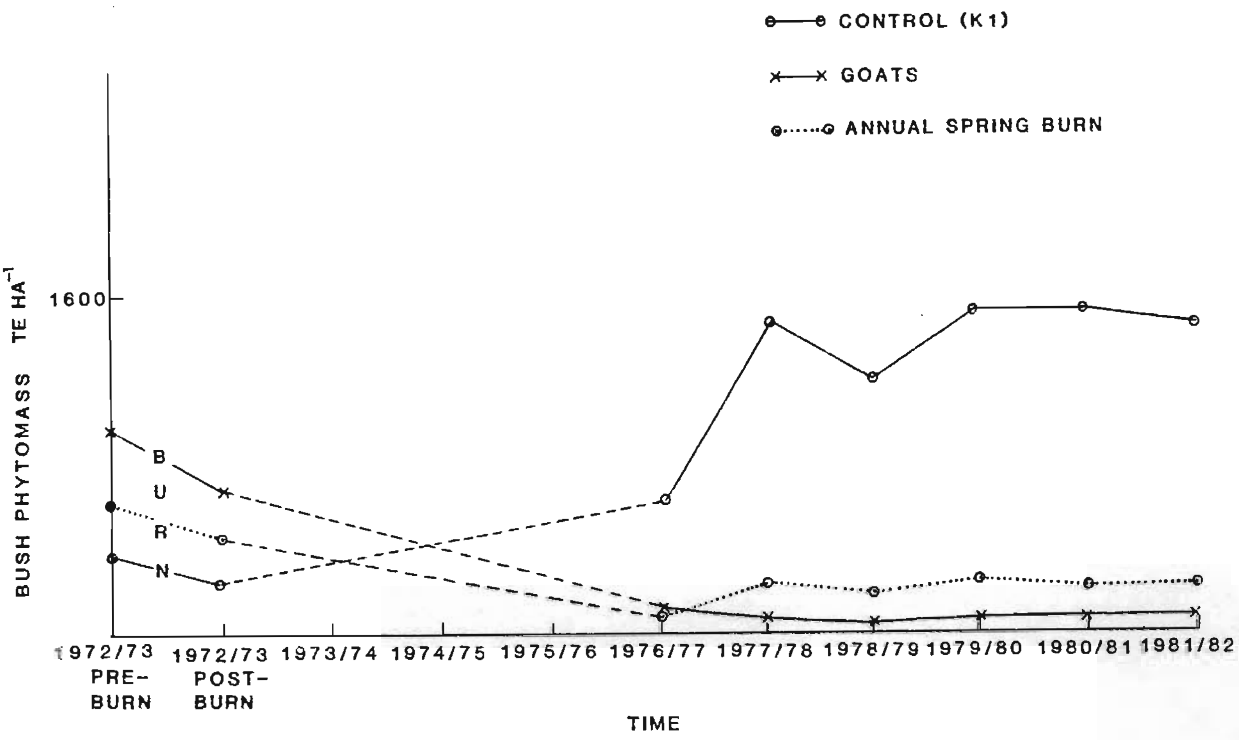

FIGURE 3.2. The effect of the control (K1), goat and annual spring burn treatments on the phytomass of the bush as represented by tree equivalents per hectare.

The control (K1) treatment clearly illustrates the point that in the absence of any form of repeated defoliation like browsing or burning, the bush develops unchecked and in this case completely recovered and finally exceeded the original number of tree equivalents ha^{-1} by 278 per cent after five years. Finally, the results in both Table 3.4 and Figure 3.2 would suggest that after a certain period a dynamic equilibrium is reached between the bush and its environment where the phytomass remains fairly constant, with minor fluctuations no doubt caused by seasonal differences in climate.

The effect of the follow-up treatments on the density of the bush (plants per hectare) presented in Table 3.4 show a similar trend to their effect on the phytomass of the bush, except in the case of the annual spring burn treatment. This treatment caused an initial decrease in the density of the bush but this trend was reversed after 1975/76 when there was a drastic increase in the density of the bush. This result shows that frequent burning does not necessarily cause a decrease in the density of bush. The effect of continuous stocking with goats on the density of the bush also deserves comment because subsequent to 1977/78 the bush density tended to increase gradually. Thus in both the goat and annual spring burn plots recruitment of bush occurred despite the application of these treatments. These results are illustrated in Figure 3.3.

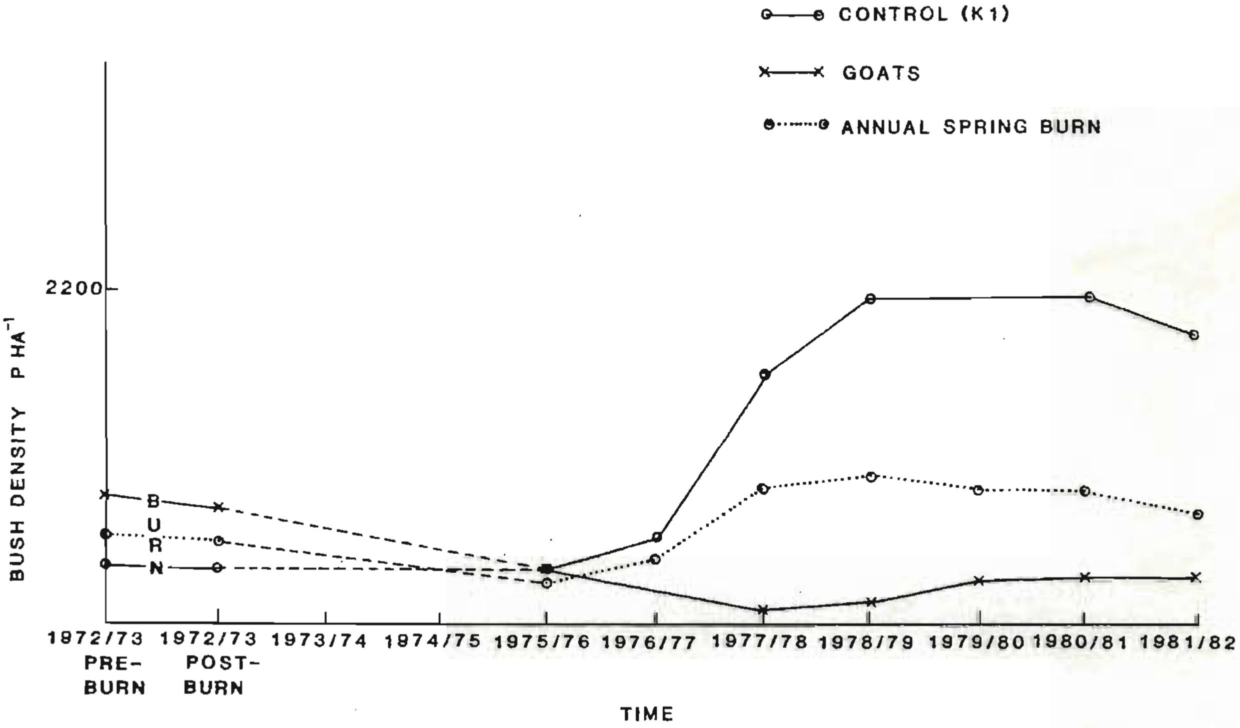

FIGURE 3.3. The effect of the control (K1), goat and annual spring burn treatments on the density of the bush.

Unfortunately there are no data available on the population dynamics of the bush seedlings but some indication can be obtained of this from the population dynamics of the bush occurring in the 0,5m stratum of the different plots. The results are presented in Table 3.5, and show that the initial burn reduced the majority of the bush to this height stratum. However, in the control (K1) plot the proportion of bush decreased in this stratum as the woody vegetation recovered after the initial burn. This decrease occurred despite the development of a markedly higher density of bush in this stratum from the 1977/78 season onwards. This result indicates that there was a significant germination of bush seedlings in this plot which explains why there was an overall increase in the bush density with this treatment as shown in Figure 3.3.

TABLE 3.5. The density of the bush in the 0,5m stratum of the control (K1), goat and annual spring burn plots expressed as plants per hectare (P ha^{-1}) and as a percentage of the total bush population.

	Control (K1)		Goat		Annual Spring Burn	
Season	P ha^{-1}	%	P ha^{-1}	%	P ha^{-1}	%
1972/73 - pre-burn	9	2,3	32	3,9	16	3,0
1972/73 - post-burn	242	71,5	539	71,5	373	71,5
1973/74	-	-	-	-	-	-
1974/75	-	-	-	-	-	-
1975/76	-	-	-	-	-	-
1976/77	2	0,4	120	58,0	438	96,2
1977/78	316	19,0	56	60,3	817	90,0
1978/79	1 005	46,2	143	91,8	862	90,3
1979/80	840	38,8	239	90,0	759	86,0
1980/81	828	38,1	274	90,7	738	87,0
1981/82	631	32,8	314	92,2	597	80,5

Note: Post-burn surveys were not conducted separately for each treatment.

There was initially a marked decrease in the density of the bush in the 0,5m stratum in the goat plot but in later years the tendency was reversed. This treatment has resulted in the majority of the bush being confined to the 0,5m stratum in the form of shortly cropped bushes and seedlings. The increase in density of the bush in this stratum in the last four years indicates that there has been a significant recruitment of seedling plants.

There was an overall increase in the density of the bush in the 0,5m stratum in the annual spring burn plot except for a gradual decrease during the last four years. The increase in the proportion of plants in this stratum to a maximum of 96,2 per cent during the 1976/77 season would indicate that the increase in the number of small plants was due mainly to taller bushes being burnt down by the annual spring burns. However, subsequently the proportion of bush in this stratum decreased during 1977/78 and 1978/79 despite an increase in bush density, which indicates that there was a recruitment of seedling plants.

The relatively high density of bush in the 0,5m stratum in the goat and annual spring burn plots indicates the resilience of these bush communities even when subjected to treatments that would be expected to cause their death.

3.3.2.2 Effect on grass sward

The long term effects of the follow-up treatments on the botanical composition and basal cover of the grass sward are presented in Table 3.6.

The salient points that emerge from these results are that in all cases the basal cover of the grass sward decreased during the period 1973 to 1978. The annual spring burn treatment caused the greatest decrease and a visual inspection of the plot showed that the grass sward comprised elevated tufts with severely crusted bare soil between them. The decrease in the basal cover was not as marked in the control (K1) and goat treatments and

TABLE 3,6 The botanical composition and the basal cover of the grass sward in the control (K1), goat and annual spring burn plots expressed as a percentage.

Plant species	Treatments											
	Control				Goats				Follow-up Burn			
	1973	1976	1978	1981	1973	1976	1978	1981	1973	1976	1978	1981
Themeda triandra	38,4	50,9	47,3	48,5	40,6	53,2	50,0	50,5	46,3	67,0	65,9	68,0
Setaria neglecta	-	-	0,5	-	1,0	-	0,7	1,0	-	-	0,7	-
Panicum stapfianum	26,6	5,4	14,5	2,5	10,9	3,7	8,4	6,0	16,5	2,5	7,0	6,0
Panicum maximum	-	-	-	-	1,0	-	-	-	-	-	-	-
Cymbopogon plurinodes	2,3	5,4	5,2	3,0	8,9	0,9	1,7	0,5	14,4	2,5	2,8	6,5
Aristida congesta sub-spp. *barbicollis*	-	-	-	-	-	-	-	-	-	-	-	-
Cynodon dactylon	-	-	0,5	2,0	-	-	0,9	1,0	-	0,3	-	-
Digitaria eriantha	16,3	19,6	13,6	19,5	24,7	16,5	16,5	14,5	11,3	16,5	14,0	9,0
Eragrostis chloromelas	-	-	-	0,5	-	-	0,1	0,5	-	-	-	-
Eragrostis curvula	4,7	1,8	5,9	2,0	1,0	-	7,3	0,5	2,1	2,6	0,9	1,0
Eragrostis obtusa	1,2	-	0,5	2,0	-	-	0,2	1,0	2,1	-	-	-
Eustachys mutica	3,5	6,3	2,0	3,0	2,0	3,7	2,7	1,5	2,1	-	1,2	0,5
Michrocloa caffra	-	-	-	-	-	-	-	0,5	-	-	-	-
Sporobolus capensis	-	-	-	-	-	-	-	-	-	-	-	1,0
Sporobolus fimbriatus	7,0	10,7	7,5	12,0	8,9	22,0	7,9	10,5	5,2	8,9	6,9	3,0
Karroochloa curva	-	-	0,2	-	-	-	0,5	-	-	-	-	-
Forbs	-	-	2,3	6,0	1,0	-	3,1	12,0	-	-	0,3	5,0
Basal cover	15,5	10,4	11,5	-	18,7	10,6	10,5	-	16,6	7,6	8,5	-
Number of points	553	1 076	1 000	200	540	1 031	1 000	200	585	1 034	1 000	200

Note: Basal cover data are not presented for 1981 because the number of sample points were too few.

there was a significant amount of plant litter covering the ground between the grass tufts with these treatments.

The decrease in the basal cover of the grass sward was most probably caused by the relatively infrequent defoliation of the grass plants in all the treatments. All the plots were severely defoliated only once each year and even in the goat treatment grazing was very light and the grass plants attained full maturity every year. This type of defoliation encourages elevated tillering in the grass plants, therefore limiting the lateral spread of the tufts. The greater effect caused by the annual spring burn treatment is merely indicative of the extreme nature of this form of defoliation. Burning causes a greater mortality of grass tillers than grazing by cattle and therefore has a more severe effect on the basal cover of the grass sward.

The other important result shown in Table 3.6 is that there was a pronounced increase (46,9%) in the proportion of *Themeda triandra* in the annual spring burn treatment. This grass species also increased in the control (K1) and goat treatments relative to other species but not to the same extent. This result is particularly pertinent because it provides further evidence that *Themeda triandra* is a fire climax species and is encouraged by burning. The probable explanation for this response is that with lenient defoliation the basal tillers of the tufts of *T. triandra* become elevated, resulting in aerial tillering and a consequent general decrease in the vigour of the grass plant. Conversely, burning encourages basal tillering in *T. triandra* because it removes all aerial growth and forces the plant to tiller from ground level, thus maintaining it in a vigorous state.

Another important result shown in Table 3.6 is that *Cymbopogon plurinodis* decreased significantly in the goat and annual spring burn treatments. Field observations have shown that this grass is a preferred species to goats and this result supports this observation. The decrease in frequency of *C. plurinodis* in the annual spring burn treatments is consistent with other results obtained in this veld type which showed that this species increases with infrequent burning and vice versa (Robinson, Gibbs Russel, Trollope & Downing, 1979).

The reasons for the recorded long term effects of the follow-up treatments on the productivity of the grass sward are difficult to assess because there are so many factors that affect grass production. Nevertheless, the annual grass production (1st May - 30th April) for the period 1972/73 to 1980/81 in the follow-up treatments is presented in Table 3.7.

TABLE 3.7. Annual grass production in the control (K1 and K2), goat and annual spring burn treatments for the period 1972/73 to 1980/81 expressed in kg ha^{-1}.

Season	Treatments			
	Control-K1	Control-K2	Goats	Annual Spring Burn
1972/73	4 330	-	4 085	4 085
1973/74	8 298	-	8 709	5 719
1974/75	3 950	-	4 928	3 940
1975/76	4 655	-	6 523	6 457
1976/77	3 801	5 271	3 605	3 712
1977/78	3 575	3 458	3 083	3 396
1978/79	2 455	3 679	2 631	2 926
1979/80	2 344	2 647	2 359	2 973
1980/81	3 450	3 763	2 579	3 493
Mean	4 095	3 764	4 278	4 078

An F-test using a one way analysis of variance indicated that the follow-up treatments did not have overall significantly different effects on the seasonal production of grass (F = 0,01; DF = 3 and 28; NS). However, grass yield varied widely from year to year, and in an attempt to identify the main factors contributing to this variation, multiple regression analyses were conducted on the grass yield data. The first multiple regression analysis was on grass production data from the control (K1 and K2) and goat treatments. The independent variables were:

Bush density - expressed in tree equivalents per hectare;

Veld composition score - expressed as a percentage and determined according to the procedure proposed by Tainton (1981) and using the benchmark developed by Danckwerts (1981);

Continuous stocking with goats - expressed as ha ssu^{-1} - a small stock unit is defined as a mature 6 tooth kapater with a mass of 70kg;

Annual rainfall - expressed in mm for the period 1st May to 30th April;

Mean daily maximum temperature - expressed in °C for the period 1st May to the 30th April.

The dependent variable was the annual grass production expressed in kg ha^{-1} for the period 1st May to 30th April.

The multiple regression coefficient was highly significant ($R = 0,9091$; $P \leq 0,01$) and the results indicated that 82,6 per cent of the annual variation in the grass yield was accounted for by the independent variables. The results are presented in Table 3.8.

It can be concluded from Table 3.8 that annual rainfall was the most important factor influencing grass production i.e. the higher the rainfall the greater the production of grass. The mean daily maximum temperature also had a highly significant positive effect on grass production. The continuous stocking with goats also had a significant effect and accounted for 10 per cent of the variation in the production of grass, which

TABLE 3.8. The effect of bush competition, continuous stocking with goats, veld condition, rainfall and temperature on the annual production of grass expressed as a percentage (n = 13).

Independent Variable	Effect	Significance
Annual rainfall	42,7	$P \lesssim 0,01$
Mean daily maximum temperature	25,6	$P \lesssim 0,01$
Continuous stocking with goats	10,0	$P \lesssim 0,05$
Bush density	4,1	NS
Veld composition score	0,2	NS
TOTAL	82,6	

indicated that the goats were utilising a certain proportion of the grass. A comparison was made between the grass yield in the control (K2) and goat plots using a t-test with paired means for the period 1976/1977 to 1980/1981 i.e. 3 764 kg ha^{-1} vs 2 851 kg ha^{-1}. The t-test was significant ($t = 3,53$; DF = 4; $P \lesssim 0,05$) indicating that for this period the goats had decreased the standing crop of grass by 24,3 per cent in the goat plot.

Finally the results in Table 3.8 indicate that the density of the bush and the condition of the veld had had no significant effect on the production of grass. The non-significant effect of bush density on grass production is a surprising result and requires further investigation. The result may indicate that there were insufficient data to make a valid statistical comparison because a perusal of the data does show a tendency for the bush density to have a depressing effect on grass production.

The non-significant effect of the veld composition score on the grass production is understandable as the condition of the veld in the control (K1 and K2) and goat plots was excellent in all cases.

The effect of annual spring burning on grass production was assessed by comparing the production of grass in the annual spring burn plot with that for the goat plot for the period 1972/1973 to 1975/1976 and from the control (K2) plot for the period 1976/1977 to 1980/1981 (Table 3.7). The use of the data from the goat plot was deemed permissible since the results presented in Table 3.7 indicated that the goats were probably not utilising significant quantities of grass up to that stage. The results are presented in Table 3.9.

TABLE 3.9. The annual production of grass from veld burnt annually in spring and from unburnt veld for the period 1972/1973 to 1980/1981.

Season	Treatment		Difference
	Annual Spring Burn(a)	Unburnt(b)	% (b-a)
	kg ha^{-1}	kg ha^{-1}	
1972/73	4 085	4 085	0
1973/74	5 719	8 709	34,3
1974/75	3 940	4 928	20,0
1975/76	6 457	6 523	1,0
1976/77	3 712	5 271	29,6
1977/78	3 396	3 458	1,8
1978/79	2 926	3 679	20,5
1979/80	2 973	2 647	-12,3
1980/81	3 493	3 763	7,2
Mean	4 078	4 785	11,3

Standard Error Mean = 371 kg ha^{-1}

The data in Table 3.9 were analysed using an F-test and a t-test. Both tests showed that there were no significant differences in grass production between the burnt veld and the unburnt veld. However, the existence of differences in grass production during certain years indicate that the effect of annual spring burning may have been confounded with differences in seasonal climatic conditions and fire intensity. This was investigated using a multi regression analysis to determine the variation in grass production caused by annual rainfall, temperature and fire intensity. The analysis was conducted using data from the annual spring burn, goat and control (K2) plots for the period 1974/1975 to 1980/1981. Again the grass yields from the goat and control plots represented grass production for unburnt veld and for these data the fire intensity was assumed to be zero.

The independent variables in the analysis were:

Fire intensity - expressed in kJ s^{-1} m^{-1} of fire front;

Annual rainfall - expressed in mm for the period 1st May to 30th April;

Mean maximum daily temperature - expressed in °C for the period 1st May to 30th April.

The results of the analysis, which are represented in Table 3.10, indicate that only rainfall and temperature had a significant effect on grass production.

TABLE 3.10. The effect of fire intensity, rainfall and temperature on the annual production of grass expressed as a percentage (n = 14).

Independent Variable	Effect	Significance
Annual rainfall	40,30	$P \lesssim 0,05$
Mean maximum daily temperature	19,60	$P \lesssim 0,01$
Fire intensity	0,04	NS
TOTAL	59,94	

Fire intensity accounted for only 0,04 per cent of the variation in annual grass production and was not significant. Thus it can be concluded that fire intensity had no significant effect on the production of grass during the season following the application of the annual spring burns.

3.4 GENERAL DISCUSSION AND CONCLUSIONS

The object of this experiment was to test the hypothesis that the role fire can play in controlling bush encroachment in the arid savannas is to maintain bush at an available height and in an acceptable state for browsing animals. It is the considered opinion of the author that the results from the experiment do not disprove this hypothesis and emphasize the point that fire alone is unlikely to be effective in controlling bush encroachment in arid savannas.

This conclusion can be drawn because the results show that the initial burn applied in 1972 killed the stems and branches of the majority of the bushes but that the mortality of the trees and shrubs was low. Continuous stocking with goats on veld which had been burned resulted in the severe browsing of the coppice growth of the bush and the continued application of this treatment caused a drastic reduction both in the phytomass and density of the bush. Conversely, the bush recovered fully in the control treatment after the initial fire and the phytomass and density of the bush eventually surpassed that of its original state prior to burning. In addition, the browsing treatment with goats did not initially result in significant quantities of grass being utilised and together with the fact that fire intensity had no significant effect on the following seasons production of grass, indicates that a program of burning and then browsing with goats can be used to control bush encroachment under certain circumstances.

Having established the role fire can play in combatting bush encroachment, the key questions that needed to be answered for the practical application of this method were:

(i) what type and intensity of fire are required to burn down bush of a particular size and species;

(ii) during what season should burning be applied to reduce bush to an available height for browsing animals;

(iii) what is the acceptability of different bush species to goats;

(iv) what stocking rate of goats must be applied to control bush that has been reduced to an available height;

(v) what type of browsing management must be applied to control bush that has been reduced to an available height?

These key questions were researched in a series of field experiments and the results are presented in later chapters.

Other pertinent information that has emerged from this experiment is that as the phytomass and the density of the bush decreased the goats started utilising significant quantities of grass. This indicates that in a practical farming situation the stocking rate of goats must be adjusted to the browsing capacity of the bush in order to minimise the competition for forage between grazers and browsers.

A result that is pertinent to the key question as to what type of browsing management must be applied to control bush that is at an available height, was the marked reduction that occurred in the phytomass and density of the bush in response to light continuous stocking with goats. This result shows that this type of browsing management, when applied to coppice growth of bush after a fire, will cause a significant mortality of trees and shrubs that are acceptable to goats. Conversely, field experience gained on the research farm of the University of Fort Hare shows that rotational stocking with goats designed to ensure maximum browse production does not have this effect. Similar results were obtained by du Toit (1972a) in the Eastern Cape who found that continuous stocking with goats caused a significant mortality of coppicing bushes of Acacia karroo. Conversely rotational stocking resulted in a gradual recovery of the coppicing plants of this species. Thus the principle emerges that if the objective of management is to eradicate bush, continuous browsing with goats must be used, whereas if the bush is regarded as an economic asset, rotational browsing with goats must be applied in order to maintain the bush in a productive and vigorous condition. These results on the effect of continuous browsing are of a preliminary nature and this aspect was investigated further and the results are presented in Chapter 5.

Another significant result was that even with continuous stocking with goats for 9 years there were still juvenile trees and shrubs in the goat plot. This result emphasises the difficulty of completely eradicating bush from encroached veld. Similar results were obtained by the late Mr. E. D. Matthews on the farm "Tukulu" in the Alice district, where in a bush eradication program using herbicides and stretching over 50 years it was still necessary to periodically control the regeneration of bush from seedlings. Thus even if the aim is to eradicate the bush with fire and continuous browsing with goats, these results indicate that re-encroachment will always be a problem that will necessitate a resident but low population of goats to control regeneration from seedlings.

The long term effects of annual spring burning on bush are of particular interest because of the fact that such frequent burning did not eradicate the bush. This lends further support to the earlier stated role fire can play in controlling bush encroachment in the arid savannas.

The other important aspect concerning annual spring burning was that it did not cause an overall reduction in grass production during the following season when compared with unburnt veld. This is in contrast to results obtained in Natal (Scott, 1970; Tainton, Groves & Nash, 1977) where it was found that burnt veld produced less grass material in the following season than unburnt veld that had been mown. It is possible that the difference lies in the fact that the unburnt veld in this experiment was defoliated by grazing with cattle rather than mowing. This is possibly a more severe treatment than mowing in that it incorporates trampling and the tearing action of grazing. Nevertheless it is an interesting result that deserves further investigation.

The result that fire intensity had no effect on the production of grass in the following season has important implications and this matter definitely requires further investigation. The view that "cool" fires are less damaging to the grass sward than "hot" fires is widely held by scientists and farmers alike. However, this result disproves this hypothesis and after due consideration, the absence of any detrimental effect of hot fires seems reasonable. As a general rule high intensity fires favour the development and maintenance of a wholly or predominantly grassland community at the expense of trees and shrubs, and *vice versa*. Therefore if hot, intense, fires also have a deleterious effect on the grass sward this type of treatment would not be expected to result in the development and/or maintenance of grassland communities.

Finally the apparent preference of goats for the grass species *Cymbopogon plurinodis* is also of considerable interest because this species is discriminated against by cattle and sheep. Thus the introduction of goats into the farming system may provide an economic solution to the current encroachment of this grass species into extensive areas of sweetveld in the Eastern Cape.

CHAPTER 4

CHARACTERISTICS OF FIRE BEHAVIOUR IN THE ARID SAVANNAS OF SOUTHEASTERN AFRICA

4.1 INTRODUCTION

In attempting to answer the key question "what type and intensity of fire is required to burn down bush of a particular size and species?" it was necessary to determine the characteristics of fire behaviour in the arid savannas of southeastern Africa. This is because the effect of fire on natural ecosystems involves the response of living organisms to the release of heat energy through the combustion of plant material. The manner in which and the factors that influence the release of heat energy involves the study of fire behaviour. Such a study necessitates a basic understanding of the phenomenon of combustion. This according to Brown & Davis (1973) is an oxidation process comprising a chain reaction where the heat energy released during a fire originates from solar energy via the process of photosynthesis. Combustion is similar to photosynthesis in reverse and is clearly illustrated in the following two general formulae:

Photosynthesis

$$CO_2 + H_2O + \text{Solar Energy} \longrightarrow (C_6 H_{10} O_5)n + O_2$$

Combustion

$$(C_6 H_{10} O_5)n + O_2 + \text{Kindling Temperature} \longrightarrow CO_2 + H_2O + \text{Heat}$$

The kindling temperature in the combustion formula merely has a catalytic role of initiating and maintaining the combustion process.

There are three phases in the combustion of plant fuels. First is the pre-heating phase in which plant material ahead of the flames is raised to its ignition point and involves the driving off of moisture and the generation of fire which are often cited in the literature.

4.2 FIRE BEHAVIOUR PARAMETERS PERTINENT TO FIRE EFFECTS

Various fire behaviour parameters have been developed that quantitatively describe the amount, rate and vertical level at which heat energy is released during a fire.

4.2.1 Available heat energy

The total amount of heat energy available for release during a fire is determined partly by the fuel load (Luke & McArthur, 1978). It determines the heat load to which living cells are subjected and results presented in Chapter 5, show that fuel load is highly positively correlated with the degree of topkill of stems and branches of trees and shrubs occurring during a surface head fire. The total amount of heat energy contained per unit mass of fuel is called the heat of combustion. In both the U.S.A. and Australia the average heat of combustion of fuels consumed in forest and bush fires is assumed to be 20 000 kJ kg^{-1} on a dry mass basis (Brown & Davis, 1973; Luke & McArthur, 1978; Vines, 1981). In the current study the heat of combustion of four of the most common grasses occurring in the False Thornveld of the Eastern Cape were determined with a Gallencamp automatic adiabatic bomb calorimeter. A composite grass sample harvested from veld dominated by *Themeda triandra* was also analysed. These determinations were limited to grass because the major portion of the fuel load in savanna areas comprises surface fuels in the form of the standing grass sward. The samples from the different grass species were collected from veld that had been resting for one and two growing seasons respectively. The composite grass sample was harvested from mature veld that had been resting for two growing seasons. Sampling was conducted on a random basis. Ten separate samples of the different grass species were collected at random points on a transect approximately 400m long. The composite grass sample was obtained by harvesting ten square metre quadrats arranged at random over an area of approximately one hectare. Sub-samples were then taken for analytical purposes. Three replicate determinations were conducted on each sample and the mean heat of combustion was calculated from the values.

The results of the analyses are presented in Table 4.1.

TABLE 4.1. The heat of combustion of different grass species commonly burnt in surface fires in the arid savannas of south eastern Africa. Data expressed in kilojoules per kilogram (kJ kg^{-1}) on a dry mass basis.

Grass Species	Description	Heat of combustion kJ kg^{-1}
Cymbopogon plurinodis	Vegetative leafy stage	17 643 ± 48,1
C. plurinodis	Mature leaf/culm stage	18 133 ± 46,0
Digitaria eriantha	Vegetative leafy stage	16 722 ± 140,2
D. eriantha	Mature leaf/culm stage	17 538 ± 96,3
Panicum maximum	Vegetative leafy stage	17 936 ± 144,4
P. maximum	Mature leaf/culm stage	17 677 ± 56,5
Sporobolus fimbriatus	Vegetative leafy stage	17 543 ± 157,0
S. fimbriatus	Mature leaf/culm stage	17 212 ± 46,0
Themeda triandra	Vegetative leafy stage	17 170 ± 16,7
T. triandra	Mature leaf/culm stage	17 727 ± 44,0
All species	Mean composite grass sample	18 024 ± 149,0

The data in Table 4.1 indicate that the heats of combustion of grass fuels in the arid savannas of southeastern Africa are similar to the values commonly used in the U.S.A. and Australia and that a mean value of 18 024 kJ kg^{-1} (composite grass sample) is an acceptable figure to use. This value is also similar to the mean heat of combustion (18 558 ± 550 kJ kg^{-1}) of the herbaceous fine fuels determined by Smith (1982) for the shrublands of the Drakensberg mountain range in Natal.

Not all the heat of combustion is released during a fire. Some of the heat energy remains in the unburnt plant material while other heat energy is used to drive off fuel moisture (Luke & McArthur, 1978; Vines, 1981). Therefore the available heat energy is always somewhat less than the heat of combustion of natural plant fuels and this parameter is referred to as the heat yield. It is closely related to the current moisture content of the fuel and the mean heat yield used in Australia for grass and forest fuels is 16 000 kJ kg^{-1} (Luke & McArthur, 1978). In the U.S.A. Albini (1976) quoted the average heat yield for forest fuels as being 18 640 kJ kg^{-1}.

The heat yield of fine grass fuels was investigated in the arid savannas of southeastern Africa. This was done by collecting ash remaining after intense surface head and back fires burning during late winter in the False Thornveld of the Eastern Cape. The same random sampling procedure was used as for the unburnt grass samples. The heat of combustion of the ash material was determined with a bomb calorimeter using the same procedure as before. The heat yield was calculated by subtracting the potential heat energy remaining in the ash material from the heat of combustion of the unburnt composite grass sample presented in Table 4.1 i.e. 18 024 kJ kg^{-1}. The results are presented in Table 4.2.

TABLE 4.2. The heat yield of grass fuels in the arid savannas of southeastern Africa burning as surface head and back fires, expressed in kilojoules per kilogram (kJ kg^{-1}).

Type of fire	Heat yield kJ kg^{-1}	Fuel moisture percentage
Head fire	16 890	32,4
Back fire	17 781	36,0

The values in Table 4.2 are for fully cured, dormant, winter grass where research results presented later show that with fuel moisture contents of less than 45 per cent, maximum combustion occurs. The heat yield for grass fuels burning as back fires was slightly higher (5,3 per cent) than that for head fires. This result was consistently supported by the observations that back fires left a residue of grey coloured ash whereas the head fires produced black ash, indicating a higher carbon content and less complete combustion of the grass fuel. This aspect was investigated further and it was found that the following plant constituents were lost or remained after surface head and back fires (Table 4.3).

TABLE 4.3. The plant constituents that were lost and remained after surface head and back fires in the arid savannas of southeastern Africa.

Type of fire	Constituent	Percentage
Head fire	Organic matter lost	83,4
	Organic matter remaining	5,6
	Mineral ash remaining	11,0
Back fire	Organic matter lost	87,8
	Organic matter remaining	1,2
	Mineral ash remainig	11,0

Returning to the heat yields presented in Table 4.2, the results are in close agreement with the heat yields quoted and used in the U.S.A. and Australia (Albini, 1976; Luke & McArthur, 1978). It is also interesting to note that Dillon (1980) obtained a heat yield of 15 700 kJ kg^{-1} for dormant grass fuel in the Tall Grassveld of Natal. Therefore the heat yields presented in Table 4,2 can be concluded to be acceptable and will be used for calculating fire behaviour parameters in this study.

The amount of heat energy released during a veld fire is the product of the fuel load (kg/m^{-2}) and the heat yield (kJ kg^{-1}) and is expressed as kilojoules per square metre. From this it is clear that the total potential amount of heat energy released during a fire is greatly influenced by the fuel load.

The total heat yield of a fire can also be estimated by recording the temperature profile during a fire. The area underneath the resultant temperature curve represents the total amount of heat energy released during a fire. Tunstal, Walker, Gill (1976) have also, found that the area underneath the temperature curve is positively correlated with the maximum temperature of a fire. Consequently maximum temperatures can also serve as an index of the total amount of heat energy released during a veld fire.

4.2.2 Rate of heat energy release

Albini (1976) has stated that the rate of heat energy release during a fire is one of the most poorly defined and misunderstood measures of fire intensity. Byram (1955) defined fire intensity as the release of heat energy per unit time per unit length of fire front. Numerically it is the product of the available heat energy and the forward rate of spread of the fire front and can be written as the equation:

$$I = H\,w\,r$$

where:

I = fire intensity - kJ s^{-1} m^{-1};
H = heat yield - kJ kg^{-1};
w = mass of available fuel - kg m^{-2};
r = rate of spread of the fire front - m s^{-1}.

The estimation of the rate of spread of a fire can be done in a variety of ways. Kruger (1977) reported that in Australia rate of spread is measured by placing metal tags at two or four minute intervals at the front of a fire. After the burn the distance between the tags is recorded and the rate of spread is calculated and expressed in metres per second. This method of measuring rate of spread is best suited to slow moving fires such as back fires, but is generally too dangerous to use in surface head fires and crown fires.

Kruger (1977) described a simple technique for estimating rate of spread in fynbos communities where burning conditions can be very hazardous. Prior to the fire metal stakes one metre long are located vertically at grid points spread over the area to be burnt. Thin wire is attached to each stake using half to one metre lengths of nylon thread. The wire is then stretched to an observation point beyond the perimeter of the area to be burnt. At each observation point the wire is drawn over a horizontal bar approximately 1,5m above ground level and is held taut by attaching a heavy object to the end of the wire. Each observation point is numbered and the time recorded when the fire melts the nylon thread and the heavy object falls to the ground. In this way the rate of spread of the fire front from stake to stake can be measured and a mean value calculated for the fire under consideration. This method is applicable for measuring rates of spread in both surface and crown fires.

During the course of the current study a successful procedure was developed for estimating the mean rate of spread of fires burning as back or head fires. It can also be used for crown fires. The technique involves recording the period of flaming combustion of a fire burning an area of known size and using the data in the following equation:

$$\mathrm{ROS} = \frac{A}{T \times L}$$

where:

ROS = mean rate of spread - m s^{-1};

A = area burnt - m^2;

T = period of flaming combustion - s;

L = mean length of fire front - m.

The technique is best suited for measuring rates of spread in approximately square or rectangular areas but can also be used for irregular areas provided the perimeter and area dimensions are known. The exact procedure used for determining the rate of spread with this technique depends, however, on the manner in which the area is burnt. A description will be given for measuring the rate of spread of a fire burning a square area that has been set alight according to the normally accepted modus operandi. (see Figure 4.1).

The procedure for estimating the rate of spread of head fires is illustrated in Figure 4.1.

Commencing at the starting point, two back fires are simultaneously initiated along the two leeward sides to corners A and B of the area to be burnt. The back fires are allowed to burn until the situation is deemed secure, at which time a head fire is initiated by ring firing the windward sides from points A and B to point C as swiftly as possible. The mean length of fire front that is used in the formula is equal to half of the initial total length of fire front along the windward sides. This is because when ring firing an area, the length of fire front tends to zero as the burnt area increases. In calculating the area burnt as a head fire, a correction must be made for the portion that was initially burnt as a back fire along the two leeward sides.

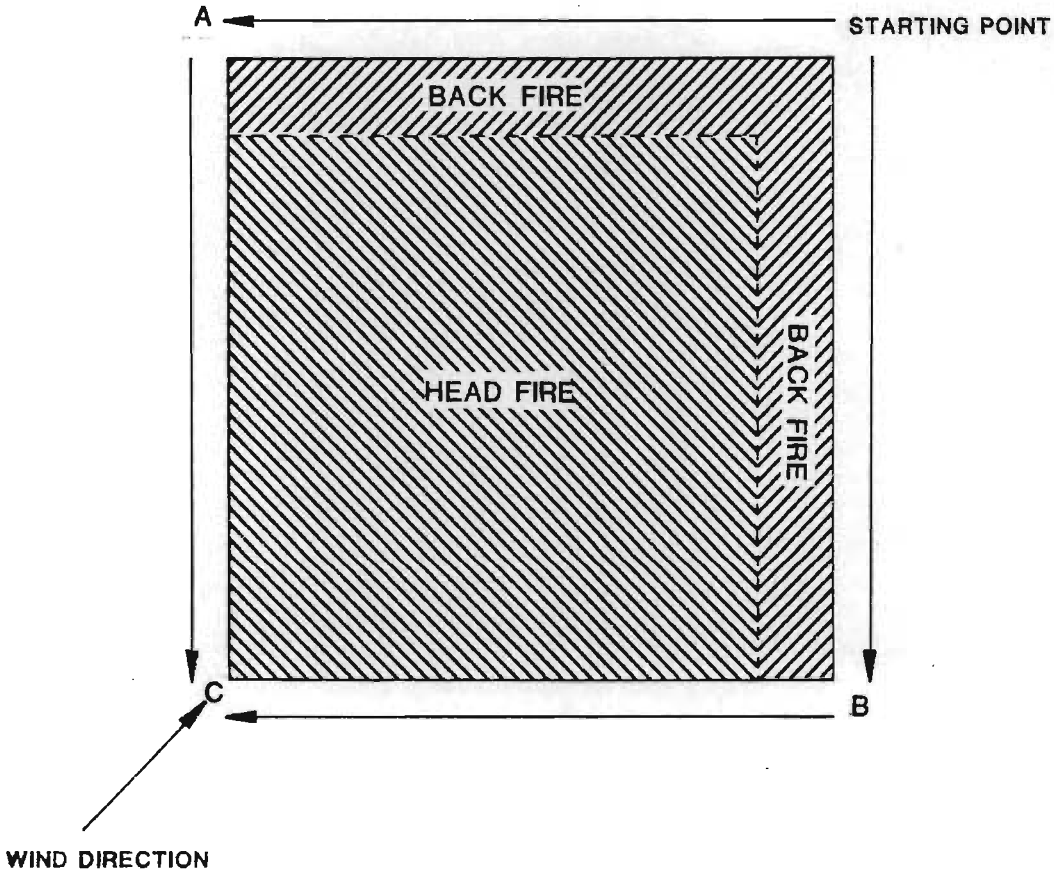

FIGURE 4.1. Procedure for measuring the rate of spread of a head fire when the wind is blowing diagonally across the area to be burnt.

The period of flaming combustion is recorded as the time it takes to burn an area once it has been ring fired.

The procedure for measuring the rate of spread of back fires is presented in Figure 4.2.

Two diverging back fires are set along the two leeward sides to corners A and B of the area to be burnt. These two lines of back fires are allowed to burn the entire area. As in the case of the head fires the mean length of fire front that is used in the formula is equal to half the initial total length of fire front set along the two leeward sides. The period of flaming combustion is recorded as the total time required to burn the area.

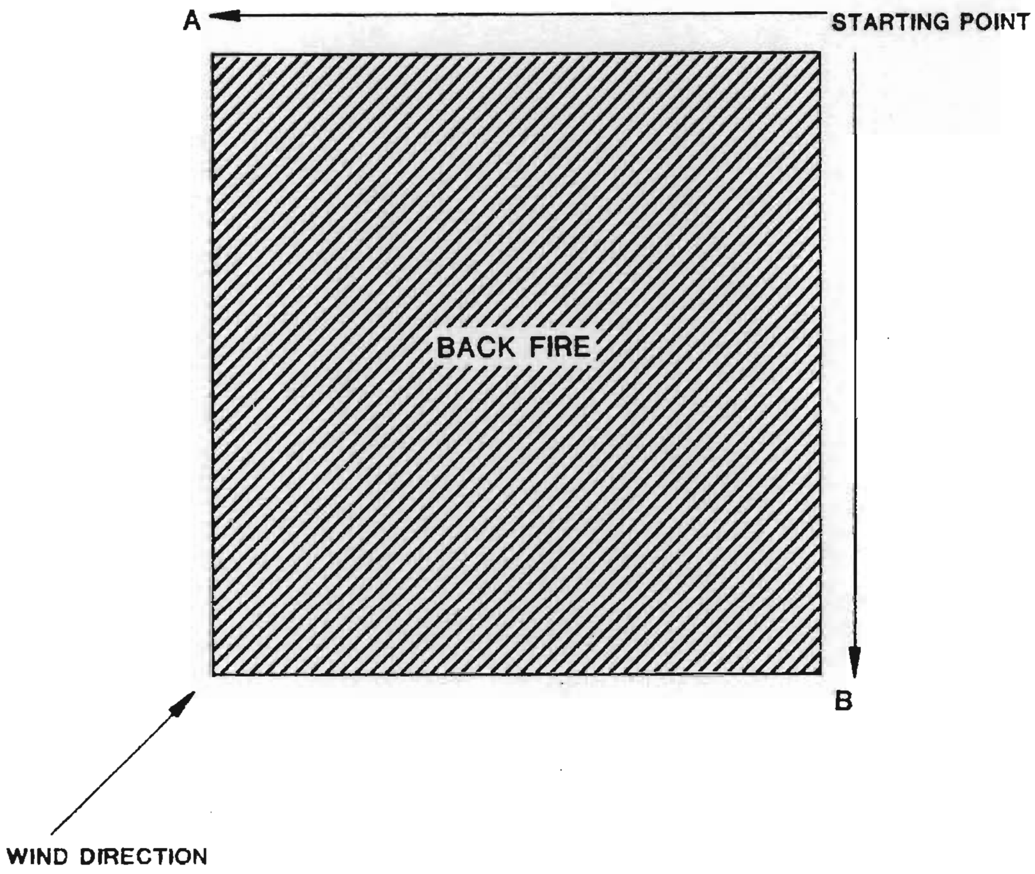

FIGURE 4.2. Procedure for measuring the rate of spread of a back fire when the wind is blowing diagonally across the area to be burnt.

In presenting these two procedures for measuring the rates of spread of surface head and back fires, it is recognised that the direction of the wind could be parallel rather than diagonal to the sides of the area to be burnt. This would necessitate a different pattern of setting the fire lines and calculating the different components of the formula. Nevertheless the examples given are by far the most frequently encountered in practice and serve to illustrate the principles upon which the technique is based.

Albini (1976) stated that Byram's fire intensity has proved to be very useful in fire behaviour studies and quotes van Wagner (1973) who found that fire intensity was significantly correlated with the height of lethal scorching of coniferous tree crowns. Results presented in Chapter 5 support this view as highly significant correlations were obtained between fire intensity and the topkill of stems and branches of trees and shrubs in the False Thornveld of the Eastern Cape.

The intensity of a fire can also be estimated by recording the temperature profile of a fire. The slope of the resultant curve indicates the rate of release of heat energy during a fire. The results of fire behaviour studies presented in section 4.3.5 also show that there is a highly significant positive correlation between fire intensity and the maximum temperature recorded during a fire. Thus, besides maximum temperature being an index of the total release of heat energy it can also serve as an indication of the intensity of a fire.

4.2.3 Vertical distribution of heat energy

A reliable indicator of the vertical distribution of heat energy released during a fire is the perpendicular height of the flames from ground level i.e. flame height. Results presented in section 5.1.2 show that there were significant improvements in the correlation between flame height and the top kill of stems and branches as the height of the trees increased.

The vertical distribution of heat energy in a fire can also be measured by recording temperatures at different heights above the ground. Results presented in section 5.1.1 and 5.1.2 show significant relationships between the temperatures recorded at different heights above the ground and the response of the grass sward and woody components of the vegetation.

4.3 MODELLING FIRE BEHAVIOUR

4.3.1 Introduction

There is a serious lack of quantitative data on the effect of various factors on the behaviour of different types of fires in South Africa. Conversely in the U.S.A. and Australia the study of fire behaviour is at an advanced level and very sophisticated mathematical models have been developed to predict the behaviour of fires. However, Luke & McArthur (1978) in Australia believe that for practical field use the fire models that have been developed by Rothermel (1972) and others in the U.S.A are difficult to apply in the field. They prefer, instead, simpler models based on general fuel characteristics such as particle size, distribution, and moisture content together with slope, relative humidity, air temperature and wind speed.

A similar approach was adopted in the current study and for the sake of clarity attention will be focussed on the effect of the different variables on fire intensity. This is because results in this study showed that fire intensity was significantly correlated with the rate of spread, flame height and maximum temperatures recorded at different heights above the ground during burning.

4.3.2 Factors influencing the behaviour of fires

The factors influencing the behaviour of fires will be discussed in terms of those variables that should be considered when applying controlled burns. A review of the literature reveals that these can be listed as fuel, air temperature, relative humidity, wind speed, slope of the terrain and the size of the burn (Brown & Davis, 1973; Luke & McArthur, 1978; Cheney, 1981; Leigh & Noble, 1981; Shea, Peet & Cheney, 1981; Wright & Bailey, 1982).

4.3.2.1 Fuel

Fuel characteristics such as fuel size, distribution, compaction, moisture content and quantity have very marked effects on the intensity of a fire but have not been studied to any significant degree in South Africa.

(i) Fuel size

Luke & McArthur (1978) have classified plant fuels into two broad types, namely fine fuels and heavy fuels. Fine fuels comprise plant material with a diameter of up to 6mm and include standing grasses and other herbaceous plants, fallen leaves, bark, twigs and branches within this diameter class. Fine fuels burn very readily and in a grass fire almost complete combustion normally occurs. Conversely in heavy fuels, such as are present in forests, combustion is incomplete because of the great bulk of some of the dead stems and branches.

(ii) Fuel distribution

Fire behaviour is greatly influenced by the vertical distribution of plant fuels and Brown & Davis (1973) recognised three broad groups, namely, ground, surface and aerial fuels.

Ground fuels include all combustible material below the loose surface litter and comprise decomposed plant material. These fuels support glowing combustion in the form of ground fires and are very difficult to ignite but are very persistent once ignited (Brown & Davis, 1973).

Surface fuels occur as standing grass swards, shrublet communities, seedlings and forbs. They also include loose surface litter like fallen leaves, twigs and bark. All these materials are fine fuels and can support intense

surface fires in direct proportion to the quantity of fuel per unit area (Brown & Davis, 1973).
Aerial fuels include all combustible material, live or dead, located in the understory and upper canopy of tree and shrub communities. The main aerial fuel types are mosses, lichens, epiphytes and branches and foliage of trees and shrubs (Brown & Davis, 1973). This is the fuel type that supports crown fires.

Apparently there is no published data on the effects of fuel distribution on fire behaviour in South Africa.

(iii) Fuel compaction

Fuel compaction refers to the placement of individual pieces of fuel in relation to one another. Combustion is most favoured when fuel is sufficiently loosely packed to enable adequate quantities of oxygen to reach the flame zone but dense enough for efficient heat transfer to occur. Fuel spacing is especially critical in heavy fuels but generally adequate ventilation occurs in the majority of fuel types (Luke & McArthur, 1978).

(iv) Fuel moisture

Fuel moisture is normally expressed on a dry matter basis and is a critical factor in determining the intensity of a fire. This is because it effects the ease of ignition, the quantity of fuel consumed and the combustion rate of the different types of fuel. The most important influence of moisture on fire behaviour is the smothering effect of the water vapour released from the burning fuel. It reduces the amount of oxygen in the immediate proximity of the burning plant material, thus decreasing the rate of combustion (Brown & Davis, 1973).

Luke & McArthur (1978) distinguish between the moisture content of living plant tissue and cured plant material. The former varies gradually in response to seasonal and climatic changes whereas cured plant material is hygroscopic and the moisture content is affected on an hourly and daily basis mainly by adsorption and desorption in response to changes in the relative humidity of the adjacent atmosphere. The important effect of fuel moisture is also illustrated by research conducted in the Kruger National Park. It was clearly shown that the quantity of green grass and the preceeding month's rainfall were the only factors that had a significant effect on the mean maximum temperatures recorded during fires applied at different frequencies and seasons of the year (Potgieter, 1974).

(v) Fuel load

Fuel load is regarded as one of the most important factors influencing fire behaviour because the total amount of heat energy available for release during a fire is related to the quantity of fuel (Luke & McArthur, 1978). Assuming a constant heat yield the intensity of a fire is directly proportional to the amount of fuel available for combustion at any given rate of spread of the fire front (Brown & Davis, 1973). Consequently the fuel load is a very important variable to consider when modelling fire behaviour.

4.3.2.2 Air temperature

Air temperature plays an important role in fire behaviour (Wright & Bailey, 1982). Its direct effect is to influence the temperature of the fuel and therefore the quantity of heat energy required to raise it to its ignition point (Brown & Davis, 1973). Air temperature also has indirect effects via its influence on the relative humidity of the atmosphere and moisture losses by evaporation (Luke & McArthur, 1978).

4.3.2.3 Relative humidity

The relative humidity of the atmosphere influences the moisture content of the fuel when it is fully cured (Luke & McArthur, 1978). It is positively correlated with fuel moisture (Wright & Bailey, 1982) and therefore plays an important role in controlling the flammability of fine fuels (Brown & Davis, 1973).

4.3.2.4 Wind

The combustion rate of a fire is positively influenced by the rate of oxygen supply to the fire (Brown & Davis, 1973; Cheney, 1981); hence the effect of wind speed on fire behaviour. Wind also causes the angle of the flames to become more acute. With increased wind velocities the flames are forced into the unburnt material ahead of the fire front resulting in more efficient preheating of the fuel and greater rates of spread in surface head fires (Luke & McArthur, 1978; Cheney, 1981). Beaufait (1965) found that wind speeds ranging from zero to 3,6 metres per second increased the rate of spread of surface head fires exponentially but had no effect on the rate of spread of back fires. Apparently the this effect on back fires is a widely observed phenomenon (Gill, 1980). Beaufait (1965) suggested that even though flames are blown away from the fuel immediately adjacent to the fire front during back fires, flame propogation results from preheating and ignition mechanisms occurring beneath the surface of the fuel.

Brown & Davis (1973) and Luke & McArthur (1978) stated that increased wind speeds cause greater rates of spread and therefore more intense fires. However, flame height does not necessarily increase with increased wind speeds because these cause the flames to assume a more acute angle and this may prevent the ignition of aerial fuels. This, partly explains why crown fires do not always occur during high winds. Luke & McArthur (1978) stated, however, that once the wind velocity exceeds 50 km/hour the rate of spread of fires in grassland tends to decrease. This is probably because, as wind speed and rate of spread increase, the amount of fuel consumed in the flaming zone of the fire tends to decrease and the flames are blown out. This phenomenon appears to occur only when the fuel load of grass is low (Brown & Davis, 1973; Cheney, 1981).

4.3.2.5 Slope

Slope significantly influences the forward rate of spread of surface fires by modifying the degree of preheating of the unburnt fuel immediately in front of the flames. In a head fire, this is achieved, as with wind, by changing the flames to a very acute angle and with slopes exceeding 15 - 20° the flame propogation process involves almost continuous flame contact. Conversely a down slope decreases the rate of spread of surface head fires (Luke & McArthur, 1978) and at low wind speeds has the effect of converting a head fire into a back fire.

In Australia (Cheney, 1981) a general exponential relationship is used for estimating the effect of slope on the rate of spread of surface head fires. The equation is:

$$R = Roe^{bx}$$

where:

R = rate of spread - m s^{-1};
Ro = rate of spread on level ground - m s^{-1};
e = exponential function;
b = 0,0693;
x = angle of the slope - degrees.

This relationship should not be used for gradients greater than 30° because the distribution of the surface fuel usually becomes discontinuous on steep slopes (Cheney, 1981).

Experience gained in the U.S.A. indicates that the increasing effect of slope on the rate of spread of head fires doubles from a moderate slope (0 - 22°) to a steep slope (22 - 35°) and doubles again from a steep slope to a very steep slope (35 - 45°) (Luke & McArthur, 1978).

4.3.2.6 Size of burn

Research in the U.S.A. and Australia has shown that initially fires go through an acceleration phase before they reach a stable state (Luke & McArthur, 1978). In grass fires this acceleration process has been attributed to the formation of a strong convection column that develops over the fire (McArthur, 1966). However, all these researchers are referring to the behaviour of fires that initiate from a single ignition point. In contrast, in controlled burns in South Africa, the ignition of a fire is as described and illustrated in Figure 4.1. In this case the area being burnt is ring fired and the fire burns to a point rather than from a point. Nevertheless, observations by the author indicate that these types of fires also go through an accelleration phase. The degree of accelleration would appear to be influenced (positively) by the size of the convection column produced by the area being burnt i.e. the larger the area being burnt the larger is the convection column and the greater and longer is the degree of acceleration. Therefore the size of the area being burnt should be considered when studying the behaviour of fires.

4.3.3 Development of fire behaviour models

Statistical models were developed in this study for predicting the fire intensity and flame height of surface head fires. This was because these are the important fire behaviour parameters that can be used for predicting and explaining the effect of burning on the vegetation. A model was also developed for predicting the rate of spread of surface head fires because this parameter is very useful in the formulation of procedures for applying controlled burns and in the control of wild fires.

4.3.3.1 Procedure

The procedure that was adopted in the development of these models was to burn as many fires as possible under the widest range of environmental conditions possible. In all 107 fires were burnt, the majority being on the research farm of the University of Fort Hare and the remainder on farms situated elsewhere in the False Thornveld of the Eastern Cape.

(i) Measurements

Measurements were taken before, during and after the fires and comprised the following parameters:

(a) Fuel load

The fuel load in savanna areas comprises primarily surface fuels in the form of the standing grass sward. Initially the fuel load was estimated by harvesting 20 to 30 square metre quadrats in the area to be burnt using a stratified random sampling procedure. The grass samples were oven dried for 96 hours at 80°C and the fuel load was expressed in kilograms per square metre ($kg\ m^{-2}$). However, since the development of the disc pasture meter by Bransby & Tainton (1977), the fuel loads were estimated with this apparatus. Danckwerts & Trollope (1980) had found in the False Thornveld of the Eastern Cape that this technique compared favourably with traditional methods of estimating the standing crop of grass. Furthermore, its attractiveness lay in the rapidity with which estimates of the amount of grass could be made and the non-destructive nature of the sampling. The mean fuel load was estimated with 100 disc meter readings arranged in a stratified random manner in the area to be burnt. The following regression equation was used for estimating the standing crop of grass.

$$y = (340 + 388{,}3x) \div 10\ 000$$

where:
y = mean fuel load - kg m^{-2};
x = mean disc height - cm.

This calibration equation was derived from 43 pairs of data using a simple linear regression analysis. The correlation coefficient was 0,9126 ($P \leq 0{,}01$) which means that the disc height was accounting for 83,3 per cent of the variation in the fuel load. The residual standard deviation was 0,0826. Finally the data used in the simple linear regression analysis covered the following range of conditions:

Variable	Mean	Minimum	Maximum
Disc height (cm)	9,4	1,3	18,1
Fuel load (kg m^{-2})	0,4029	0,0297	0,8689

The procedure used for deriving the calibration needs explaining because it differs from the method recommended by Bransby & Tainton (1977). The normal procedure comprises recording the settling height of the disc then harvesting the plant material directly below the disc using a circular quadrat of the same diameter. These paired data are then used for developing a linear regression between settling height and the mass of grass material harvested. Initially this procedure was followed and during the period from the 21st March, 1977 to the 4th May, 1981 a total of 43 calibrations were conducted. These comprised 100 samples per calibration and different sample sites were chosen from a wide variety of homogenous areas on the University of

Fort Hare research farm. The calibrations were conducted in the False Thornveld of the Eastern Cape on veld that varied from lush succulent material to mature grass with moisture contents ranging fom 62,5 per cent to 20,6 per cent, expressed on a wet mass basis. Calibrations were also conducted in different grass communities ranging from Themeda to Cymbopogon to Sporobolus/Digitaria dominant swards in different stages of growth.

Individual simple linear regression equations were developed for each of the 43 sample sites. In many cases the slopes and intercepts of the different equations varied significantly from one another. An important contributing cause for this phenomenon was that the range in disc heights tended to be very small in the homogenous sample sites, thus emphasizing the effect of the particular condition of the sward. These results indicate that different calibration equations would be necessary for estimating fuel loads in different grass communities at different stages of growth. This posed a serious problem because even though a wide range of calibration equations had been developed it would still be necessary to subjectively select the appropriate calibration for a particular situation. This would undoubtedly have led to errors and therefore significantly decrease the potential usefulness of the disc pasture meter as a rapid means of estimating fuel loads.

This problem was eventually solved when it was discovered that there was a highly significant linear relationship between the mean disc height and the mean mass of grass material harvested directly below the disc pasture meter in the 43 different sample sites. A scattergram of the data together with a fitted line are presented in Figure 4.3.

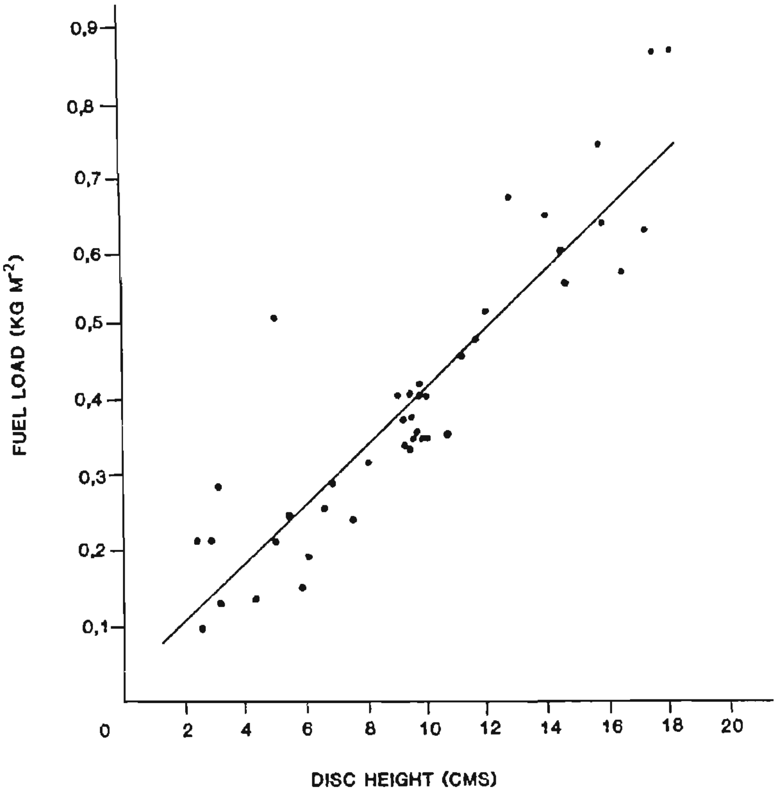

FIGURE 4.3. The linear regression between the mean disc height and the mean fuel load of grass at different sample sites in the False Thornveld of the Eastern Cape.

The results in Figure 4.3 indicate a remarkably good relationship between the mean disc height and mean fuel load of grass under a wide variety of sward conditions. This procedure of using mean values to develop the calibration equation is regarded as valid because in practice the disc pasture meter is used for estimating the <u>mean</u> standing crop of herbaceous material in a sample area. An important requirement though in the development of calibration equations based on mean values, is that sampling must be conducted over the full range of disc heights that are likely to occur in the particular type of herbaceous plant community under consideration. This allows the determination of the true overall slope of the linear regression line. It was the failure to meet just this requirement that caused the individual calibration equations to be different from one another.

The validity of the aforementioned calibration equation was tested empirically by comparing the fuel loads predicted with this equation with the fuel loads predicted with a linear regression equation developed from the total number of sample pairs i.e. 4 300. This latter regression was highly significant ($r = 0{,}8081$; D.F. = 4298; $P \lesssim 0{,}01$). The mean disc heights from the 43 sample sites were used in the comparison and the relationship between the two sets of predicted values was tested with a simple linear regression analysis. The results are presented in Figure 4.4.

The results of the regression analysis illustrated in Figure 4.4 showed that the fuel loads predicted with the two equations were perfectly correlated ($r = 1{,}0000$; D.F. = 41; $P \lesssim 0{,}01$). The resultant regression equation also showed that the fuel loads predicted with the two calibration equations differed negligibly over the range of fuel loads presented in Figure 4.4.

(b) Fuel moisture

The fuel moisture was estimated by cutting ten random grass samples at ground level in the area to be burnt immediately before the application of the fire. The samples were placed in sealed bottles while in the field and later dried at 80°C for 96 hours. The fuel moisture was expressed as a percentage on a dry mass basis in accordance with international procedure.

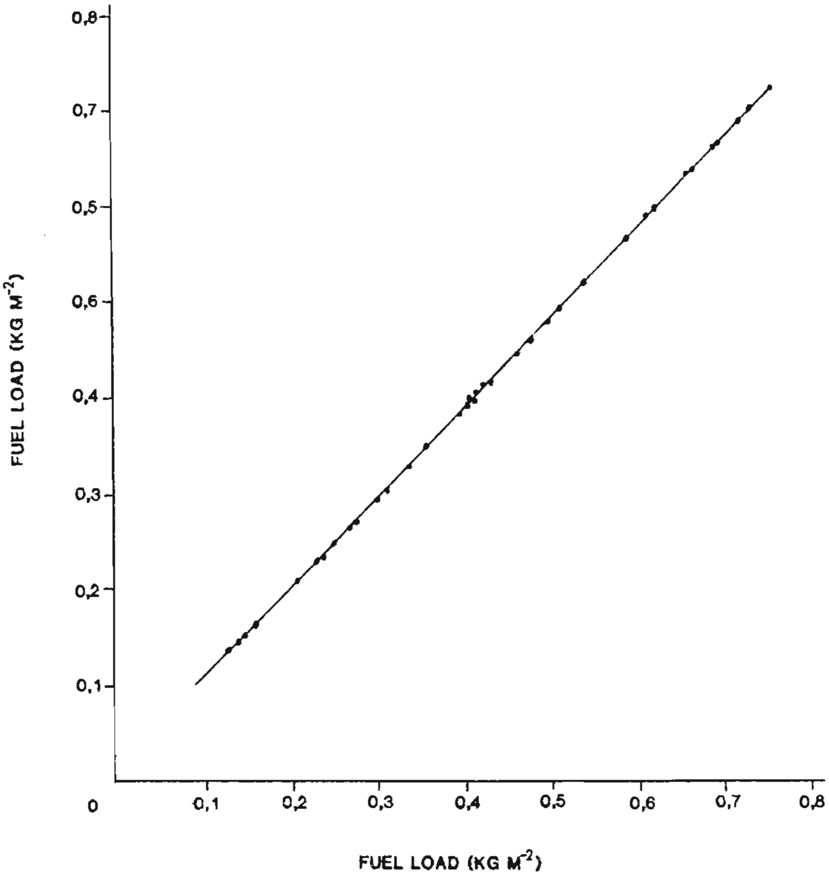

FIGURE 4.4. The linear regression between the fuel loads predicted with the calibration equation developed from mean values (x) and the fuel loads predicted with the calibration equation developed from the total number of sample pairs (y).

(c) Fuel compaction

The fuel compaction was estimated before burning by measuring the mean canopy height of the grass sward and together with the fuel load, calculating the quantity of fuel per unit volume i.e. kg m^{-3}.

(d) Air temperature

The air temperature was recorded with a mercury thermometer immediately before the application of a burn and was expressed in °C.

(e) Relative humidity

The relative humidity was recorded with a whirling psychrometer immediately before the application of a fire and was expressed as a percentage.

(f) Soil moisture

No mention is made in the literature of the effect of soil moisture on fire behaviour. However, this parameter was included because of the importance attached to it in all veld burning regulations in South Africa. Ten stratified random samples were taken to a depth of approximately 20cm prior to burning and the soil was dried at 80°C for 96 hours. The soil moisture was expressed as a percentage on a dry mass basis.

(g) Size of burn

The size of the area burnt as a surface head fire was recorded for each burn and expressed in m^2.

(h) Wind

Initially the wind speed was measured by using a hand held anemometer at a height of 1,7m. Subsequently a self recording cup anemometer was used and located at the same height. The recording of mean wind speed was limited to the period when the plots were burning as head fires and the apparatus was located approximately 50m from the burning area in order to measure only general atmospheric wind conditions and not those generated by the fire itself. The wind speed was measured at a height of 1,7m because this is the approximate level of a one's face and thus making the measurements conceptually meaningful. The wind speed was expressed in $m\ s^{-1}$.

(i) Slope

This factor was not considered in the study because all burning plots were on a moderate slope that did not exceed 22°.

(j) Rate of spread

The rate of spread of surface head fires was recorded as described in section 4.2.2.

(k) Flame height

The mean height of the flames occurring during the surface head fires was estimated visually and expressed in m.

(ii) Analysis of data

The fire behaviour models were developed with the aid of multiple regression analyses. To fulfill the statistical requirement that the independent variables must have a linear relationship with the dependent variable in a multiple regression analysis, tests were conducted to see whether the data needed to be transformed or not. On the advice of Mr. W.R. Smith, biometrician at the Dohne Agricultural Research Station in the Eastern Cape, the independent variables were transformed using logarithmic (lnx), square (x^2), square root ($\sqrt{x}$) and reciprocal ($\frac{1}{x}$) transformations. Simple linear regression analyses were then conducted between the independent variables and the dependent variable using both transformed and untransformed data. The form of the independent variable that gave the highest correlation coefficient was used in the multiple regression analysis.

Finally, two series of multiple regression analyses were conducted. In the first series the independent variables were fuel load, fuel moisture, fuel compaction, air temperature, relative humidity, wind speed, size of burn and soil mosture. In the second series the independent variables were limited to fuel load, fuel moisture, air temperature, relative humidity and wind speed because the results showed that fuel compaction and soil moisture had no significant effect on fire behaviour. The size

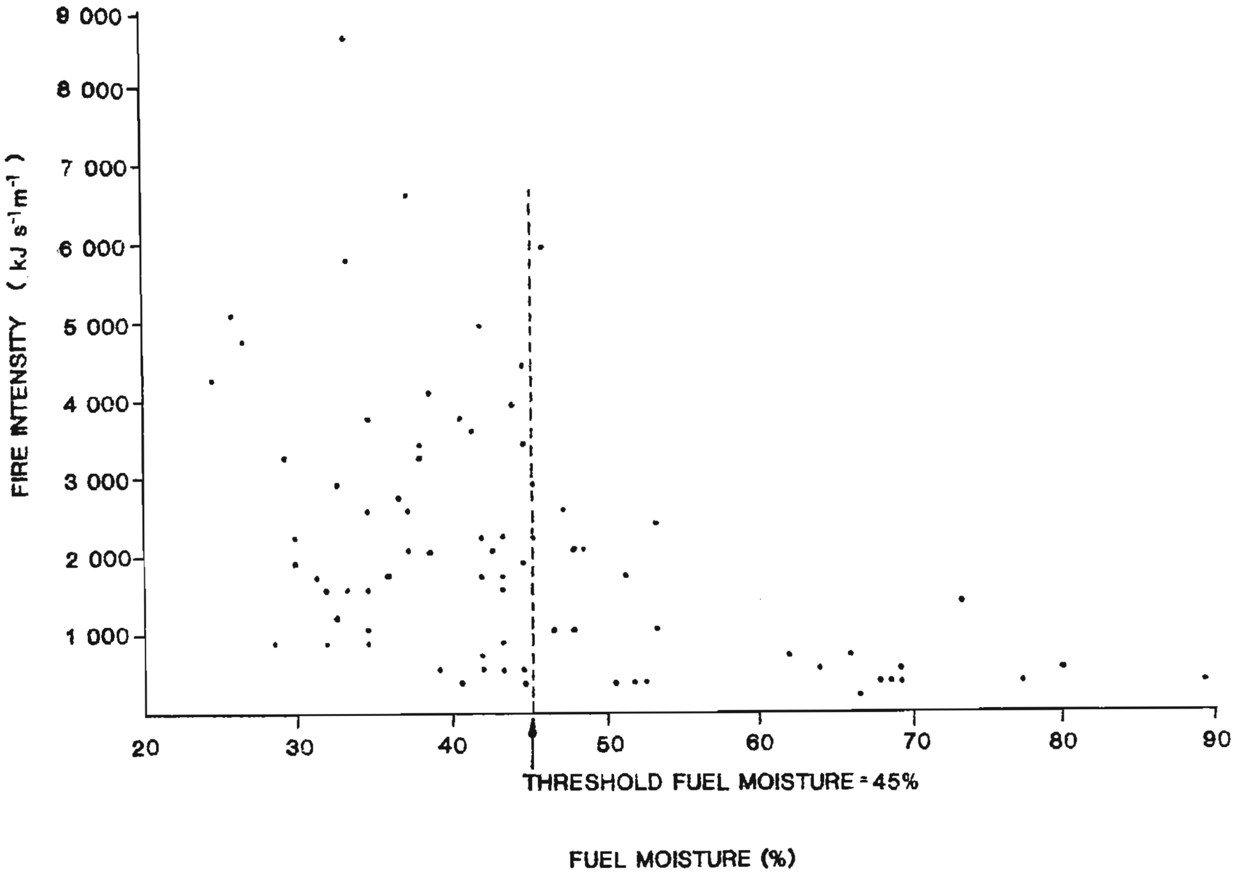

FIGURE 4.5. A scattergram showing the relationship between fuel moisture and fire intensity.

45 per cent. However, it was not possible to develop a fire intensity model using results where fuel moisture did not exceed this threshold value because of insufficient data.

The results of the multiple regression analysis where the number of independent variables was limited are presented in Table 4.6.

The results in Table 4.6 are similar to those in Table 4.5 for the independent variables that were included. In this case the independent variables accounted for 54,71 per cent of the variation in the fire intensity, the lower value being caused by the omission of the size of the burn. In view of the slight reduction (4,22 per cent) in the reliability of the regression equation and because the size of burn is not always known before the

TABLE 4.6. The effect of fuel load, fuel moisture, air temperature, relative humidity and wind speed on fire intensity expressed as a percentage (n= 70).

Independent Variable	Transformation	Effect	Significance
Fuel load	x	27,48	$P \lesssim 0,01$
Fuel moisture	$\sqrt{x}$	18,76	$P \lesssim 0,01$
Relative humidity	x^2	3,54	$P \lesssim 0,01$
Wind speed	$\frac{1}{x}$	4,89	$P \lesssim 0,05$
Air temperature	x	0,04	NS
TOTAL		54,71	

event, it was decided to use the results in Table 4.6 instead of Table 4.5 for predicting fire intensity. The regression equation is as follows:

$$FI = 4\,782 + 3\,341\,x_1 - 550\,\sqrt{x_2} - 0{,}2620\,x_3^2 - 797\,\frac{1}{x_4}$$

where:

FI = fire intensity - $kJ\ s^{-1}\ m^{-1}$;
x_1 = fuel load - $kg\ m^{-2}$;
x_2 = fuel moisture - %;
x_3 = relative humidity - %;
x_4 = wind speed - $m\ s^{-1}$.

This regression equation is based on the following statistics:

Number of cases = 70;
Multiple correlation coefficient (R) = 0,7394 ($P \lesssim 0,01$);
Coefficient of determination (R^2) = 0,547.

The multiple correlation coefficient is highly significant and the regression equation accounted for 54,7 per cent of the variation in the fire intensity.

(ii) Flame height

The results of the multiple regression analysis when all the independent variables were included are represented in Table 4.7.

TABLE 4.7. The effect of fuel load, fuel moisture, fuel compaction, air temperature, relative humidity, wind speed, size of burn and soil moisture on flame height expressed as a percentage (n = 35).

Independent Variable	Transformation	Effect	Significance
Fuel load	$\sqrt{x}$	36,70	$P \overline{<} 0,01$
Fuel moisture	$\frac{1}{x}$	10,54	$P \overline{<} 0,05$
Size of burn	$\sqrt{x}$	6,59	$P \overline{<} 0,05$
Soil moisture	$\ln x$	3,28	NS
Relative humidity	x	1,72	NS
Fuel compaction	$\frac{1}{x}$	1,16	NS
Wind speed	x	0,09	NS
Air temperature	x	0,03	NS
TOTAL		60,11	

The independent variables in Table 4.7 accounted for 60,11 per cent of the variation in flame height. Fuel load had the greatest effect on the height of the flames while fuel moisture and the size of the burn also had significant but lesser effects. The remaining variables had no significant effect on flame height.

The results of the multiple regression analysis when the independent variables were limited to fuel load, fuel moisture, air temperature, relative humidity and wind speed are presented in Table 4.8.

The results in Table 4.8 indicate that the independent variable accounted for 56,61 per cent of the variation in the flame height. This is a reduction of only 3,50 per

TABLE 4.8. The effect of fuel load, fuel moisture, air temperature, relative humidity and wind speed on flame height expressed as a percentage (n = 46).

Independent Variable	Transformation	Effect	Significance
Fuel load	$\sqrt{x}$	43,02	$P \lesssim 0{,}01$
Fuel moisture	$\frac{1}{x}$	8,20	$P \lesssim 0{,}01$
Air temperature	x	4,45	$P \lesssim 0{,}05$
Wind speed	x	0,92	NS
Relative humidity	x	0,02	NS
TOTAL		56,61	

cent from the results presented in Table 4.7. In this case the variables that had a significant effect were fuel load, fuel moisture and air temperature. The probable reason why air temperature had a significant effect on flame height in the latter multiple regression analysis is that this variable was significantly correlated with the size of burn and fuel compaction. Both these correlations have no physical basis to them and therefore the problems associated with the co-linearity of independent variables in multiple regression analyses were undoubtedly occurring. The multiple regression equation based on the significant variables in Table 4.8 is as follows:

$$FH = -5{,}60 + 6{,}32\sqrt{x_1} - 78{,}68\,\frac{1}{x_2} + 0{,}0795\,x_3$$

where:

FH = flame height - m;

x_1 = fuel load - kg m^{-2};

x_2 = fuel moisture - %;

x_3 = air temperature - °C.

The regression is based on the following statistics:

Number of cases = 46;

Multiple correlation coefficient (R) = 0,7461 ($P \lesssim 0,01$); Coefficient of determination (R^2) = 0,557.

The multiple correlation coefficient is highly significant and the regression equation accounted for 55,7 per cent of the variation in flame height.

(iii) Rate of spread

The results of the multiple regression analysis when all the independent variables were included are presented in Table 4.9.

TABLE 4.9. The effect of fuel load, fuel moisture, fuel compaction, air temperature, relative humidity, wind speed, size of burn and soil moisture on the rate of spread expressed as a percentage (n = 70).

Independent Variable	Transformation	Effect	Significance
Fuel moisture	x	23,26	$P \lesssim 0,01$
Wind speed	$\sqrt{x}$	6,99	$P \lesssim 0,01$
Relative humidity	$\frac{1}{x}$	6,46	$P \lesssim 0,05$
Size of burn	$\ln x$	3,07	NS
Soil moisture	$\frac{1}{x}$	2,20	NS
Air temperature	$\frac{1}{x}$	2,92	NS
Fuel compaction	$\frac{1}{x}$	0,96	NS
Fuel load	$\frac{1}{x}$	0,05	NS
TOTAL		45,91	

The results in Table 4.9 indicate that the independent variables accounted for 45,91 per cent of the variation in the rate of spread of the fire front.

Fuel moisture played a dominant role but wind speed and relative humidity also had a significant effect. The other variables had no significant effect on the rate of spread.

The results of the multiple regression analysis when the independent variables were limited to fuel load, fuel moisture, air temperature, relative humidity and wind speed are presented in Table 4.10.

TABLE 4.10. The effect of fuel load, fuel moisture, air temperature, relative humidity and wind speed on the rate of spread expressed as a percentage ($n = 70$).

Independent Variable	Transformation	Effect	Significance
Fuel moisture	x	23,26	$P \lesssim 0{,}01$
Wind speed	$\sqrt{x}$	6,99	$P \lesssim 0{,}01$
Relative humidity	$\frac{1}{x}$	6,46	$P \lesssim 0{,}05$
Fuel load	$\frac{1}{x}$	1,35	NS
Air temperature	$\frac{1}{x}$	1,75	NS
TOTAL		39,81	

The results in Table 4.10 differ from those presented in Table 4.9 in that the independent variables only accounted for 39,81 per cent of the variation in the rate of spread. This was caused by the omission of the other independent variables in the multiple regression analysis. However, fuel moisture, wind speed and relative humidity were still the only variables that had a statistically significant effect on the rate of spread of the fire front. The resultant regression equation is as follows:

$$\text{ROS} = 0{,}2504 - 0{,}0051\, x_1 + 0{,}0891\, \sqrt{x_2} + 2{,}32\, \frac{1}{x_3}$$

where:

x_1 = fuel moisture - %;
x_2 = wind speed - m s^{-1};
x_3 = relative humidity - %.

This regression equation is based on the following statistics:

Number of cases = 70;
Multiple correlation coefficient (R) = 0,6059 ($P \lesssim 0{,}01$);
Coefficient of determination (R^2) = 0,367.

The multiple correlation coefficient is highly significant and the regression equation accounted for 36,7 per cent of the variation in the rate of spread of the fire front.

4.3.3.3 Discussion and conclusions

The coefficients of determination (R^2) indicate that the models for predicting fire intensity and flame height are more reliable than the model for predicting rate of spread. Nevertheless by normal statistical standards these coefficients of determination are all rather low. Generally regression equations are used only for predictive purposes when the coefficient of determination accounts for at least 95 per cent of the variation in the dependent variable. However, experience gained during this research would indicate that it is virtually impossible to attain these levels of accuracy when modelling such a complex phenomenon as fire behaviour. The fact that the results from the statistical analyses were significant, conceptually meaningful and logical, indicates that these results can be used as a guide for predicting the behaviour of fires. Therefore if the results are used in this context it is firmly beleived that they can serve as a useful guide for management purposes. It should never be forgotten though that fire is a highly complex phenomenon that is very difficult to model accurately.

Another point that arises fom the results is that not all the factors that are known to influence the behaviour of a fire were statistically significant in this study. This is one of the disadvantages of modelling using statistical procedures such as a multiple regression analysis. Statistical models merely reflect the relationship between the dependent and independent variables as they occurred in a particular study. It is very difficult to cover all the possible combinations of the dependent and independent variables in field trials. This is responsible for the non-significance of certain independent variables in multiple regression analyses of this kind. For example, in the model for predicting the rate of spread, the results showed that fuel load had no significant effect on this fire behaviour parameter. This is contrary to research experience presented in the literature (Luke & McArthur, 1978). The probable reason for this is that, considering the range of fuel loads that occurred in this study i.e.0,186 - 1,050 kg m^{-2}, the continuity of the fuel bed was such that there was always sufficient fuel to carry the fire. Field experience indicates that when fuel loads are less than 0,15 kg m^{-2}, the rate of spread of surface head fires is significantly reduced due to the discontinuous nature of the fuel bed.

The aforementioned characteristic of statistical models makes it essential that the fire models developed in this study are used only within the limits set by the maximum and minimum values of the independent variables. This does not constitute a serious limitation to the usefulness of these models because the range in the values of the independent variables was generally wide enough to be used over a considerable range of climatic conditions prevailing during late winter and early spring in the arid savannas of southeastern Africa.

Finally, another reason for some of the independent variables not having significant effects on the dependent variables is the problem of co-linearity between independent variables. One of the assumptions for a valid multiple regression analysis is that the independent variables are not correlated with one another. Failure to comply with this requirement often results in one of the independent variables masking the effect of the other independent variable with which it is correlated. This happened with the results presented in Table 4.7 where the effect of air temperature on flame height was masked by the size of burn and fuel compaction. Similarly, air temperature and relative humdity were correlated in all the multiple regression analyses presented, causing only one of these variables to be significant in any one analysis.

The solution to this problem is to ensure that none of the significant variables in a multiple regression equation are correlated with one another. This requirement was met in all the statistical models that were developed for predicting fire intensity, flame height and rate of spread in this study.

4.3.4 Behaviour of different types of fires

One of the components of the fire regime is the type of fire. Its inclusion as part of the fire regime is justified on the basis that different types of fires behave differently and have contrasting effects on the vegetation.

It was mentioned in section 2.3.1 that in the savanna areas surface fires burning as head and back fires are the most common types of fire.

It was therefore decided to study the behaviour of surface fires burning with and against the wind in order to better understand the mechanisms behind the different effects of these types of fires on the vegetation. The parameters that were used for comparing the behaviour of head and back fires were rate of spread, fire intensity, flame height and fire temperature.

4.3.4.1 Procedure

The data for rate of spread, fire intensity, flame height and fire temperatures were collected from an experiment that was conducted on the research farm of the University of Fort Hare. It was situated in the False Thornveld of the Eastern Cape (Acocks, 1953). The experimental area comprised two sites of sweet grassveld approximately one kilometre apart and both situated on a gentle southeastern slope. The results of a grass frequency survey of the two sites, comprising a total of 950 square metre samples arranged in a stratified systematic manner, are presented in Table 4.11.

TABLE 4.11. The botanical composition of the grass sward at the two experimental sites expressed as percentage frequency.

Species	Site 1[1]	Site 2[2]	Mean
Themeda triandra	98	56	77
Sporobolus fimbriatus	76	96	86
Panicum stapfianum	76	86	81
Cymbopogon plurinodis	64	68	66
Digitaria eriantha	60	80	70
Eragrostis chloromelas	30	4	17
Sporobolus capensis	18	90	54
Eustachys mutica	16	18	17
Cynodon dactylon	8	36	22
Eragrostis obtusa	6	8	7
Setaria neglecta	6	46	26
Melica decumbens	4	6	5
Panicum maximum	1	1	1
Aristida congesta subsp. barbicollis	-	1	1

Site 1 : 12 plots
Site 2 : 7 plots

The data presented in Table 4.11 show that Themeda triandra was much more widely represented at site 1 than site 2.

The experiment was situated at an altitude of 580m in an area that received a mean annual rainfall of 539mm during the period 1925 to 1982. The soil type at both experimental sites was a sandy loam of the Glenrosa form.

(i) Treatments

Ten head fires and nine back fires were applied to plots 45m x 45m in size. Twelve fires were applied at the one site and seven fires at the other. At each site the plots were arranged in the form of a simple random design with a rectangular shape. The head and back fire treatments were applied consecutively to ensure that the two types of fires were comparable over a similar range of environmental variables. The treatments were applied from the 22nd to 30th September, 1976 during which time the soil and grass fuel were initially very dry. However, rain fell during the experimental period and thoroughly wetted the soil, so that some of the treatments were applied when the soil and fuel were moist.

The head fires were applied according to the accepted safety procedure of initially laying two diverging lines of fire down the two leeward sides of the plot. Once the situation was deemed safe the rest of the plot was ring fired along the windward sides. Thus the initial total length of down wind-fire front was approximately 90m per plot in the head fires. The back fires were applied as a single fire front along the leeward side of the plot, giving a total fire front of 45m per plot.

(ii) Measurements

(a) Fuel load

The fuel load was estimated in each plot by cutting five 2m x 2m quadrats in the interplot area on either side of the plots. The cut material comprised mainly grass and represented in both cases approximately two growing seasons growth i.e. old, mature grass. Samples were not cut in the plots because this may have affected the behaviour of the fires. The cut material was oven dried at 80°C for 96 hours and was expressed as kg m^{-2}.

(b) Fuel moisture

Ten stratified, random samples were taken in each plot immediately before burning, oven dried at 80°C for 96 hours and the moisture percentage expressed on a dry mass basis.

(c) Air temperature

The air temperature was recorded at the beginning and end of each fire with a mercury thermometer and expressed in °C.

(d) Relative humidity

The relative humidity was recorded at the beginning and end of each fire with a whirling psychrometer and expressed as a percentage.

(e) Wind

The wind was recorded at the start, during and at the end of each fire with a hand anemometer held at a height of approximately 1,7m. Wind speeds recorded during the fire were assessed to be the most representative and were expressed in $m\ s^{-1}$.

(f) Cloud cover

The cloud cover was estimated on a scale of 0 to 10 covering the range from clear sky to complete cloud cover. This variable was included because McArthur (1966) stated that the presence of clouds frequently tend to lower the surface fuel temperatures and raise fuel moisture contents.

(g) Soil moisture

Ten stratified, random soil samples were taken in each plot to a depth of 20cm, immediately before burning. The samples were dried at 80°C for 96 hours and the soil moisture was expresed as a percentage on a dry mass basis.

(h) Rate of spread

The rate of spread was estimated using the procedure described in section 4.2.2 and was expressed in m s^{-1}.

(i) Flame height

The mean height of the flames was estimated visually and expressed in m.

(j) Fire intensity

The intensity of the fires was estimated according to the procedure described in section 4.2.2 and was expressed in kJ s^{-1} m^{-1}.

(k) Fire temperature

Temperatures were recorded during the fires with chrome-alumel thermocouples. The temperatures were measured at ground level, grass canopy and one metre above the grass canopy.

The thermocouples were connected to portable electronic recorders with extension cables. There were sufficient thermocouples for temperatures to be recorded at only one site per burn. Consequently great care was taken in selecting sites representative of the plot being burnt. The temperature recordings spanned the duration of the fire and were discontinued once the temperatures had returned to ambient levels.

The thermocouples were checked for accuracy, bearing in mind the results of Walker & Stocks (1968) who showed that the temperatures recorded by thermocouples depended upon the diameter of the thermocouple wire. The thickness of the wire was 0,65mm and the thermocouples were encased in a thin metal sheath 3mm in diameter and 1m long. The recorders were graduated in 20°C divisions and two covered the range 0°C to 800°C and one the range 130°C to 670°C.

4.3.4.2 Results

(i) Rate of spread

Differences in the rate of spread was one of the most striking features of the behaviour of head and back fires and the maximum, minimum and mean rates of spread for the two types of fires are presented in Table 4.12.

TABLE 4.12. The rate of spread of head and back fires expressed in $m\ s^{-1}$.

Type Of Fire	n	Mean	Minimum	Maximum
Head fire	10	0,15±0,03	0,04	0,35
Back fire	9	0,02±0,002	0,01	0,03

The results in Table 4.12 show that on average head fires were seven and a half times faster than back fires in this study. Furthermore the standard errors of the mean rate of spread of the two types of fires show that the head fires were far more variable than the back fires and were therefore more significantly influenced by the environmental variables prevailing at the time of the fires.

(ii) Fire intensity

The mean, minimum and maximum intensities of surface fires burning with and against the wind are presented in Table 4.13.

TABLE 4.13. The intensity of head and back fires expressed in kJ s^{-1} m^{-1}.

Type Of Fire	n	Mean	Minimum	Maximum
Head fire	10	1359±327	338	3557
Back fire	9	194±18	87	268

The results in Table 4.13 bear a close relationship to those for rate of spread of head and back fires because this parameter is an important component in the calculation of fire intensity.

The head fires were on average approximately seven times more intense than the back fires. The intensity of the head fires was far more variable than that of the back fires. They ranged from very cool fires to extremely hot fires, whereas the back fires were all very cool. Therefore as in the case of rate of spread, the intensity of head fires was far more significantly influenced by the environmental conditions pervailing at the time of the burn than the back fires.

(iii) Flame height

The mean, minimum and maximum flame heights of the head and back fires are presented in Table 4.14.

TABLE 4.14. The flame height of head and back fires expressed in m.

Type Of Fire	n	Mean	Minimum	Maximum
Head fire	10	2,8±0,4	1,2	5,0
Back fire	9	0,9±0,1	0,5	1,5

The data in Table 4.14 clearly illustrates the greater height of flames occurring in head fires than back fires. Again the wide range in the height of flames of head fires indicates the potential variability of this type of fire in comparison to back fires due to the influence of environmental variables.

(iv) Fire temperatures

(a) Maximum temperatures

A frequency distribution of maximum temperatures that were recorded at ground level, grass canopy and one metre above the grass canopy in the head and back surface fires is presented in Table 4.15.

TABLE 4.15. The frequency distribution of maximum temperatures recorded at ground level, grass canopy and one metre above the grass canopy in head and back fires expressed as a percentage.

Temperature	Ground level		Grass canopy		One metre above grass canopy	
(°C)	HF	BF	HF	BF	HF	BF
≲ 130	67	22	-	-	45	78
131 - 200	-	45	20	11	33	22
201 - 300	11	33	50	33	11	-
301 - 400	-	-	20	56	11	-
401 - 500	11	-	-	-	-	-
501 - 550	11	-	10	-	-	-

Note: HF = Head fire
BF = Back fire

Bearing in mind that the head and back fires were applied over a wide range of environmental variables the results in Table 4.15 indicate certain characteristics that are attributable to the behaviour of these two types of fires.

At ground level the majority of head fires had maximum temperatures of less than 130°C while the majority of back fires exceeded 130°C. However, it is pertinent to note that the temperatures in some of the head fires exceeded 500°C while none of the back fires exceeded 300°C at ground level.

At the grass canopy height the maximum temperatures of both head and back fires generally were higher than those at ground level, the majority occurring in the range 131°C to 400°C. Generally the back fires tended to be hotter than the head fires but nevertheless the temperatures of some of the head fires exceeded 500°C, indicating the greater potential of this type of fire to have a higher fire intensity, given the appropriate set of environmental conditions.

The maximum temperatures that occurred at a height of one metre above the grass canopy clearly illustrate that head fires were hotter than back fires at this level. The majority of head fires exceeded 131°C while most of the back fires were less than 131°C.

The overall impression gained from the temperature data presented in Table 4.14 is that back fires were generally more intense than head fires at ground level whereas head fires were hotter than back fires at levels above the canopy of the grass sward.

It is also clear that head fires had a greater potential for developing higher temperatures than back fires at all levels given the appropriate environmental conditions.

(b) Temperature duration

The duration of different temperatures was obtained from the temperature profiles recorded with the thermocouples during the different fires. An example of a temperature profile is presented in Figure 4.6.

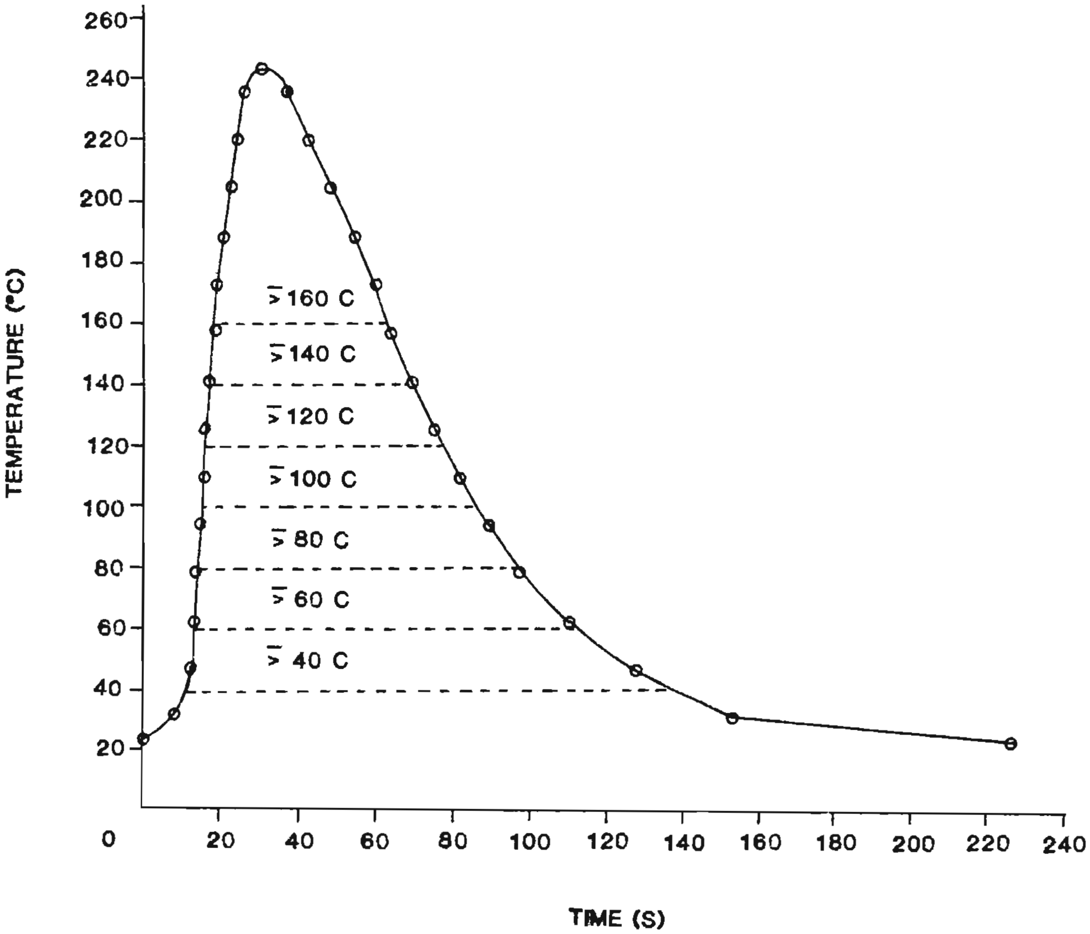

FIGURE 4.6. An example of a temperature profile recorded at the grass canopy during a head fire.

The duration of different temperatures

recorded at ground level, grass canopy and one metre above the grass canopy is presented in Table 4.16.

TABLE 4.16. The duration of temperatures (s) recorded at ground level, grass canopy and one metre above the grass canopy during head and back fires.

Temperatures	Recording Height					
	Ground Level		Grass Canopy		One Metre Above Grass Canopy	
	HF	BF	HF	BF	HF	BF
40°C	269 ± 28	321 ± 22	192 ± 20	224 ± 23	175 ± 15	201 ± 33
60°C	171 ± 18	257 ± 28	146 ± 15	160 ± 14	115 ± 6	47
80°C	106 ± 19	187 ± 18	117 ± 10	123 ± 8	89 ± 5	24
100°C	55	150 ± 15	97 ± 7	99 ± 6	68 ± 8	19
120°C	31	114 ± 15	81 ± 4	84 ± 5	51 ± 9	14
140°C	24	89 ± 18	67 ± 5	72 ± 4	35	9
160°C	22	63 ± 26	56 ± 5	58 ± 7	22	4

Note: HF = head fire;
BF = back fire;
Standard error of the mean not calculated when zero duration periods occurred in the data.

The data representing temperatures recorded at ground level and one metre above the grass canopy height are not complete because, as was mentioned earlier, one of the temperature recorders covered the range 130°C to 670°C. To overcome this problem this recorder was used during seven fires for recording ground level temperatures and for 12 fires for recording temperatures at one metre above the grass canopy. Furthermore, for the sake of clarity, temperature duration data are not presented for temperatures exceeding 160°C. This lower temperature range constituted the bulk of the data and omitting figures for higher temperatures does not alter the differences between head fires and back fires.

Considering the duration of temperatures at ground level the data in Table 4.16 clearly show that the various temperatures were maintained for a longer period in the back fires than in the head fires. An F-test indicated that the main difference occurred at temperatures $\geq$ 60°C and $\geq$ 80°C where head fires had significantly ($P \leq 0,05$) lower duration periods than back fires. This was probably caused by the greater rate of spread in head fires, resulting in the process of combustion occurring for shorter periods of time at any one point.

At the grass canopy there were no statistically significant differences between the duration periods of different temperatures in the head and back fires. Nevertheless there was a tendency for the duration period during back fires to be greater, particularly at temperatures up to 80°C. Thus a similar pattern of behaviour would appear to have occurred in the duration of different temperatures in head and back fires at the grass canopy as occurred at ground level.

At one metre above the grass canopy there was a very clear distinction between the behaviour of head and back fires. The back fires caused only minor increases in temperature and only for brief periods. Conversely, the duration of temperatures during head fires was still very significant at this level as indicated by the considerably longer duration periods. The most probable cause for the large differences in the duration of temperatures during head and back fires was undoubtedly the greater flame height of head fires, which ensured that this stratum above the ground still formed part of or was immediately adjacent to the zone of flaming combustion.

In conclusion the data in Table 4.16 strongly indicates that in head fires the highest duration of temperatures occurred in the vicinity of the grass canopy. Conversely, in back fires, the highest temperature duration was close to the soil surface.

4.3.4.3 Discussion and conclusions

The comparisions of the behaviour of head and back fires clearly illustrates the differences between these two types of fires. The contrasts in fire intensity, flame height and fire temperatures have great biological significance as they indicate the rate and vertical level at which heat energy is released during head and back fires. It will be shown in section 5.1 how this information can be used for interpreting the effects of burning on the vegetation.

The contrasting behaviour of head and back fires is also pertinent to the formulation of safety procedures for controlled burning. The fire behaviour data illustrate how by merely altering the type of fire a burn can be converted from a very cool one to a raging inferno under the same fuel and atmospheric conditions. These results provide the rationale behind the safety procedures that are incorporated in the modus operandi for controlled burning illustrated in Figure 4.1.

Finally bearing in mind the limits set by the accuracy of the temperature recording equipment and the limited number of measuring points, it is nonetheless believed that the data recorded in this study are both physically and biologically meaningful.

4.3.5 Relationships between different fire behaviour parameters

The relationships between the different fire behaviour parameters were investigated for surface head fires using simple linear regression analyses. The analyses were conducted with the independent variables in an untransformed and transformed form. Logarithmic (lnx), square (x^2), square root ($\sqrt{x}$) and reciprocal ($\frac{1}{x}$) transformations were used to ensure linearity between the dependent and independent variables. The form of the independent variable with the highest correlation coefficient was selected to represent the relationship between the fire behaviour parameters.

The temperature data presented in this section were derived from various sources. Use was made of the fire temperatures recorded with the thermocouples described in section 4.3.4. Additional thermocouple data were collected during the fires that were used for developing the fire behaviour models presented in section 4.3.3. Finally, fire temperatures were recorded at ground level, grass canopy and one metre above the grass canopy in this latter study with bi-metallic thermometers. These instruments could measure only maximum temperatures and were graduated in 10°C divisions and covered the range 0° to 550°C. There were sufficient bi-metallic thermometers for temperature recordings to be made at two measuring sites per plot. The measuring sites were subjectively chosen to represent the general condition of the plot. In situations where bush was present the temperatures were recorded in the open spaces between the trees and shrubs.

It was found that the temperature recordings made with the bi-metallic thermometers at all three levels above the ground were highly positively correlated with data derived from the thermocouples (r =

0,8325; DF = 41; $P \lesssim 0,01$). However, the temperatures recorded with the thermocouples were consistently higher than those recorded with the bi-metallic thermometers. The reason for this was that the bi-metallic thermometers were not as sensitive to changes in temperature as the thermocouples and therefore had a lag time. In view of this it was decided to adjust all the temperature data recorded with the bi-metallic thermometers to make these values compatible with the temperatures recorded with the thermocouples. This was done with the following linear regression equation based on the results of the aforementioned relationship between the two sets of data:

$$T = 73,28 + 1,18B$$

where:

T = thermocouple temperature - °C;
B = bi-metallic thermometer temperature - °C.

This adjustment was deemed necessary because it then enabled all the fire temperature data to be compared and assessed on the same basis.

4.3.5.1 Fire intensity versus flame height

The simple linear regression analysis showed that there was a highly significant positive correlation between fire intensity and flame height using untransformed data ($r = 0,6124$; DF = 29; $P \lesssim 0,01$). However, the coefficient of determination (r^2) was only 0,375, which indicates that while these two parameters are highly correlated the relationship is not reliable enough to predict flame height from fire intensity and vice versa.

4.3.5.2 Fire intensity versus fire temperatures

The relationship between fire intensity and the maximum temperatures recorded at different levels above the ground are presented in Table 4.17. The results are limited to the temperatures recorded with bi-metallic thermometers because the thermocouple data were incomplete.

TABLE 4.17. The relationship between fire intensity and the maximum temperatures recorded at ground level, grass canopy and one metre above the grass canopy ($n = 54$).

Recording Height	Transformation	r	Significance
Ground level	$\frac{1}{x}$	-0,2255	NS
Grass canopy	$\sqrt{x}$	0,6221	$P \lesssim 0,01$
One metre above grass canopy	$\frac{1}{x}$	-0,5746	$P \lesssim 0,01$

Note: r = correlation coefficient;

The results in Table 4.17 indicate that fire intensity had no significant effect on the maximum temperatures recorded at ground level during surface head fires. However, it had a highly significant positive effect on the maximum temperatures recorded at the grass canopy and one metre above the grass canopy. The higher correlation coefficient at the grass canopy would suggest that this is the vertical level where the greatest heat load occurs during a head fire. This conclusion is supported by the result in Table 4.15 where the majority of the maximum temperatures recorded during head fires at the grass canopy were higher than those recorded at ground level and one metre above the grass canopy.

4.3.5.3 Relationships between fire temperatures recorded at different levels

The differences between the maximum temperatures recorded at different levels above the ground with the bi-metallic thermometers were tested in a one way analysis of variance. The results are presented in Table 4.18.

The results in Table 4.18 show that the temperatures recorded at the various levels were all highly significantly different from one another. The highest temperatures were at the grass canopy and the lowest one metre above the grass canopy.

TABLE 4.18. The mean maximum temperatures recorded at ground level, grass canopy and one metre above the grass canopy in surface head fires. Data expressed in °C ($n = 60$).

Recording Height	Mean	Significant Differences*	
		$P \lesssim 0,05$	$P \lesssim 0,01$
Grass canopy	258	│	│
Ground level	200	│	│
One metre above grass canopy	169	│	│

Standard error mean = 8°C;

Least significant differences = 22°C ($P = 0,05$);

= 29°C ($P = 0,01$).

* Lines on the same vertical axis link non-significantly different means.

The relationships between the fire temperatures recorded at the different levels are presented in Table 4.19.

TABLE 4.19. The relationships between the maximum temperatures recorded at ground level (GL), grass canopy (GC) and one metre above the grass canopy (MGC) ($n = 60$).

Comparison	Transformation	r	Significance
GL vs GC	x	0,6664	$P \lesssim 0,01$
GL vs MGC	x^2	0,5030	$P \lesssim 0,01$
GC vs MGC	$\sqrt{x}$	0,8173	$P \lesssim 0,01$

Note: r = correlation coefficient.

The results in Table 4.19 show that there were highly significant positive correlations between the maximum temperatures recorded at the different levels above the ground. The highest correlation was between temperatures recorded at the grass canopy and one metre above the grass canopy. The lowest correlation was between the temperatures recorded at ground level and one metre above the grass canopy. From these results it can be concluded that temperatures recorded at the grass canopy are a very good index of the overall temperature regime occurring during a surface head fire, since they were well correlated with temperatures both at ground level and with those one metre above the grass canopy.

4.3.5.4 Maximum temperatures versus temperature duration

The relationships between the maximum recorded temperature and the duration of different threshold temperatures were determined for surface head fires. The data comprised temperatures recorded at ground level, grass canopy and one metre above the grass canopy using thermocouples. The results are presented as the duration of temperatures, expressed in seconds, equal to or greater than (≥) 60°C, 80°C, 100°C, 120°C, 140°C and 160°C associated with different maximum temperatures. The results for the maximum temperatures recorded at ground level are presented in Table 4.20.

TABLE 4.20. The relationship between the maximum temperatures recorded at ground level and the period of time expressed in seconds that temperatures were maintained in the range ≥ 60°C to ≥ 160°C during surface head fires (n = 44).

Temperature	Transformation	r	r^2	a	b	Significance
≥ 60°C	lnx	0,8402	0,706	-498	133	$P \leq 0{,}01$
≥ 80°C	lnx	0,8807	0,776	-472	118	$P \leq 0{,}01$
≥ 100°C	lnx	0,8845	0,782	-426	103	$P \leq 0{,}01$
≥ 120°C	lnx	0,8771	0,769	-361	85,7	$P \leq 0{,}01$
≥ 140°C	$\sqrt{x}$	0,8740	0,764	-101	11,9	$P \leq 0{,}01$
≥ 160°C	x	0,8646	0,748	-27,4	0,3639	$P \leq 0{,}01$

Note: r = correlation coefficient;
r^2 = coefficient of determination;

correlations only between the maximum temperature and the period of time the threshold temperatures ≥ 140°C and ≥ 160°C were maintained. In this case the coefficients of determination were much lower than in the analysis presented in Table 4.20.

The results of the linear regression analysis of the temperature data recorded at one metre above the grass canopy are presented in Table 4.22.

TABLE 4.22. The relationship between the maximum temperature recorded one metre above the grass canopy and the period of time expressed in seconds that the temperatures were maintained for in the range ≥ 60°C to ≥ 160°C during surface head fires (n = 17).

Temperature	Transformation	r	r^2	a	b	Significance
≥ 60°C	lnx	0,3668	0,135	-	-	NS
≥ 80°C	$\frac{1}{x}$	-0,5310	0,282	131	-8669	$P \leq 0,05$
≥ 100°C	$\frac{1}{x}$	-0,7433	0,552	122	-10480	$P \leq 0,01$
≥ 120°C	$\frac{1}{x}$	-0,8511	0,724	108	-10929	$P \leq 0,01$
≥ 140°C	lnx	0,8993	0,809	-283	60,4	$P \leq 0,01$
≥ 160°C	$\sqrt{x}$	0,9119	0,832	-81	7,55	$P \leq 0,01$

Note: r = correlation coefficient;
r^2 = coefficient of determination;
a = y intercept;
b = slope of the regression line.

The results in Table 4.22 show that except for ≥ 60°C all the periods of time that the other threshold temperatures were maintained for were significantly positively correlated with the maximum temperature. However, the coefficients of determination indicate that the maximum temperature accounted for a considerable amount of variation in the duration of temperatures only in the upper range of ≥ 120°C to ≥ 160°C. The range in temperatures over which these results were obtained and within which the regression equations should be used are presented in Table 4.23.

TABLE 4.23. The range in temperatures that were recorded at ground level, grass canopy and one metre above the grass canopy during the surface head fires.

Recording height	Temperatures - °C	
	Minimum	Maximum
Ground level	97	345
Grass canopy	109	493
One metre above grass canopy	105	345

Based on the results in Tables 4.20, 4.21, and 4.22 the estimated duration of threshold temperatures associated with maximum temperatures recorded at ground level, grass canopy and one metre above grass canopy are given in Table 4.24. The maximum temperatures used approximate the range in minimum and maximum values mentioned earlier.

The results in Table 4.24 indicate the existence of distinct trends. Firstly at all levels for which there were data the duration period of the threshold temperatures increased with an increase in the maximum temperature.

Secondly the duration period decreased as the magnitude of the threshold temperatures increased.

Finally the duration period of the threshold temperatures decreased with an increase in the recording height of the maximum temperatures above the ground. However, the difference in the duration period recorded at the grass canopy and one metre above the grass canopy decreased to negligible proportions as the maximum temperature increased. Unfortunately there were data available only for the two upper threshold temperatures and it is not known what happened at the lower threshold temperatures. Despite the lack of a complete set of data these results are valuable because an increase in the intensity of

TABLE 4.24. The estimated duration (s) of threshold temperatures in the range ≥60°C to ≥160°C associated with maximum temperatures recorded at ground level (GL), grass canopy (GC) and one metre above the grass canopy (MGC).

Threshold Temperatures	Level	Maximum Temperatures					
		100°C	150°C	200°C	250°C	300°C	350°C
≥60°C	GL	114	168	207	236	261	281
	GC	-	-	-	-	-	-
	MGC	-	-	-	-	-	-
≥80°C	GL	71	119	153	180	201	219
	GC	-	-	-	-	-	-
	MGC	44	73	88	96	102	106
≥100°C	GL	48	90	120	143	161	177
	GC	-	-	-	-	-	-
	MGC	17	52	70	80	87	92
≥120°C	GL	-	68	93	112	128	141
	GC	-	-	-	-	-	-
	MGC	-	35	53	64	72	77
≥140°C	GL	-	45	67	87	105	122
	GC	-	32	48	57	64	68
	MGC	-	20	37	50	62	71
≥160°C	GL	-	-	45	64	82	100
	GC	-	-	34	46	54	60
	MGC	-	-	26	38	50	60

surface head fires is generally accompanied by an increase in the height of the flames (see section 4.3.5.1). Consequently, at high temperatures the grass canopy and one metre above the grass canopy are all in the zone of flaming combustion, and under these conditions there is little difference in the duration of threshold temperatures at these two levels.

4.3.5.5 Rate of spread versus temperature duration

The relationship between the rate of spread of the fire front and the duration of different threshold temperatures was determined using the same statistical procedures described in section 4.3.5.4. The results for temperatures recorded at ground level are presented in Table 4.25.

TABLE 4.25. The relationship between the rate of spread and the duration of threshold temperatures in the range ≥ 60°C to ≥ 160°C recorded at ground level during surface fires (n = 44).

Temperature	Transformation	r	r^2	Significance
≥ 60	x^2	-0,2467	0,061	NS
≥ 80	x^2	-0,2173	0,047	NS
≥ 100	x^2	-0,1864	0,035	NS
≥ 120	x^2	-0,1858	0,035	NS
≥ 140	x^2	-0,1675	0,028	NS
≥ 160	x^2	-0,1694	0,029	NS

Note: r = correlation coefficient;
r^2 = coefficient of determination.

The results in Table 4.25 indicate that there were no statistically significant correlations between the rate of spread and the duration of the different threshold temperatures at ground level.

The relationship between the rate of spread and the duration of temperatures recorded at the grass canopy is presented in Table 4.26.

The rate of spread was significantly correlated only with the duration of threshold temperatures at ≥ 60°C and ≥ 80°C in Table 4.26. The results showed that this was a negative relationship i.e. the greater the rate of spread the shorter the duration of the temperatures.

TABLE 4.26. The relationship between the rate of spread and the duration of threshold temperatures in the range ⋝60°C to ⋝160°C recorded at the grass canopy during surface head fires (n = 21).

Temperature	Transformation	r	r^2	Significance
⋝ 60	$\frac{1}{x}$	0,5305	0,281	$P \lesssim 0{,}05$
⋝ 80	$\frac{1}{x}$	0,4635	0,215	$P \lesssim 0{,}05$
⋝ 100	$\frac{1}{x}$	0,2612	0,068	NS
⋝ 120	$\frac{1}{x}$	0,0745	0,006	NS
⋝ 140	$\sqrt{x}$	0,2329	0,054	NS
⋝ 160	$\ln x$	0,4119	0,170	NS

Note: r = correlation coefficient;
r^2 = coefficient of determination.

This is an acceptable result except it is difficult to account for the absence of significant correlations at the higher threshold temperatures.

The relationship between the rate of spread and the duration of temperatures recorded at one metre above the grass canopy is presented in Table 4.27.

The results in Table 4.27 show that there were significant positive correlations between the rate of spread and the duration of different threshold temperatures. The only exception was at the ⋝80°C threshold temperature. These results are in contradiction to those in Table 4.24 where there was a negative relationship between the rate of spread and the duration of threshold temperatures. The only explanation that can be suggested is that a linear regression analysis showed that there was a significant positive correlation between rate of spread and flame height ($r = 0{,}4942$; DF = 29; $P \lesssim 0{,}01$) i.e. the faster the rate of spread the greater was the height of the flames. Therefore the temperature recording probes at one metre

TABLE 4.27. The relationship between the rate of spread and the duration of threshold temperatures in the range $\gtrsim 60°C$ to $\gtrsim 160°C$ recorded at one metre above the grass canopy during surface head fires (n = 17).

Temperature	Transformation	r	r^2	Significance
$\gtrsim 60$	x^2	0,5208	0,271	$P \lesssim 0,05$
$\gtrsim 80$	x^2	0,4817	0,232	NS
$\gtrsim 100$	x^2	0,4966	0,247	$P \lesssim 0,05$
$\gtrsim 120$	x^2	0,5135	0,264	$P \lesssim 0,05$
$\gtrsim 140$	x	0,5401	0,29	$P \lesssim 0,05$
$\gtrsim 160$	x^2	0,5348	0,286	$P \lesssim 0,05$

Note: r = correlation coefficient;
r^2 = coefficient of determination.

above the grass canopy were probably in greater contact with the zone of flaming combustion during fires with high rates of spread than during slow moving fire with low flames. Conversely, at the grass canopy the temperature recording probes undoubtedly were always in the zone of flaming combustion, thus accounting for high rates of spread resulting in shorter temperature durations. Support for this explanation is also provided by the results in Table 4.24. These show that with high temperatures there was not a great difference in the duration of temperatures at the grass canopy and one metre above the grass canopy. However, at lower temperatures the temperature duration at one metre above the grass canopy was considerably less.

4.3.5.6 Discussion and conclusions

The results show clearly that fire intensity was highly significantly correlated with flame height and the maximum temperatures recorded during surface head fires. Bearing this in mind and the fact that this parameter is the product of the heat released during a fire and the rate of spread of the fire front, it can be concluded that fire intensity is well suited for quantitatively describing the general behaviour of surface head fires. This provides additional justification for recognising fire intensity as one of the components of the fire regime.

No comparisions were made between flame height and fire temperatures because of insufficient data. This is unfortunate as it could have provided direct evidence of flame height being a reliable index of the vertical distribution of the release of heat energy during a fire. It is therefore an aspect that should be given some research attention in the future.

Vines (1981) expressed reservations about the use of temperature measurements for characterising the intensity of fires. He believed that it indicated failure to appreciate the distinction between flame temperature and fire intensity. However, the fire temperature data obtained in this study yielded results that correlated well with fire intensity. These data gave a good indication of the dynamics involved in the release of heat energy during surface head fires. It was never intended to measure the temperatures of flames but rather the temperatures occurring at a point in the fire or in close proximity to a fire. Thus, from a biological point of view, these temperatures represent the amount and rate of heat energy released that a living organism would be subjected to at different levels above the ground during a fire. It is also recognised that the temperature recorded at such a point represents the heat energy reaching that point by heat transfer via conduction, convection and/or radiation or directly from combustion occurring at that point.

Finally, the results showed that the maximum temperatures recorded at the grass canopy are a good indication of the temperatures occurring at different levels above the ground during surface head fires. In addition maximum temperatures are a reliable index of the duration of different temperatures above the ground. These are particularly useful results as it is much easier and less expensive to measure maximum temperatures than it is to measure temperature profiles. These measurements require sophisticated and expensive temperature recording equipment.

CHAPTER 5

BURNING AND BROWSING AS MANAGEMENT PRACTICES IN CONTROLLING BUSH ENCROACHMENT IN THE ARID SAVANNAS OF SOUTHEASTERN AFRICA

5.1 INTRODUCTON

In this chapter attention will be focused on the development of practical procedures associated with the role fire can play in controlling bush encroachment in the arid savannas. These procedures take the form of the answers to the key questions posed in section 3.4. They comprise the technology required for using fire to reduce bush to an available height and utilising the regrowth with goats.

The technology was developed in a series of experiments designed to determine the effect of the pertinent components of the fire regime on the grass sward and the bush. Research was also conducted on those aspects related to the utilisation of bush with goats, namely, the acceptability of different bush species, stocking rate and browsing management.

5.2 EFFECT OF FIRE ON THE VEGETATION

5.2.1 Effect on the grass sward

5.2.1.1 Type of fire

The effect of surface fires, burning as head or back fires, on the grass sward was investigated in the experiment described in section 4.3.4. The effect of head and back fires was assessed in terms of the recovery of the grass sward measured on three occasions over a two month period at the end of the first growing season after the burns. The mean yield of grass was estimated with a disc pasture meter as described by Bransby & Tainton (1977). One hundred disc height readings arranged in a random, stratified manner were taken per plot. The mean production of grass expressed in kilograms per hectare was calculated using the calibration equation for the disc pasture meter presented in section 4.3.3.1.

(i) Results and discussion

The results of the disc pasture meter survey are presented in Table 5.1.

TABLE 5.1. The mean production of grass in the plots burnt as head and back surface fires expressed in kg ha^{-1}.

Type Of Fire	Grass Production		
	Estimated 9/3/77	Estimated 31/3/77	Estimated 16/5/77
Head Fire	4107	3796	4184
Back Fire	3757	3446	3912

A two way analysis of varience was conducted on the data in Table 5.1. This was considered to be statistically acceptable because instead of the treatments being separated by space they were separated by time and therefore met with the requirements for this type of analysis (Retief, 1982: personal communication). The results showed that the back fires depressed the regrowth of grass significantly in comparison to the head fires (F = 155.29; DF = 1 and 2).

The explanation for the different effects of head and back fires on the regrowth of the grass is provided by the relationship between the grass production after the burns and the period of time certain temperatures were maintained at ground level and within the grass canopy. These relationships were determined in a series of simple linear regression analyses where the independent variable was transformed using logarithmic (lnx), square (x^2), square root ($\sqrt{x}$) and reciprocal ($\frac{1}{x}$) transformations. The resultant highest correlation coefficient was used to represent the relationship between grass production and the duration of different threshold temperatures. The results are presented in Table 5.2.

TABLE 5.2. The correlation between grass production and the duration of different threshold temperatures at ground level (n = 7) and the grass canopy (n = 19). Data expressed as correlation coefficients.

	Grass Production					
Threshold Temperature	Ground Level			Grass Canopy		
	Date 9/3/77	Date 31/3/77	Date 16/5/77	Date 9/3/77	Date 31/3/77	Date 16/5/77
≥ 40°C	-0,5946 L	0,7498 R	0,6908 R	-0,0871 S	-0,1323 S	0,2566 R
≥ 60°C	-0,6943 S	-0,6483 S	-0,6524 S	-0,1631 S	-0,1799 S	0,3205 R
≥ 80°C	-0,7473 S	-0,7099 S	-0,7066 S	-0,2078 S	-0,2502 S	0,3916 R
≥ 95°C	-0,7573*S	-0,7288 S	0,7227 R	-	-	-
≥ 100°C	-	-	-	-0,3290 S	-0,3186 S	0,4120 R
≥ 120°C	-	-	-	-0,4901*S	-0,4747*S	0,4981*R
≥ 140°C	-	-	-	-0,6033**S	-0,5269*S	-0,4952*SR
≥ 160°C	-	-	-	-0,4810*S	0,4199 R	0,2884 R

Note: Transformations	Significance
L = lnx	* = (P ≤ 0,05)
S = x^2	** = (P ≤ 0,01)
R = $\frac{1}{x}$	
SR = $\sqrt{x}$	

The results in Table 5.2 show that there were significant correlations between grass production and the duration of different threshold temperatures. In all cases an increase in the duration of the threshold temperature had a depressive effect on grass production. The critical threshold temperature that was maintained at ground level for a sufficient period to adversely affect the grass sward was approximately $\geq$ 95°C. A statistically significant correlation was obtained at $\geq$ 95°C with the first estimate of grass yield. No correlation coefficients are presented for ground level temperatures above 95°C because of a lack of sufficient data and it should be noted that, in general, there were insufficient data recorded at ground level to provide reliable results. The critical threshold temperature at the grass canopy was approximately $\geq$ 140°C because all three grass yields were significantly correlated with time to the greatest degree at this temperature.

It seems reasonable to assume that the reason for the lower threshold temperature at ground level compared with that at the grass canopy is because the short apices of the grass sward are generally borne close to ground level. If this is so, the lower threshold temperature at ground level represents the minimum input of heat energy that is required to damage the delicate shoot apices of the grass plants. West (1965) stated that 60°C is regarded as the lethal temperature for destroying plant tissues and therefore a critical threshold temperature of $\geq$ 95°C is acceptable in view of the possible insulating effects of the grass leaves protecting the shoot apices. The higher threshold temperatures at the grass canopy are probably because this is the zone where the main heat load of a fire is situated. In addition, judging from the maximum temperatures recorded at the different levels in Table 4.17 these higher temperatures at the grass canopy could be equivalent to a temperature approaching 95°C at ground level.

Relating these threshold temperatures to the behaviour of the two types of fires it was found that at a threshold temperature of ≥140°C at the grass canopy, 60 per cent of the head fires had a duration of 58,8 ± 4,8 seconds and 66 per cent of the back fires a duration of 78,6 ± 3,3 seconds. An F-test indicated that these two duration periods were significantly different (F = 11,56; DF = 1 and 10; P ≤ 0,01), which means that the majority of head fires maintained the critical threshold temperatures for shorter periods of time and therefore did less damage to the shoot apices of the grass sward. The converse is true for the back fires. Data are presented only for the threshold temperatures recorded at the grass canopy because it was the most comprehensive set of temperature data available.

5.2.1.2 Fire intensity

It was concluded in Chapter 3 that over a six year period of annual burning fire intensity had had no significant effect on the recovery of the grass sward. In view of the important implications of this result in recommendations governing the use of fire in veld management it was decided to investigate further the effect of fire intensity on the grass sward. This aspect is particularly pertinent to the use of fire in controlling bush encroachment because extremely intense fires are necessary. It is therefore important to determine what effect these high intensity fires have on the grass sward.

(i) Procedure

The investigation was conducted on the research farm of the University of Fort Hare during the application of the fires that were used for modelling the behaviour of fires described in section 4.3.3. The experiment comprised burning 12 plots approximately 0,5 hectares in size at the end of winter and recording the recovery of the grass sward at the end of the first and second growing seasons after the burns. The plots had been resting for three years and the grass was dormant when the burns were applied. The fires were applied over a wide range of environmental conditions in order to obtain significantly different fire intensities. The fire intensities ranged from 925 kJ s^{-1} m^{-1} to 3326 kJ s^{-1} m^{-1} with a mean intensity of 2292 kJ s^{-1} m^{-1} and a coefficient of variation of 27,3 per cent.

The response of the grass sward to the different fire intensities was assessed in terms of the standing crop of grass that had accumulated in the burnt plots at the end of the first and second growing seasons. The grass production was measured with a disc pasture meter as described by Bransby & Tainton (1977) and the calibration equation presented in section 4.3.3.1 was used for expressing the standing crop of grass in kilograms per hectare.

A veld condition assessment was conducted in all the plots during the autumn of the second growing season according to the method used by Danckwerts (1981). The survey comprised taking 1 000 points per plot and recording the number of strikes and the nearest herbaceous plant to each point. These data were used for calculating the veld composition score for each plot. The mean veld composition score for the twelve plots was 69,7 per cent and ranged from 58,8 per cent to 84,8 per cent, with a coefficient of variation of 12,6 per cent.

The effect of fire intensity on the grass sward was determined by a series of multiple regression analyses where the independent variables were:

Fire intensity - kJ s^{-1} m^{-1};

Veld composition score - %.

The dependent variable was grass production expressed in kg ha^{-1}.

The veld composition score was included as an independent variable because Danckwerts (1981) had found that this parameter was positively correlated with the productivity of the grass sward. Therefore it was deemed advisable to include this parameter in order to isolate the true effect of fire intensity on the grass sward.

Finally the multiple regression analyses were conducted using transformed and untransformed data as described in section 4.3.3.1 (ii).

(ii) Results and discussion

The response of the grass sward to the different fire intensities was assessed at the end of the 1978/79 and 1979/80 growing seasons. The mean standing crop of grass on these two occasions was 2 399kg ha^{-1} and 3 572kg ha^{-1} respectively, which were significantly different from one another ($t = -22,89$; $DF = 11$; $P \leqq 0,01$). The results of the two multiple regression analyses of these data are presented in Table 5.3.

The results in Table 5.3 show that fire intensity had no significant effect on the recovery of the grass sward at the end of the first or the second growing seasons. This confirms the earlier result presented in Table 3.10 where the intensity of annual fires had no significant effect on the recovery of the grass sward. Conversely, the

TABLE 5.3 The effect of fire intensity and veld condition on the production of grass expressed as a percentage (n = 12).

Independent Variable	Transformation	1978/79 Season		1979/80 Season	
		Effect	Significance	Effect	Significance
Veld composition score	x^2	69,76	$P \lesssim 0,01$	62,84	$P \lesssim 0,01$
Fire intensity	x^2	0,13	NS	0,13	NS
TOTAL		69,89		63,15	

condition of the veld, as represented by the veld composition score, was clearly responsible for a major portion of the variation in the grass production. This confirms the results of Danckwerts (1981).

The lack of any significant effect of fire intensity on the recovery of the grass sward is very important from the point of view of using fire to control bush encroachment. This is because high intensity fires are generally required for this purpose and if they have no deleterious effect on the grass sward it makes this method of controlling bush encroachment more acceptable to the land user. This result also simplifies the practical use of fire for removing moribund and/or unacceptable grass material as it enables veld to be burnt under a wide range of environmental conditions where the only consideration is for the fire to be kept under control.

5.2.1.3 Season of burning

One of the most vexed questions concerning the use of fire in veld management is the season of burning. It was shown in section 2.5.3 that in the humid grasslands of Natal burning before the onset of the growing season in spring had the least deleterious effect on the recovery of the grass sward. This was in contrast to the extremely damaging effect of burning later in the season when plant growth had already commenced. Similar effects were observed in a preliminary trial conducted in the sweet grassveld on the research farm of the University of Fort Hare. These results are very pertinent to the use of fire in controlling bush encroachment. A very intense fire is required for this purpose and is best obtained by burning at the end of winter before the first spring rains, when the grass sward is still dormant and tinder dry.

It was therefore decided to investigate the effect of season of burning on the regrowth and botanical composition of the grass sward.

(i) Procedure

The effect of season of burning on the grass sward was investigated in an experiment conducted on the research farm of the University of Fort Hare. This is situated in the veld type called the False Thornveld of the Eastern Cape (Acocks, 1953).

Attention was focussed on the effect of burning when applied during mid-winter, spring, late spring and early summer i.e. ranging from when the grass sward was dry and dormant to when it was green and actively growing. The details of the treatments are:

B1 - burnt in mid-winter when the grass was dormant - 16/7/79;

B2 - burnt immediately after the first spring rains - 28/8/79;

B3 - burnt three weeks after the application of the

B2 treatment - 14/9/79;

B4 - burnt nine weeks after the application of the B2 treatment - 25/10/79.

The burns were applied as surface head fires to plots 15m x 15m in size. The treatments were replicated twice and were arranged in a randomised block design. The plots were situated on a gentle south eastern slope in open grassland which was in excellent condition and dominated by <u>Themeda triandra</u>. The grass sward comprised largely mature vigorous plants that had been resting for two growing seasons.

Measurements concerning the fuel load, fuel moisture, air temperature, relative humidity, soil moisture, wind speed, rate of spread and flame height were recorded for each burn according to the procedure outlined in section 4.3.3.

A point quadrat survey was conducted with a Levy bridge in all the plots prior to the burns. The points were arranged in a stratified random manner and comprised 520 points per plot. The nearest grass plant to each point was recorded together with the number of strikes and misses of living rooted plant material. The survey was limited to grass plants because attention was being focused on the effect of season of burning on the important grass component of the vegetation.

The post-treatment measurements comprised measuring the recovery of the grass sward with a disc pasture meter. Fifty readings were taken per plot at approximately monthly intervals commencing one month after the application of the B4 treatment. The disc pasture meter surveys were limited to the first growing season and the standing crop of grass was estimated for each occasion with the calibration equation presented in section 4.3.3.1.

The effect of the treatments on the botanical composition of the grass sward was determined in a point quadrat survey conducted at the end of the first and second growing seasons after the application of the treatments i.e. during 1980 and 1981. The same procedure was used as in the pre-treatment point quadrat survey except that 520 point positions were examined at the end of the first season, and 150 at the end of the second season. The reduction in the number of points in the third survey was deemed permissible because they were found to be adequate for determining the botanical composition of the treated plots. Furthermore, the previous survey had shown that the treatments had had no significant effect on the basal cover of the grass sward, thus reducing the necessity for excessive accuracy in the measurement of this parameter.

(ii) Results and discussion

The results of the disc pasture meter surveys conducted on the burnt plots during the first post-fire growing season are presented in Table 5.4.

The results in Table 5.4 show that burning in late winter (B1) consistently resulted in a significantly better recovery in the grass sward during the first growing season than the other treatments. The same tendency was shown at both levels of significance except that it was more consistent at the 5 per cent level of significance.

TABLE 5.4. The standing crop of grass recorded at approximately monthly intervals during the first growing season in veld that had been burnt in late winter (B1), spring (B2), late spring (B3) and early summer (B4). Data expressed in kg ha^{-1}.

Treatments	Survey Data	Mean	Significant Differences*					
		kg ha^{-1}	$P \leq 0,05$			$P \leq 0,01$		
B1	19/11/79	2922	│			│		
B2		2456		│		│	│	
B3		2185		│			│	│
B4		1738			│			│
B1	11/12/79	2806	│			│		
B2		2418		│		│	│	
B3		2126		│			│	│
B4		1719			│			│
B1	16/1/80	2844	│			│		
B2		2573	│	│		│	│	
B3		2282		│	│		│	│
B4		1990			│			│
B1	22/2/80	3039	│			│		
B2		2612		│		│	│	
B3		2398		│	│		│	│
B4		2068			│			│
B1	20/3/80	3777	│			│		
B3		3194		│			│	
B2		3117		│			│	
B4		2554			│			│

Standard error of the mean = 121 kg ha^{-1};
Least significant differences = 358 kg ha^{-1} ($P = 0,05$)
= 489 kg ha^{-1} ($P = 0,01$).

* Lines on the same vertical axis link treatments that are not significantly different from one another.

The results indicate that burning immediately after the first spring rains (B2) caused a marginally better recovery in the grass sward than burning three weeks after the growing season had commenced (B3). This difference, however, had disappeared by the end of the first growing season. Burning nine weeks after the commencement of the growing season (B4) had a consistently depressive effect on the recovery of the grass sward in relation to the other treatments and this was still distinctly apparent at the end of the first growing season.

The effect of the burning treatments on the composition of the grass component of the sward is presented in Table 5.5.

TABLE 5.5. The pre- and post-treatment composition of the grass sward of veld burnt in late winter (B1), spring (B2), late spring (B3) and early summer (B4). Data expressed as percentage frequency.

Grass Species	Burning Treatment											
	B1			B2			B3			B4		
	1978	1980	1981	1978	1980	1981	1978	1980	1981	1978	1980	1981
Themeda triandra	72,4	72,6	74,3	77,0	76,9	72,9	72,2	72,7	67,7	78,1	71,9	66,8
Panicum stapfianum	3,2	1,9	2,2	2,6	2,0	2,5	5,6	6,2	5,2	2,8	2,2	2,6
Panicum maximum	-	-	-	-	0,2	-	-	-	-	-	-	-
Heteropogon contortus	-	-	-	0,2	-	-	-	-	-	0,1	-	-
Setaria neglecta	-	-	-	-	0,1	-	-	-	-	-	-	-
Cymbopogon plurinodis	6,2	3,2	4,4	4,5	5,4	11,4	6,5	5,6	9,2	7,6	9,1	11,1
Melica decumbens	-	-	-	1,1	0,3	1,1	0,2	-	0,4	0,2	0,1	0,4
Aristida congesta	0,1	1,6	2,9	-	0,6	0,7	0,4	0,7	0,4	-	0,7	-
Cynodon dactylon	3,1	5,7	3,3	3,2	4,0	0,4	0,1	2,0	-	0,6	1,3	-
Digitaria eriantha	2,4	2,4	1,8	2,9	3,0	3,6	3,0	3,1	2,9	2,5	4,7	7,7
Eragrostis chloromelas	-	-	-	-	-	-	-	-	-	-	-	-
Eragrostis curvula	0,7	0,7	0,7	1,2	0,6	2,1	0,9	0,5	2,2	2,2	2,6	1,8
Eustachys mutica	0,3	-	-	0,3	0,1	-	-	-	-	0,1	0,8	2,2
Sporobolus fimbriatus	11,6	11,9	10,4	7,0	6,8	5,3	11,1	9,2	12,0	5,8	6,6	7,4
Basal Cover	6,9	8,2	8,7	4,5	7,2	6,7	5,0	8,0	7,7	4,7	7,6	8,4

Note: 1978 = pre-burn data
1980 and 81 = post burn data.

The data in Table 5.5 indicate that the burning treatments had no major effect on the percentage frequency of the different grass species. Nevertheless the grass species that showed the greatest response was Themeda triandra where the early summer burning treatment (B4) led to a decrease in this species with slight concomitant increases in Digitaria eriantha, Cymbopogon plurinodis and Sporobolus fimbriatus. However, a two way analysis of variance showed that these differences in the percentage frequency of Themeda triandra were not statistically significant (F = 1,60; DF = 7 and 7).

Similarly, the burning treatments had no significantly different effect on the basal cover of the grass sward (F = 0,43; DF = 7 and 7). They did result, however, in an overall significant improvement in the basal cover after the application of the treatments. The improvement occurred during the first growing season (t = - 4,18; DF = 14; P ≲ 0,01) as there were no significant differences in the basal cover recorded during the second growing season (t = - 0,21; DF = 14).

Thus the overall effect of the treatments was that burning when the grass sward was actively growing adversely affected the recovery of the veld when compared with burning when the grass was dormant. Conversely, the season of burning had no differential effects on the botanical composition, and especially the amount of Themeda triandra, and the basal cover of the grass sward. These latter results would appear to be in contrast to the experience in Natal where Dillon (1980) found that late burning, when the veld was actively growing, had an extremely adverse effect on Themeda triandra. The anomaly would appear to have been caused by the use of the point quadrat survey technique. This is because the effect of the treatments on the individual grass plants is not reflected by the percentage frequency of the different grass species. All that this parameter indicates is the frequency of occurrence of a plant species irrespective of its size and condition. In this particular case it was also unfortunate that the surveys were limited to grasses, since an analysis of the presence and absence of forbs would have indicated more clearly the effect of the season of burning on the community as a whole.

The absence of differences in the basal cover associated with the different burning treatments is also possibly not reflecting the true response of the grass sward to the burning treatments. Morris & Müller (1970) showed that this parameter is subject to seasonal variations. Thus, while not discounting these results, it is possible that the effects of the treatments on the basal cover had disappeared by the end of the first growing season, when the initial survey was conducted. Certainly field observations showed that the burns applied during early summer (B4) when the veld was actively growing had an initial detrimental effect on the basal cover, but they had become less obvious by the end of the growing season.

The explanation for the varying effects of different seasons of burning on the recovery of the grass sward is basically threefold. Firstly, the various treatments resulted in the grass sward in the plots having different recovery periods; secondly, the degree of dormancy in the grass plants differed when the various treatments were applied; and thirdly, the different fires had different rates of spread, which could have influenced the duration of critical threshold temperatures. These factors were confounded with one another and it was not possible to statistically isolate individual effects in this study.

Considering the different recovery periods associated with the various burning treatments, it is first necessary to determine the commencement of the growing season and relate this time to the different treatments. This was done by studying the rainfall and temperature regimes that prevailed during the period when the treatments were applied. The details are presented in Figure 5.1. The data were obtained from a meteorological station situated in similar terrain approximately half a kilometre from the experimental site.

The data in Figure 5.1 show that the mid-winter burn (B1) was applied during a dry period and data for the preceding autumn and early winter indicates that not much rain fell during that time. However a considerable amount of rain fell within a week of the application of the mid-winter burn (B1) and immediately before the application of the spring burn (B2). Thereafter rain fell fairly regularly during and after the application of the late spring (B3) and early summer (B4) burns. Therefore moisture conditions were adequate for plant growth for all but a period of one week following the mid-winter burn. However a perusal of the mean maximum daily temperature curve indicates that it was only after the spring burn (B2) treatment was applied that

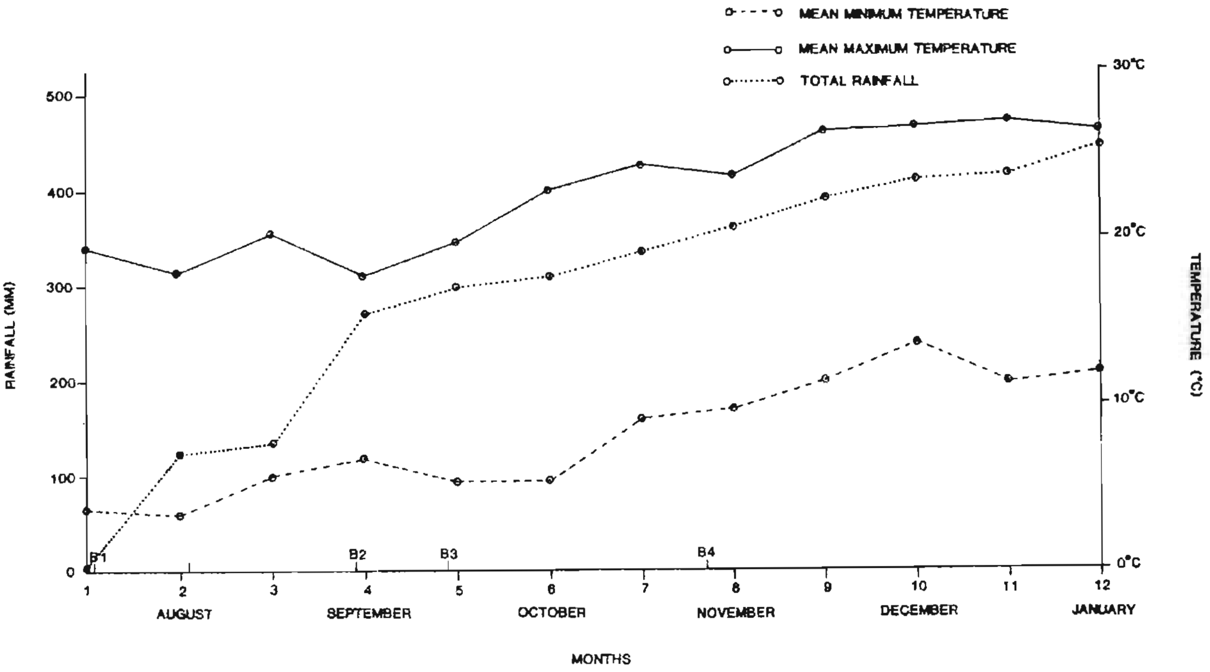

FIGURE 5.1. The total rainfall, mean maximum and mean minimum daily temperatures for half monthly periods during the application of the mid-winter (B1), spring (B2), late spring (B3) and early summer (B4) burning treatments.

there was a consistent increase in the mean daily temperature. There was a slight lag in the time when the mean minimum daily temperature started rising. However, warm days and cool nights favour plant growth because photosynthesis is encouraged during the day and respiration is retarded at night. Therefore it can be assumed that the time when the spring burn (B2) was applied constituted the approximate commencement of the growing season. This conclusion is supported by field observations, where it was noted that dormant buds were showing green leaf at about the time of the spring (B2) burn. Conversely, at the time of the late spring burn

(B3), the condition of the grass was recorded as a mixture of dry and green material exhibiting a distinct spring flush.

Assuming that the growing season commenced when the spring burn (B2) was applied, then the late spring (B3) and early summer (B4) burns had 17 and 58 days respectively, less in which to recover than did the winter (B1) and spring (B2) burn treatments. It is perhaps not completely correct to assume that the grass in the winter (B1) and spring (B2) burns had identical recovery periods. Observations made at the time of the spring burn (B2) showed that the grass in the winter burn (B1) was already green even though it was not growing rapidly. Therefore the grass in this treatment was able to commence rapid growth before that in the spring burn (B2), which still had to first develop new tillers before rapid growth could take place. This lag period in the recovery of the grass between the two treatments could account for the consistently greater production of grass in the winter burns (B1) presented in Table 5.4.

However, variations in the recovery period cannot account for all the differences in the recovery of the grass sward associated with the different seasons of burning. The fact that in Table 5.4 there was a period when the late spring (B3) and early summer (B4) burns did not have significantly different quantities of grass in the plots illustrates this point.

The other possible important factor that influenced the effect of the season of burning was the physiological state that the grass plants were in when the burns were applied. Unfortunately no direct measurements were taken of the degree of dormancy of the grass plants at the time of the burns. However, some indication can be obtained from the moisture content of the grass fuel when the treatments were applied. The results are presented in Table 5.6.

TABLE 5.6. The mean moisture content of the grass fuel when the mid-winter (B1), spring (B2), late spring (B3) and early summer (B4) burning treatments were applied. Data expressed as a percentage on a dry mass basis.

Treatments	Mean	Significant Differences*	
		$P \lesssim 0,05$	$P \lesssim 0,01$
B2	38,9	│	│
B3	45,5	│	│
B1	45,9	│	│
B4	66,4	│	│

Note: Standard error of mean = 2,08%;
Least significant differences = 9,4% (P = 0,05);
= 17,2% (P = 0,01).

* Lines on the same vertical axis link non-significantly different treatment means.

The results in Table 5.6 indicate that the moisture content of the grass fuel was significantly higher when the early summer (B4) burn was applied than when the other treatments were applied. This confirms observations made at the time of the early summer burn (B4) when it was recorded that the grass was actively growing and that the Themeda triandra was in full seed. There were no significant differences in the moisture contents of the grass fuel in the other treatments. This indicates that this parameter was probably not sensitive enough to distinguish between living plant material and moist dead material when the differences in moisture content are relatively small. As mentioned earlier observations made at the time of the burn indicated that the grass was dormant when the mid-winter (B1) and spring (B2) burns were applied. Conversely the grass was showing a distinct spring flush when the late spring burn (B3) was applied.

From the aforegoing it would appear that the grass was begining to grow when the late spring (B3) burn was applied and was highly active when the early summer (B4) burn was applied. Thus burning at these times, when the grass tillers were actively growing and the shoot apices were in an elevated and vulnerable position, must have caused a significant mortality of live tillers. The mortality must have been less with the late spring (B3) burn because the degree of tillering was not as advanced as in the grass that was burnt in early summer (B4). This provides a partial explanation for the slight set-back in the recovery of the grass in the late spring (B3) burn and the severe setback suffered with the early summer (B4) burn illustrated in the results in Table 5.4.

The final probable reason for the differences in the recovery of the grass sward were the different rates of spread that occurred with the various burning treatments. As shown earlier in Table 4.24, the rate of spread of a fire was negatively correlated with certain critical threshold temperatures. These in turn were shown in Table 5.2 to be negatively correlated with the amount of grass that was produced after a fire. Therefore the slower the rate of spread the greater is the damage done to the grass and vice versa. This would indicate that part of the different effect of season of burning on the recovery of the grass sward was its effect on the rate of spread and the resultant duration of critical threshold temperatures. Relating this hypothesis to the current study, the rates of spread recorded during the application of the burning treatments are presented in Table 5.7.

TABLE 5.7. The mean rate of spread of the fires recorded during the application of the mid-winter (B1), spring (B2), late spring (B3) and early summer (B4) burning treatments. Data expressed in $m\ s^{-1}$.

Treatment	Mean	Significant Differences*		
		$P \lesssim 0,05$		$P \lesssim 0,01$
B3	0,36	│		│
B1	0,32	│		│
B2	0,26	│		│
B4	0,11		│	│

Note: Standard error of mean = 0,03 $m\ s^{-1}$;
Least significant dfferences = 0,14 $m\ s^{-1}$ ($P = 0,05$);
= 0,26 $m\ s^{-1}$ ($P = 0,01$);
* Lines on the same vertical axis link non-significantly different treatment means.

The results in Table 5.7 show that the rate of spread recorded during the application of the early summer (B4) burn was significantly less than in the earlier burns ($P \lesssim 0,05$). This result indicates that the poor recovery in the grass sward in the early summer (B4) burn treatment may have been partly due to an increased duration of critical threshold temperatures. Of course the highly vulnerable state of the grass tillers associated with this treatment would also have accentuated the effect of the increased duration of critical threshold temperatures. This was clearly shown by Dillon

(1980) in the Tall Grassveld of Natal who found that when veld was burnt during early summer when the grass was actively growing, there was a high mortality of tillers of Themeda triandra.

5.2.2 Effect on bush

5.2.2.1. Type of fire

One of the key questions posed in Chapter 3 was "what type of fire is required to burn down bush of a particular size and species?" The effect of different types of fire was, however, not formally investigated in this study. Field experience gained during the characterization of fire behaviour, showed very clearly that head fires were the only form of surface fire capable of causing any significant topkill of stems and branches of trees and shrubs. Of course crown fires are also capable of causing severe damage to bush but they seldom occur in the arid savannas of southeastern Africa. In any event they only develop in relatively dense bush communities under extreme atmospheric and fuel conditions which made them logistically impossible to investigate in this study.

It was also decided not to research the effect of back fires because besides having a minimal effect on the topgrowth of bush, it was shown in section 5.2.1 that they caused a significantly lower recovery in the grass sward than head fires. It was, therefore, decided to concentrate the research effort on the effect of surface head fires on the topkill of stems and branches of the bush.

5.2.2.2. Fire intensity

Another key question posed in Chapter 3 was "what intensity of fire is required to burn down bush of a particular size and species?" This question was investigated in the series of fires that were used for developing the fire behaviour models described in section 4.3.3. In all, the effect of 64 fires on the topkill of stems and branches of the bush was studied in a series of burns that covered a wide range of fire intensities.

(i) Procedure

The response of the bush to different fire intensities was determined by conducting bush surveys in the burnt areas approximately six months after the application of the fires. The surveys comprised recording the response of the the different sizes and species of bush in a two metre wide transect arranged in a stratified manner over the plot. A ten metre wide border around the perimeter of the burnt area was excluded in the surveys in order to ensure that the bush had been subjected only to a surface head fire. The number of two metre wide transects surveyed was determined by the length of transect required to record at least 500 bushes per plot.

The reaction of the bush was classified into two catagories:

(a) Top growth killed.

This included all trees and shrubs that were either killed by the fire and included those which subsequently coppiced from the base of the stem. The mortality of the trees and shrubs was relatively low as was shown in Table 3.2 where the majority of the bush in this catagory coppiced from the base of the stem.

(b) Top growth not killed

This included all trees and shrubs that were shooting from the branches, irrespective of whether or not they were also coppicing from the base of the stem. The proportion of the bush that was either shooting or shooting and coppicing varied according to the intensity of the fire. However it was considered advisable to amalgamate these two groups of plants because the amount of coppice growth produced by the coppicing and shooting plants was considerably less than when the bush suffered a total kill of stems and branches. This was undoubtedly caused by the incomplete removal of the effect of apical dominance in the plants that suffered partial damage to the aerial parts of the plant. Thus the major effect of the fires on the bush depended on whether the top growth of the stems and branches was killed or not.

The relationship between fire intensity and the response of the bush was determined with a simple linear regression analysis. Fire intensity was the independent variable and the percentage topkill of stems and branches the dependent variable. Analyses were conducted with data where all the bush species were combined and with data for individual bush species and they were conducted separately for half metre height classes in the range 0 to 4,5 metres. Finally, the regression analyses were conducted with untransformed data and where the independent variable was transformed using logarithmic ($\ln x$), square (x^2), square root ($\sqrt{x}$) and reciprocal ($\frac{1}{x}$) transformations. The form of the independent variable that gave the highest correlation coefficient was used to represent the relationship between fire intensity and the topkill of bush.

(ii) Results and discussion

(a) All bush species

The relationship between fire intensity and the topkill of bush of all species is presented in Table 5.8.

TABLE 5.8. The relationship between fire intensity and the percentage topkill of bush for different height classes of all species.

Height class	n	Transformation	r	r^2	Significance
0 - 0,50m	52	$\frac{1}{x}$	-0,3408	0,116	$P \leqq 0,05$
0,51 - 1,00m	55	$\frac{1}{x}$	-0,5940	0,353	$P \leqq 0,01$
1,01 - 1,50m	55	$\frac{1}{x}$	-0,6029	0,363	$P \leqq 0,01$
1,51 - 2,00m	55	$\frac{1}{x}$	-0,4311	0,186	$P \leqq 0,01$
2,01 - 2,50m	55	$\frac{1}{x}$	-0,2372	0,056	NS
2,51 - 3,00m	55	$\frac{1}{x}$	-0,1394	0,019	NS
3,01 - 3,50m	52	$\frac{1}{x}$	-0,1666	0,028	NS
3,51 - 4,00m	41	$\frac{1}{x}$	-0,0981	0,010	NS
4,01 - 4,50m	31	x	-0,1230	0,015	NS

Note: n = number of cases;
r = simple correlation coefficient;
r^2 = coefficient of determination.

The results in Table 5.8 indicate that fire intensity had a significant effect on the topkill of bush to a maximum height of two metres. The results also show that the best relationship occurred in the 1,01 - 1,50m height class but decreased at lower and higher heights. These results indicate that short bushes suffered a significant topkill of stems and branches irrespective of fire intensity, hence the relatively low correlation coefficient for the 0 - 0,50m height class. However, as the bushes became taller so the fire intensity required to cause a topkill of stems and branches became more critical, resulting in a high correlation coefficient for the 1,01 - 1,50m height class. Above this level the bushes became increasingly more resistant to fire and even high intensities did not cause a significant kill of stems and branches. Consequently, the correlations for the height classes above two metreswere not significant.

Support for this conclusion is provided by the percentage topkill that occurred in all bush species during the course of this study. The results are presented in Table 5.9.

TABLE 5.9. The mean, minimum and maximum percentage topkill of all species of bush that occurred during the study of the effect of fire on bush.

Height class	n	Percentage Topkill Of Bush Species		
		Mean	Minimum	Maximum
0 - 0,50m	57	87,9	0	100,0
0,51 - 1,00m	60	78,7	0	100,0
1,01 - 1,50m	60	60,5	0	100,0
1,51 - 2,00m	60	32,0	0	100,0
2,01 - 2,50m	60	14,8	0	62,0
2,51 - 3,00m	59	7,3	0	50,0
3,01 - 3,50m	56	7,6	0	80,0
3,51 - 4,00m	44	2,4	0	50,0
4,01 - 4,50m	34	3,8	0	100,0
4,51 - 5,00m	13	0	0	0

Note: n = number of fires.

The results in Table 5.9 clearly show that bush was very resistant to a topkill of stems and branches when taller than 2,00m.

This point is illustrated in Table 5.10 where the effect of fire intensity on the topkill of bush in the height classes 0 - 2,00m is presented.

The results in Table 5.10 also indicate that the topkill of bush does not increase appreciably when fire intensities are greater than approximately 2500 kJ s^{-1} m^{-1}.

TABLE 5.10. The effect of fire intensity on the topkill of bush of all species in the height classes 0 - 2,00m expressed as percentage topkill.

Height Class	Fire intensity - kJ s^{-1} m^{-1}							
	500	1000	1500	2000	2500	3000	3500	4000
0 - 0,50m	81	88	91	92	92	93	93	94
0,51 - 1,00m	65	79	83	86	87	88	89	89
1,01 - 1,50m	43	60	65	68	70	71	72	72
1,51 - 2,00m	21	33	38	40	41	42	42	43

The regression equations for predicting the topkill of bush in Table 5.10 are as follows and are based on the results presented in Table 5.8.

$$TK \quad 0 - 0{,}50m = 95{,}4 - 7348 \frac{1}{FI}$$

$$TK \; 0{,}51 - 1{,}00m = 92{,}7 - 14003 \frac{1}{FI}$$

$$TK \; 1{,}01 - 1{,}50m = 76{,}7 - 17052 \frac{1}{FI}$$

$$TK \; 1{,}51 - 2{,}00m = 45{,}7 - 12236 \frac{1}{FI}$$

where: TK = topkill of bush - %;
FI = fire intensity - kJ s^{-1} m^{-1}.

(b) Individual bush species

The investigation of the effect of fire intensity on the individual bush species was limited to those species for which there were sufficient data. The total number and proportion of each bush species recorded during the surveys after the burns is presented in Table 5.11.

TABLE 5.11. The total number and proportion of each bush species recorded during the surveys conducted to determine the effect of fire on the topkill of bush. Data expressed as number of plants and as a percentage.

Bush Species	Number	Percentage
Acacia karroo	10 987	59,268
Rhus lucida	3 134	16,906
Ehretia rigida	1 758	9,483
Grewia occidentalis	963	5,195
Diospyros lycioides	554	2,988
Xeromphis rudis	426	2,298
Maytenus heterophylla	384	2,071
Scutia myrtina	184	0,993
Olea africana	48	0,259
Brachylaena ilicifolia	26	0,140
Opuntia auriculata	23	0,124
Ziziphus mucronata	22	0,119
Aloe ferox	12	0,065
Plumbago auriculata	4	0,022
Fagara capensis	3	0,016
Ptaeroxylon obliquum	3	0,016
Acacia caffra	2	0,011
Phyllanthus verrucosus	2	0,011
Cussonia spicata	1	0,005
Rhus macowanii	1	0,005
Dovyalis rhamnoides	1	0,005
TOTAL	18 538	100,000

The data in Table 5.11 show that a total of 18538 plants were recorded in the bush surveys conducted to determine the effect of fire on the topkill of trees and shrubs. The most abundant species was Acacia karroo and the only other species for which there were sufficient data to determine the relationship between fire intensity and the topkill of stems and branches were Rhus lucida, Ehretia rigida and Grewia occidentalis. It was therefore decided to analyse the data for these four species and the results of the simple linear regression analyses are presented in Table 5.12.

TABLE 5.12. The relationship between fire intensity and the topkill of Acacia karroo, Rhus lucida, Ehretia rigida, and Grewia occidentalis for different height classes. Data expressed as a correlation coefficient.

	Species											
Height Class	Acacia karroo			Rhus lucida			Ehretia rigida			Grewia occidentalis		
	n	Trans formation	r	n	Trans formation	r	n	Trans formation	r	n	Trans formation	r
0 - 0,50m	52	$\frac{1}{x}$	-0,0878 NS	39	lnx	0,3916*	36	x	0,1355 NS	40	$\frac{1}{x}$	-0,5039**
0,51 - 1,00m	56	$\frac{1}{x}$	-0,6321**	40	$\frac{1}{x}$	-0,4396**	45	lnx	0,3236*	35	$\frac{1}{x}$	-0.4548
1,01 - 1,50m	56	$\frac{1}{x}$	-0,5766**	38	$\frac{1}{x}$	-0,4876**	48	$\frac{1}{x}$	-0,3640*	36	$\frac{1}{x}$	-0,4981
1,51 - 2,00m	54	lnx	0,4763**	34	lnx	0,3046 NS	43	x	0,3706*	41	$\frac{1}{x}$	-0,4958**
2,01 - 2,50m	56	lnx	0,1985 NS	37	$\frac{1}{x}$	-0,1441 NS	44	x^2	0,3926**	35	lnx	0,1905 NS
2,51 - 3,00m	54	$\frac{1}{x}$	-0,0316 NS	28	x	0,0350 NS	39	x	0,1213 NS	24	x^2	0,3592 NS
3,01 - 3,50m	50	x^2	-0,1108 NS	23	$\frac{1}{x}$	-0,2282 NS	25	x	-0,2193 NS	20	x^2	0,1073
3,51 - 4,00m	37	$\frac{1}{x}$	0,1460 NS	-	-	-	-	-	-	13	$\frac{1}{x}$	0,9317**
4,01 - 5,00m	29	x	-0,1142 NS	-	-	-	-	-	-	5	$\frac{1}{x}$	0,9972**

Note:
n = number of cases;
r = simple correlation coefficient;
* = $P \lesssim 0,05$;
** = $P \lesssim 0,01$;
NS = non-significant.

The results in Table 5.12 show the same pattern as the effect of fire intensity on the topkill of bush of all species presented in Table 5.8. Acacia karroo and Grewia occidentalis were significantly affected to a height of 2,00m while Rhus lucida and Ehretia rigida were susceptible to heights of 1,50m and 2,50m respectively.

The effect of fire intensity on the topkill of stems and branches of the different bush species is well illustrated by considering the effect of an intense fire of 3000 kJ s^{-1} m^{-1}. The results are presented in Table 5.13 but are restricted to those height classes where the linear regressions were statistically significant. However in the case of *Grewia occidentalis* the significant regressions for the two upper height classes were omitted because they were spurious results caused by insufficient data.

TABLE 5.13. The effect of a fire of 3000 kJ s^{-1} m^{-1} intensity on the topkill of stems and branches of *Acacia karroo*, *Rhus lucida*, *Ehretia rigida* and *Grewia occidentalis* expressed as a percentage.

Species	Height Classes				
	0-0,50m	0,51-1,00m	1,01-1,50m	1,51-2,00m	2,01-2,50m
Acacia karroo	-	95,9	70,9	34,6	-
Rhus lucida	99,9	89,8	88,9	-	-
Ehretia rigida	-	93,4	80,5	49,6	21,1
Grewia occidentalis	98.5	92,1	84,7	75,7	-
All species	93,0	88,0	71,0	41,6	-

The results in Table 5.13 indicate that the individual bush species reacted differently to fire intensity. The results indicate that *Grewia occidentalis* was the most susceptible to a topkill of stems and branches since the percentage topkill among larger plants was higher than in the other species. Conversely *Acacia karroo* appeared to be more resistant to fire particularly for bushes taller than 1,00m. *Rhus lucida* and *Ehretia rigida* reacted similarly to *Grewia occidentalis* up to a height of 1,50m but for taller plants, *E. rigida* became more resistant while the situation is unknown for *R. lucida* because of a lack of data.

The reason for the differences in the response of the various bush species is most probably due to variations in the thickness of the bark and the diameter of the stems and branches. Vines (1981) stated that in Australia it was found that with Eucalyptus species the penetration of heat to the cambium layer of the stem is governed by the thickness of the bark. Thus relating these phenomena to the aforementioned results, Acacia karroo generally has thicker bark than the other species, particularly in the taller plants, hence its resistance to fire. Conversely, Grewia occidentalis which is more susceptible, has a relatively thin bark which does not thicken and become striated like that of Acacia karroo. The stems and branches of G. occidentalis also have a relatively small diameter which requires a smaller heat input to raise the temperature of the plant material to a lethal level. The bush species R. lucida and E. rigida also have fairly thin bark but the diameter of the stems and branches is much larger, particularly for taller plants, hence their greater resistance to fire in these height classes. Finally, an important result in Table 5.13 is that the topkill of bush for all species does not differ all that greatly from that of individual species except for the taller specimens of G. occidentalis. This would suggest that for practical purposes the regression equations for predicting the topkill of bush for all species will be adequate for making management decisions. The bush species G. occidentalis does not comprise a dominant species in the False Thornveld of the Eastern Cape. Consequently the regression equations for all species would provide a representative picture of the overall effect of fire intensity on the bush component in this veld type.

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5.2.2.3 Flame height

The effect of flame height on the topkill of bush was investigated because the vertical level at which heat energy is released during a fire is one of the factors that influences the effect of fire on plants. The investigation was conducted as part of the same series of fires that were used for studying the effect of fire intensity on the bush. However, in this case data from only 18 fires were used because flame height was recorded only towards the end of the fire behaviour study.

(i) Procedure

The relationship between flame height and the topkill of bush was determined with a simple linear regression analysis. Untransformed and transformed data were used in the same manner described in section 5.2.2.2 for the analysis of the fire intensity data. The analyses were, however, limited to the combined data for all bush species because there were insufficient results to determine the effect of flame height on the individual bush species.

(ii) Results and discussion

The relationship between flame height and the topkill of bush of all species is presented in Table 5.14.

The results in Table 5.14 indicate that flame height had a significantly positive effect on the percentage topkill of bush in the lowest height class and in the 2,51m to 4,00m height classes. It is difficult to explain why flame height had a significant effect in the 0 to 0,50m height class and not in the other lower height classes. The significant correlations, however, at the three upper height classes would suggest that the topkill of stems and

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TABLE 5.14. The relationship between flame height and the percentage topkill of all speciesof bush for different height classes.

Height Class	n	Transformation	r	r^2	Significance
0 - 0,50m	18	x^2	0,6241	0,390	$P \lesssim 0,01$
0,51 - 1,00m	18	x^2	0,3371	0,114	NS
1,01 - 1,50m	18	x^2	0,4249	0,181	NS
1,51 - 2,00m	18	x^2	0,4659	0,217	NS
2,01 - 2,50m	18	x^2	0,4111	0,169	NS
2,51 - 3,00m	18	x^2	0,5764	0,332	$P \lesssim 0,05$
3,01 - 3,50m	18	x^2	0,5282	0,279	$P \lesssim 0,05$
3,51 - 4,00m	18	x^2	0,5932	0,352	$P \lesssim 0,01$
4,01 - 4,50m	17	x^2	-0,1831	0,034	NS

Note:
n = number of cases;
r = simple correlation coefficient;
r^2 = coefficient of determination.

progressively higher levels. This result also indicates that the topkill of bush by fire is caused primarily by the destruction of the meristematically active terminal portions of the stems and branches rather than the girdling of the basal portion of the stem by the flames.

However, even with these significant correlations in the upper height classes the relevant regression equations showed that with extreme flames, 5m high, the topkill of bush was only 16,6 per cent, 13,8 per cent and 5,8 per cent in these three upper height classes. These results support the data presented in Table 5.9.

5.2.2.4 Fire temperatures

It was shown in chapter 4 that the maximum temperatures recorded during surface head fires were significantly correlated with fire intensity. It was also shown that the maximum temperatures recorded at different levels above the ground gave a good indication of the vertical distribution of heat released during a fire. Therefore it was felt necessary to determine the relationship between maximum temperatures recorded during a fire and the topkill of bush. These results would indicate whether maximum temperatures can be used for predicting the effect of fire on the topkill of bush and also provide information on the possible mechanism by which fires cause a topkill of bush. The data used for determining the relationship between fire temperatures and the topkill of bush were obtained from the same series of burns that were used for determining the effect of fire intensity on the topkill of bush. The data comprised fire temperatures from 41 fires.

(i) Procedure

The relationship between fire temperatures recorded at different heights above the ground and the topkill of bush was determined with a simple linear regression analysis. The same analytical procedure was used as described for fire intensity in section 5.2.2.2.

Analyses were only conducted with data representing the combined bush species as the objective in this investigation was to ascertain the effects of fire temperatures on the overall bush component.

(ii) Results and discussion

The results of the simple linear regression analyses conducted to determine the relationship between fire temperature and the topkill of bush are presented in Table 5.15.

TABLE 5.15. The relationship between fire temperatures recorded at ground level, grass canopy and one metre above the grass canopy and the percentage topkill of bush of all species in the different height classes.

Height Class	n	Ground Level		Grass Canopy		One Metre Above Grass Canopy	
		Transformation	r	Transformation	r	Transformation	r
0 - 0,50m	40	$\frac{1}{x}$	0,0741	lnx	0,1570	x^2	0,1295
0,51 - 1,00m	41	$\frac{1}{x}$	0,0154	x	0,3683*	lnx	0,3438*
1,01 - 1,50m	41	$\frac{1}{x}$	-0,2822	lnx	0,5793**	$\frac{1}{x}$	-0,4899**
1,51 - 2,00m	41	$\frac{1}{x}$	-0,3168*	$\sqrt{x}$	0,5144**	x	0,4624**
2,01 - 2,50m	41	x^2	0,1736	x	0,1866	x^2	0,1566
2,51 - 3,00m	40	$\frac{1}{x}$	-0,0903	x	0,2558	x^2	0,3316*
3,01 - 3,50m	37	x^2	0,1653	x	0,3402*	x^2	0,4583**
3,51 - 4,00m	26	x^2	0,3245	x	0,1912	$\frac{1}{x}$	-0,1698
4,01 - 4,50m	17	x	-0,2114	x^2	-0,1572	x^2	-0,0865

Note:
n = number of cases;
r = correlation coefficient;
* = ($P \lesssim 0,05$);
** = ($P \lesssim 0,01$).

The results in Table 5.15 show that there were significant positive correlations between the topkill of bush and the fire temperatures recorded at different levels above the ground i.e. the higher the temperature the greater the topkill of bush. However, the best results were obtained for temperatures recorded at the grass canopy and one metre above the grass canopy.

The results also indicate that the temperatures recorded at the grass canopy were more significantly correlated with the topkill of bush in the lower height classes covering the range 0,51m to 2,00m, than the temperatures recorded at one metre above the grass canopy. This trend was reversed at the upper height classes covering the range 2,51m to 3,50m, where significant and higher correlation coefficients were obtained with temperatures recorded at one metre above the grass canopy.

These results confirm that fire temperatures recorded at the grass canopy can serve as an index of the intensity of a fire, since it was shown in Table 4.16 that fire intensity is best correlated with fire temperatures recorded at this level.

A very valuable aspect of the relationship between the temperatures of the fires and the topkill of bush is that significant regressions were obtained over a fairly wide range of height classes. Therefore it is possible to obtain additional information on the relative susceptibility of the different height classes of bush to a topkill of stems and branches by fire. This was done by using the fire temperatures recorded at one metre above the grass canopy. The potential effect of different fire temperatures on the topkill of bush are presented in Table 5.16. The temperatures used in Table 5.16 are approximately within the range that was recorded in the field.

The results in Table 5.16, though incomplete, clearly indicate that bush is susceptible to a significant topkill of stems and branches to a height of 2,00m. These results are similar to those presented in Table 5.9.

TABLE 5.16. The potential effect of different maximum fire temperatures recorded at one metre above the grass canopy on the topkill of bush of all species in different height classes.

Height Classes	Percentage Topkill Of Bush At Different Fire Temperatures					
	100°C	150°C	200°C	250°C	300°C	350°C
0 - 0,50m	-	-	-	-	-	-
0,51 - 1,00m	57,4	71,4	81,3	89,0	95,3	100,0
1,01 - 1,50m	20,9	51,0	66,0	75,1	81,1	85,4
1,51 - 2,00m	10,3	23,3	36,3	49,3	62,4	75,4
2,01 - 2,50m	-	-	-	-	-	-
2,51 - 3,00m	1,4	4,7	9,2	15,0	22,2	30,6
3,01 - 3,50m	0	3,5	10,6	19,6	30,7	43,8
3,51 - 4,00m	-	-	-	-	-	-
4,01 - 4,50m	-	-	-	-	-	-
4,51 - 5,00m	-	-	-	-	-	-

Note: Data presented for only those height classes for which there were significant regressions.

5.2.2.5 Fire behaviour variables

In the preceeding sections the effects of the individual components of the fire regime on the topkill of bush have been presented and considered. This has provided a sound understanding and insight into the effect of fire on bush vegetation. However, this information does not indicate directly what independent variables must be considered when using fire to reduce bush to an available height and acceptable state for browsing by goats. It was therefore decided to investigate the relationship between the topkill of bush and the independent variables that may influence the behaviour of a fire. This was done with the objective of developing a statistical model for predicting the topkill of bush of all species. Data for the investigation were obtained from the same series of fires that were used for studying the effect of fire intensity on the bush.

Results were available from 46 fires for the investigation.

(i) Procedure

Two series of multiple regression analyses were conducted for the direct prediction of the topkill of bush. In the first series the independent variables were fuel load, fuel moisture, fuel compaction, air temperature, relative humidity, wind speed, size of burn and soil moisture. In the second series the independent variables were limited to fuel load, fuel moisture, air temperature, relative humidity and wind speed. The dependent variables were the percentage topkill of bush in the 1,01 - 1,50m and 1,51 - 2,00m height classes. The dependent variables were limited to these two height classes because the results in Table 5.8 indicated that these were the two upper height classes where fire had a statistically significant effect on the topkill of bush. In addition these are the height classes where bush becomes more difficult to control with browsing by goats because it becomes unavailable and it is then necessary to reduce the height of the bush in some other way.

(ii) Results and discussion

The results of the multiple regression analysis where all the independent variables were included are presented in Table 5.17.

The results in Table 5.17 indicate that the independent variables accounted for 63,1 and 46,6 percent of the variation in topkill of bush in the 1,01 - 1,50m and 1,51 - 2,00m height classes respectively. In both cases the fuel load was the most important variable while wind speed and the size of burn also had significant effects. Air temperature was significant in the lower height class whereas relative humidity was significant in the taller height class. Fuel compaction, fuel moisture and soil moisture had no significant effects. That fuel moisture

Table 5.17. The effect of fuel load, fuel moisture, fuel compaction, air temperature, relative humidity, wind speed, size of burn and soil moisture on the topkill of bush of all species in the 1,01 - 1,50m and 1,51 - 2,00m height classes expressed as a percentage (n = 46).

Independent Variable	Height Classes			
	1,01 - 1,51m		1,51 - 2,00m	
	Effect	Significance	Effect	Significance
Fuel load	41,8	$P \lesssim 0,01$	21,9	$P \lesssim 0,01$
Wind speed	7,1	$P \lesssim 0,01$	6,4	$P \lesssim 0,01$
Size of burn	7,9	$P \lesssim 0,05$	6,6	$P \lesssim 0,05$
Air temperature	4,0	$P \lesssim 0,05$	0,1	NS
Fuel compaction	1,4	NS	0,2	NS
Fuel moisture	0,7	NS	3,2	NS
Soil moisture	0,1	NS	0,1	NS
Relative humidity	0,1	NS	8,1	$P \lesssim 0,05$
TOTAL	63,1		46,6	

had no statistically significant effect is surprising. The probable reason for this is that a simple regression analysis showed that fuel moisture is negatively correlated with fuel load ($r = -0,4618$; DF = 44; $P \lesssim 0,01$) i.e. the lower the fuel load the higher the fuel moisture and vice versa. This confounding effect is therefore probably responsible for this anomaly because one of the assumptions in a multiple regression analysis is that the independent variables must not be correlated with one another. Another factor to consider is that most of the fires where the response of the bush was measured, were applied in late winter when fuel moisture was relatively low. The mean fuel moisture content was 43,1 ± 2,0 per cent and investigations in this study have shown that this variable only starts playing an important role in fire behaviour when it is greater than 45 per cent. Therefore these results are applicable to situations where the grass is relatively dormant and the fuel moisture is low.

The effect of the independent variables when only fuel load, fuel moisture, air temperature, relative humidity and wind speed were considered is presented in Table 5.18.

TABLE 5.18. The effect of fuel load, fuel moisture, air temperature, relative humidity and wind speed on the topkill of bush of all species in the 1,01 - 1,50m and 1,51 - 2,00m height classes expressed as a percentage (n = 46).

Independent Variable	Height Classes			
	1,01 - 1,50m		1,51 - 2,00m	
	Effect	Significance	Effect	Significance
Fuel load	41,8	$P \overline{<} 0,01$	21,9	$P \overline{<} 0,01$
Wind speed	7,1	$P \overline{<} 0,01$	6,4	$P \overline{<} 0,05$
Air temperature	7,4	$P \overline{<} 0,05$	1,3	NS
Fuel moisture	0,9	NS	3,3	NS
Relative humidity	0,8	NS	8,1	$P \overline{<} 0,05$
TOTAL	58,0		41,0	

In the 1,01 - 1,50m height class the independent variables accounted for 58,0 per cent of the variation in the topkill of bush. The significant variables were fuel load, wind speed and air temperature. In the 1,51 - 2,00m height class the independent variables accounted for 41,0 per cent of the variation in the topkill of bush and the significant variables were fuel load, wind speed and relative humidity. Again fuel moisture was non-significant but was significantly correlated with fuel load, hence the anomaly.

In selecting the most appropriate regression equation for predicting the topkill of bush for all species a comparison of the results in Tables 5.17 and 5.18 show that by limiting the number of independent variables the coefficients of determination were only slightly reduced i.e. 0,631 versus 0,580 for the 1,01 - 1,50m height class and 0,446 versus 0,410 for the 1,51 - 2,00m height class. Therefore for the sake of simplicity and greater applicability the regression equation was selected where only the limited number of independent variables were included in the multiple regression analysis. This involved ignoring the effect of the size of burn but this variable only accounted for 7,9 and 6,6 per cent of the variability in the topkill of bush in the two height classes respectively. Thus this variable had only a negligible effect and for predictive purposes it was deemed desirable to omit it because it is not always possible to know beforehand the actual size of the area to be burnt.

The regression equations for predicting the topkill of bush of all species in the two height classes are as follows:

$$\text{TK } 1{,}01 - 1{,}50\text{m} = 105 - 19{,}3\ \overset{1}{x}_1 - 23{,}8\ \overset{1}{x}_2 + 0{,}04\ x_3^2$$

where: TK = topkill of bush - %;
x_1 = fuel load - kg m^{-2};
x_2 = wind speed - m s^{-1};
x_3 = air temperature - °C.

$$\text{TK } 1{,}51 - 2{,}00\text{m} = 75{,}2 - 16{,}7\ \overset{1}{x}_1 - 23{,}8\ \overset{1}{x}_2 - 493\ \overset{1}{x}_3$$

where: TK = topkill of bush - %;
x_1 = fuel load - kg m^{-2};
x_2 = wind speed - m s^{-1};
x_3 = relative humidity - %.

These regression equations are based on the following statistics:

TK 1,01 - 1,50m: $n = 46$;
$R = 0,7504$ ($P \lesssim 0,01$);
$R^2 = 0,563$.

TK 1,51 - 2,00m: $n = 46$;
$R = 0,6026$ ($P \lesssim 0,01$);
$R^2 = 0,363$.

The regression equations were developed under the following range of values for the dependent and independent variables:

	Mean	Minimum	Maximum
Topkill 1,01 - 1,50m (%)	57,8	0	100,0
Topkill 1,51 - 2,00m (%)	33,4	0	100,0
Fuel load ($kg\ m^{-2}$)	0,3840	0,1880	0,5560
Fuel moisture (%)	42,6	21,8	76,9
Fuel compaction ($kg\ m^{-3}$)	1,51	0,84	2,43
Air temperature (°C)	22,0	12,1	29,5
Relative humidity (%)	33,0	13,0	73,0
Wind Speed ($m\ s^{-1}$)	2,56	0,56	8,61
Size of burn (m^2)	10 400	4 000	77 000
Soil moisture (%)	13,0	5,6	19,9

In the use of these regression equations it should be noted that the results have indicated that there was a threshold fuel moisture content of 45 per cent, below which this factor did not exert a significant effect on the intensity of a fire. A perusal of the raw data and field experience suggest that under normal veld conditions in the Eastern Cape the moisture content of the grass material at the end of winter is in the region of 30 to 35 per cent on a dry mass basis. Therefore when using the regression equations the grass moisture should not be higher than 45 per cent.

5.2.2.6 Discussion and conclusions

The most important conclusion that can be drawn from the results of the effect of fire on the vegetation is that burning caused a significant topkill of bush only to a maximum height of two metres. The results from analyses of the effect of fire intensity, flame height and fire temperatures on the topkill of bush support this conclusion. This is, nevertheless, a meaningful result from the practical point of view of using fire for bush control. Field surveys conducted during the course of this study showed that in bush communities comprising either dominant stands of Acacia karroo or mixed species, approximately 70 per cent of the trees and shrubs were in the first two metre height stratum above the ground. Thus the regression equations that were presented for predicting the topkill of bush in this height stratum can be used for manipulating the height of the major portion of the trees and shrubs in the arid savannas of southeastern Africa. Such manipulations are periodically necessary because the maximum browsing height of goats is approximately 1,5m (Trollope, 1981). Therefore, when encroaching bush has developed to a height of 1,5m to 2,0m it is possible to use fire to maintain it at an available height for browsing by goats.

Two methods can be used for predicting the topkill of bush with fire. The first method involves using the model presented in chapter 4 for predicting fire intensity. The resultant fire intensity value can then be used in the regression equations for predicting the topkill of bush in the height classes 1,01 - 1,50m and 1,51 - 2,00m presented in section 5.2.2.2.

The second method involves the direct prediction of the topkill of bush using the independent variables that influence the behaviour of a fire. The statistical analyses showed that the latter method resulted in much higher coefficients of determination (R^2) which indicates that the direct prediction of the topkill of bush is more reliable. However, the advantage of first predicting the fire intensity and using this value for predicting the topkill of bush is that it gives a clear conceptual model of the manner in which fire affects bush. Also, describing fire behaviour with one numerical figure facilitates the comparison of different fires with one another. Nevertheless, it can be concluded that for practical purposes the topkill of bush should rather be predicted with the multiple regression equations based on the independent variables that directly affect the behaviour of a fire.

The coefficients of determination (R^2) for the multiple regression equations for predicting the topkill of bush in the 1,01 - 1,50m and 1,51 - 2,00m height classes were 0,563 and 0,363 respectively. This means that these regression equations accounted for 56,3 and 36,3 per cent of the variation in the topkill of the bush in these two height classes. By agronomic standards this type of accuracy is not sufficient for prediction purposes and normally regressions can be used only when they account for approximately 95 per cent of the variation in the dependent variable. However, as mentioned earlier, experience gained during research into fire behaviour would indicate that it is virtually impossible to attain these agronomic levels of accuracy when modelling such a complex phenomenon as fire and its effects on the vegetation. The results should be used only as a general guide for predicting the effect of fire on bush. If they are used in this context it is firmly believed that they can serve as a useful guide for management purposes.

The fact that all the bush species in the False Thornveld of the Eastern Cape reacted fairly similarly to different fire intensities is a particularly useful result. This enables the use of a regression equation for predicting the general response of the bush to a burn. The regressions being in a quantitative form also enables them to be programmed into a programmable pocket calculator for direct use in the field.

It could be argued from the results that the topkill of bush could also be predicted by using flame height and the fire temperatures recorded at the grass canopy and one metre above the grass canopy. However, in the case of flame height there were no statistically significant regressions against the topkill of bush for the two upper height classes in the critical first two metre height stratum above the ground. The importance of the effect of flame height on the bush lay more in helping to explain how fire effects bush vegetation than in using this parameter for predictive purposes.

The use of fire temperature data for predictive purposes also has certain serious limitations. The actual temperatures recorded in the field are very much dependent on the type of instrument used for this purpose. This point is well illustrated by the consistently higher temperatures recorded with the thermocouples than with the bi-metallic thermometers described in section 4.3.5. Thus while all efforts were made to ensure that the temperatures presented were absolute values they would have to be verified further before these data could be used for predicting the effect of fire on vegetation. Again the main value of these results was to help explain the manner in which fire affects the vegetation.

Having concluded that it is practical to obtain a significant topkill of bush to a height of two metres it is now necessary to define the fire regime that will achieve this in practice. Guidelines are required regarding the type and intensity of fire and the season and frequency of burning necessary to cause a significant topkill of bush in the first two-metre height stratum.

Considering the type of fire to be used for this purpose it can be concluded from the results that a surface head fire is necessary. This type of fire caused least damage to the grass sward but is capable of causing a significant topkill of stems and branches of bush when applied under the appropriate fuel and atmospheric conditions. Crown fires can also be used, but as mentioned earlier, this type of fire is the exception rather than the rule in the arid savannas of southeastern Africa.

The results indicated that a fire intensity of approximately 2 500 kJ s^{-1} m^{-1} was necessary to cause a significant topkill of bush to a height of two metres. Of course more intense fires can be applied by either increasing the fuel load or burning under more extreme atmospheric conditions. However, such fires cause only relatively marginal increases in the topkill of bush. Field experience also indicates that the fire intensity should not exceed 3 500 kJ s^{-1} m^{-1} because fires are difficult to control beyond this point.

The finding that fire intensity had no significant effect on the recovery of the grass sward is very important from the point of view of using fire to control bush encroachment. This is because the high intensity fires that are required for this purpose will have no deleterious effect on the grass sward, making this method of controlling bush encroachment more acceptable to the land user. It also indicates that burning veld to remove moribund and/or unacceptable grass material can be done under a wide range of environmental conditions where the only consideration is for the fire to be kept under control. Also, since soil moisture conditions had no effect on the behaviour of fires or their effect on post-fire recovery, they need not be taken into account in determining when to burn.

The following general guidelines can also be used for ensuring that a fire will be intense enough to provide a significant topkill of bush to a height of 2,00m while still being reasonably safe to apply:

Fuel load	$\geq 0{,}4$kg m^{-2}
Fuel moisture	$\leq 45\%$
Air temperature	25 - 30°C
Relative humidity	$\leq 30\%$
Wind speed	$\leq 5{,}6$ m s^{-1}

The practical application of these guidelines will require planning on the part of the veld manager. Generally a fuel load of 0,4kg m^{-2} (4 000kg ha^{-1}) can be accumulated in one growing season when rainfall conditions are above average. This is in fact when burns should be applied so that valuable grazing is not sacrificed when it is needed most. Adequate fuel loads can also be accumulated over time by stocking the area to be burnt at a level below its carrying capacity. It must be clearly understood though that fuel load is the most important factor influencing the intensity of a fire and it's effect on the vegetation. Therefore it is essential that there is an adequate fuel load to ensure a successful burn.

Fuel moisture is also a critical factor in determining an effective burn and fires should be applied when the grass is dry and dormant so as to ensure that the fuel moisture is less than 45 per cent.

The guidelines for air temperature and relative humidity require that the decision to burn be taken only after considering the weather forecast. Burns can normally be expected to be effective only between 1100 hours in the morning and 1530 hours in the afternoon, when the recommended burning conditions are most likely to prevail.

The recommended wind speed of 5,6m s^{-1} (20km h^{-1}) relates to the upper limit under which burning can be applied safely. It is very difficult to manipulate this variable and generally a stiff breeze of approximately 3m s^{-1} (10km h^{-1}) will ensure a clean burn.

The most important conclusions that can be drawn from the results of the effects of season of burning is that burning during mid-winter had no deleterious effect on the recovery and condition of the grass sward when compared with burning after the first spring rains. This is very pertinent when considered in terms of using fire to control bush. It means that burns can be applied when high intensity fires can readily be obtained, in the knowledge that they will have no harmful effects on the grass sward. Thus burning during the latter part of winter when the grass is dry and dormant is an acceptable practice when using fire to reduce bush to an available height for browsing by goats. The other important result concerning the season of burning was the significantly better recovery of the grass sward when the veld was burnt when it was dormant than when it was actively growing. This indicates that the emphasis in defining the season of burning should be placed on the condition of the grass sward rather than on the season of the year. This recommendation is in contrast to most veld burning regulations in the summer rainfall areas of South Africa, which emphasize the necessity of burning after the first spring rains when the soil is moist so as to develop a vegetal cover as soon as possible after the burn in order to minimise soil erosion. This practice frequently results in the veld being burnt after the grass sward has commenced growing. For example experience in Natal has shown that during seasons in which the first "effective" spring rains are preceeded by limited quantities of precipitation some grass growth does occur. Therefore, when the first effective spring rains do fall, the grass is already growing and may be severely damaged by a fire (Tainton, 1981). The data from this experiment and research conducted in the humid grasslands of Natal, indicate that late burning when the grass is actively growing is far more detrimental to the condition and recovery of the grass sward than burning in late winter when the grass is dormant in spite of the longer period of exposure of the soil surface before a vegetal cover redevelops.

The remaining component of the fire regime is the frequency of burning. No research was conducted on this aspect because the frequency of burning in the arid savannas when using fire to control bush encroachment depends upon the rate at which the bush develops to an unavailable height for goats. This in turn depends upon the stocking rate and browsing management that is applied. Also because of variable rainfall, fire frequency is very much dependent on rainfall conditions and there is no need to apply fire at regular intervals. Therefore no fixed burning frequency can be recommended and suffice it to say that it should be as infrequently as possible.

5.3 BROWSING OF BUSH

In this section attention will be concentrated on the utilisation of bush with goats as a means of controlling the coppice growth that develops at the base of the stem after the topkill of stems and branches in response to the application of a high intensity fire.

The first step in this investigation was to determine whether the encroaching bush species are browsed by goats or not. Having established this, it was then necessary to determine the stocking rate of goats required to control the encroaching bush but a stocking rate which would not result in the excessive utilisation of the grass sward. Finally, it was essential to know what type of browsing management should be applied to control the encroaching bush. Results presented in chapter 3 showed that if the stocking rate of goats is in accordance with the browsing capacity of the bush, then optimum utilisation is obtained of the browse with minimum utilisation of the grass. These results also indicated that continuous browsing resulted in the gradual mortality of the bush and confirmed earlier results obtained by du Toit (1972a).

However, these results had been obtained where the bush component was dominated by Acacia karroo, therefore making it necessary to test these hypotheses under conditions where the veld comprised a wide range of bush species and to obtain further practically applicable results that could be used for controlling bush encroachment.

5.3.1 Procedure

The experiment was conducted in the False Thornveld of the Eastern Cape (Acocks, 1953) in an area of veld densely encroached by a wide variety of bush species on the research farm of the University of Fort Hare. The original density of the bush in the study area was approximately 2 239 plants per hectare, with a grass basal cover of 5,2 per cent. The dominant grass species were *Sporobolus fimbriatus* (44,9%) and *Digitaria eriantha* (28,4%), important associated species were *Panicum maximum*, *P. stapfianum*, *Cymbopogon plurinodis*, *Cynodon dactylon* and *Eragrostis curvula*. *Themeda triandra* was very rare and comprised only a minor component of the grass sward (3,4%).

The experiment was situated at an altitude of 580m in an area with a mean annual rainfall of 539mm. The soil type in the experimental area is a sandy loam of the Glenrosa form.

5.3.1.1 Treatments

The experimental area was initially cleared by chopping off all the bush at ground level and mowing the area with a brush cutter to ensure that all bush and grass species had been defoliated to a similar height. The cleared area was then subdivided into five plots 1,25ha in size, to which different treatments were applied.

(i) Goat treatment

This treatment comprised applying continuous stocking with goats to four of the cleared plots when the coppice growth of the recovering bush had grown to an approximate height of 150 to 300mm. Mature Boer goat wethers were used and the treatments were initiated on the 1st November, 1975. A uniform stocking rate of goats was applied. The stocking rate used was determined after studying the results of du

Toit (1972a), who had obtained effective control of coppicing bushes of Acacia karroo when the density was 2 500 plants per hectare and the stocking rate one goat per hectare. A figure of 2 000 coppicing bushes per goat was chosen because experience gained on the research farm of the University of Fort Hare had shown that a slightly higher stocking rate than that used by du Toit (1972a) could be applied without the goats being forced to supplement their diet with significant quantities of grass. The gregarious nature of goats was catered for by stocking the plots for three days per week, from sunrise to sunset, at the recommended stocking rate in order to ensure that more than one animal was present in a plot at a time. Continuous stocking was applied provided the grass sward was 50mm or more in height, the object being to control the bush without damaging the grass sward.

(ii) Control treatments

A control treatment (K1) was applied to the remaining plot and comprised no stocking with goats. The object of this treatment was to determine the recovery rate of the coppicing bush in the absence of browsing.

A second control treatment (K2) was included on the 1st September, 1977, to determine the extent to which the goats were grazing the grass. This treatment became necessary when the goats had significantly suppressed the acceptable bush species and were supplementing their diet with grass. The original control treatment (K1) no longer indicated the degree to which the goats were utilising the grass, because the bush had significantly recovered with this treatment and was suppressing the production of grass. The treatment involved eradicating all the bush from one hectare of veld by chopping off the trees and shrubs at ground level and treating the stumps with a herbicide. The plot was then rested from grazing for the growing season every year.

Finally, a uniform treatment was applied to all the plots at the end of the growing season when the grass sward was grazed off short with cattle immediately after the first frost in early winter (April/May). A non-protein nitrogen lick was provided in each plot and the stocking density of cattle approximated that which would occur in a twelve camp/one herd system with a stocking rate of three hectares per animal unit. The object of this treatment was to prevent the grass sward from becoming moribund.

The details of the treatments are presented in Table 5.19.

TABLE 5.19. The treatments applied to the different plots in the experimental area.

Plot	Treatment	Bush Density	Stocking Rate	
		$P\ ha^{-1}$	$ha\ SSU^{-1}$	No. of goats
1	Goats - G1	3668	0,55	5
2	Control - K1	1381	-	-
3	Goats - G2	2003	1,00	3
4	Goats - G3	3107	0,64	5
5	Goats - G4	1035	1,93	2
6	Control - K2	-	-	-

Note: $P\ ha^{-1}$ = plants per hectare;
$ha\ SSU^{-1}$ = hectares per small stock unit.

5.3.1.2 Measurements

Regular measurements were taken during the course of the experiment to determine the effect of the treatments on the vegetation.

(i) Bush surveys

Annual surveys of the bush occurring in the plots stocked with goats and the control (K1) treatment were conducted during early summer (November). The height of the different bush species occurring in a permanent two metre wide transect arranged in a stratified manner over the plot were recorded in each survey. The total length of the transects was approximately 600m per plot.

(ii) Grass surveys

Detailed botanical grass surveys were conducted in each plot using a point quadrat technique involving a wheel point apparatus. Initially the surveys comprised 1000 points per plot, where the number of strikes of live rooted material of the different herbaceous plant species were recorded, and from which the botanical composition and the basal cover of the grass sward were calculated. This procedure was later changed to recording the perennial, herbaceous plant species occurring nearest to each point in a 200 point survey. This is a more accurate procedure for determining the botanical composition and enables the calculation of the condition of the veld as proposed by Foran, Tainton and Booysen (1978). This latter method does not result in an accurate estimate of the grass basal cover. However, recent developments have shown that the veld composition score is a far more meaningful parameter than the grass basal cover when assessing the condition of the veld.

The seasonal production of grass was recorded in all the plots every year after the first frost in winter (April/May). Initially this was done by cutting 30 one square metre quadrats arranged in a stratified manner over the plot. However, since 1978 the disc pasture meter, as described by Bransby and Tainton (1977), has been used. One hundred stratified, random readings were taken per plot. The seasonal production of grass was estimated using the regression equation presented on page 78.

(iii) Climatic data

Rainfall data were available for this experiment from a rain guage situated approximately one kilometre from the experimental plots in similar terrain.

Other climatic data were recorded at the weather station of the University of Fort Hare situated approximately five kilometres away.

5.3.2 Results and discussion

The results concerning the acceptability of the different bush species to goats, the stocking rate of goats and the effect of browsing management on the coppicing bush will be presented separately.

5.3.2.1 Acceptability of bush species

Acceptability is a relative term that describes the sum of those factors which determine whether and to what degree plants are utilised by animals (Bransby, 1981). The acceptability of the different bush species was assessed by determining a preference ratio, which is the ratio of browse consumed to the amount of browse available. The amount of consumed and available browse was estimated from the number of tree equivalents per hectare of each bush species occurring in the control (K1) and goat plots. Using these data the preference ratio of each bush species was calculated using the following formula.

$$\text{Preference Ratio} = \frac{P - A}{A}$$

where: P = potential number of tree equivalents per hectare;
A = actual number of tree equivalents per hectare.

The potential number of tree equivalents of each bush species occurring in the different goat plots at the end of the study period (6 years) was estimated from the recovery rate of the different bush species in the control (K1) plot. The actual number of tree equivalents per hectare of the different bush species was assumed to be that present at the end of the study period.

Preference ratios were calculated for the different bush species occurring in the plots stocked with goats and the results were analysed using a two way analysis of variance. A $\ln(x + 1)$ transformation was used to normalise the data and a missing value for one bush species was estimated for one plot according to the procedure recommended by Rayner (1967). The results showed that there were highly significant differences in the acceptability of the different bush species to goats ($F = 7,52$; $DF = 9$ and 26; $P \lesssim 0,01$). The individual differences were determined with the Student-Newman-Keuls test which is a posteriori test designed for multiple comparisons among means based on equal sized samples (Sokal & Rohlf, 1969). The results are presented in Table 5.20. In assessing the results in Table 5.20 it should be noted that the greater the preference ratio the more acceptable the bush species to goats and vice versa.

TABLE 5.20. The acceptability of the different bush species to goats expressed as a preference ratio.

Species	Mean Preference Ratio		Significant Differences*								
	$\ln(x + 1)$	x	$P \lesssim 0,05$					$P \lesssim 0,01$			
<u>Scutia myrtina</u>	3,307	26,3	│					│			
<u>Acacia karroo</u>	2,571	12,1	│	│				│	│		
<u>Rhus lucida</u>	2,400	10,0	│	│				│	│		
<u>Xeromphis rudis</u>	2,296	8,9	│	│	│			│	│	│	
<u>Grewia occidentalis</u>	2,038	6,7	│	│	│	│		│	│	│	
<u>Ehretia rigida</u>	1,950	6,0	│	│	│	│	│	│	│	│	│
<u>Maytenus hetrophylla</u>	1,108	2,0		│	│	│	│		│	│	│
<u>Plumbago auriculata</u>	0,692	1,0			│	│	│			│	│
<u>Azima tetracantha</u>	0,677	1,0			│	│	│			│	│
<u>Diospyros lycioides</u>	0,294	0,3					│				│

Note: Standard error of transformed mean = 0,360;
Coefficient of variation = 41,5 per cent;
* Lines on the same vertical axis link bush species that do not have significantly different preference ratios.

The results in Table 5.20 indicate that there was a considerable overlap in the acceptability of the different bush species to goats. Nevertheless the differences that do exist at both levels of significance suggest that there are two broad groups of species that are generally acceptable and unacceptable to goats respectively. The acceptable group comprises Scutia myrtina to Ehretia rigida and the unacceptable group Plumbago auriculata to Diospyrus lycioides. Maytenus heterophylla would appear to be a marginal species that is not highly acceptable to goats but is nevertheless utilised. Based on these results it would appear that generally acceptable bush species have a preference ratio of greater than five and unacceptable species less than two. Of course the acceptability of the different bush species can be expected to be influenced by the botanical composition of the available bush in the area being utilised by the goats.

Other bush species that were present in the experimental plots but for which there were too few data to be included in the statistical analyses were Aloe ferrox, Brachylaena ilicifolia, Lippia javanica, Olea africana, Phylanthus verrucosus, Ptaeroxylon obliquum, Rhus macowanii, Opuntia auriculata and Fagara capensis. Of these species, observations made on the plants occurring in the goat plots indicate that Brachylaena ilicifolia, Olea africana, Lippia javanica, Rhus macowanii and Fagara capensis were significantly utilised by goats and could be regarded as being acceptable species.

5.3.2.2 Stocking rate of goats

The stocking rate of goats in the different plots was varied according to the density of the bush and was calculated on the basis of one mature goat per 2 000 coppicing bushes. It was hypothesised that with this stocking rate the goats would utilise primarily bush and only negligible amounts of grass. This hypothesis was tested by assessing the extent to which the goats controlled the regrowth of the coppicing bush and by estimating the quantity of grass consumed by the goats.

The effect of goats on the regrowth of the bush was assessed by determining the increase in the phytomass of the acceptable and unacceptable bush species in the control (K1) and goat treatments. The phytomass of the bush was estimated by calculating the number of tree equivalents per hectare in the different plots using the method described by Teague, Trollope & Aucamp (1981) and the acceptable and unacceptable species of bush were determined from the results in Table 5.20. In presenting the results of the effect of goats on the regrowth of the bush it should be noted that the data for the control (K1) treatment were obtained from one plot while data for the goat treatments was summed and presented as the mean of four plots. This was deemed permissible because the stocking rate was similar for all the goat plots and the results were also similar. Furthermore, it was felt to be both necessary and desirable to present the overall effects of the control (K1) and goat treatments for the sake of brevity and clarity.

The effect of the control (K1) and goat treatments on the phytomass of the acceptable species of bush is presented in Figure 5.2.

The results in Figure 5.2 clearly illustrate the manner in which the goats effectively controlled the regrowth of the acceptable bush species. At the end of the study period the number of tree equivalents had increased by 537,0 per cent in the control (K1) treatment whereas in the goat treatment the number of tree equivalents had decreased by 8,9 per cent. The shape of the curve for the goat treatment indicates that for all practical purposes the phytomass of the bush remained virtually constant

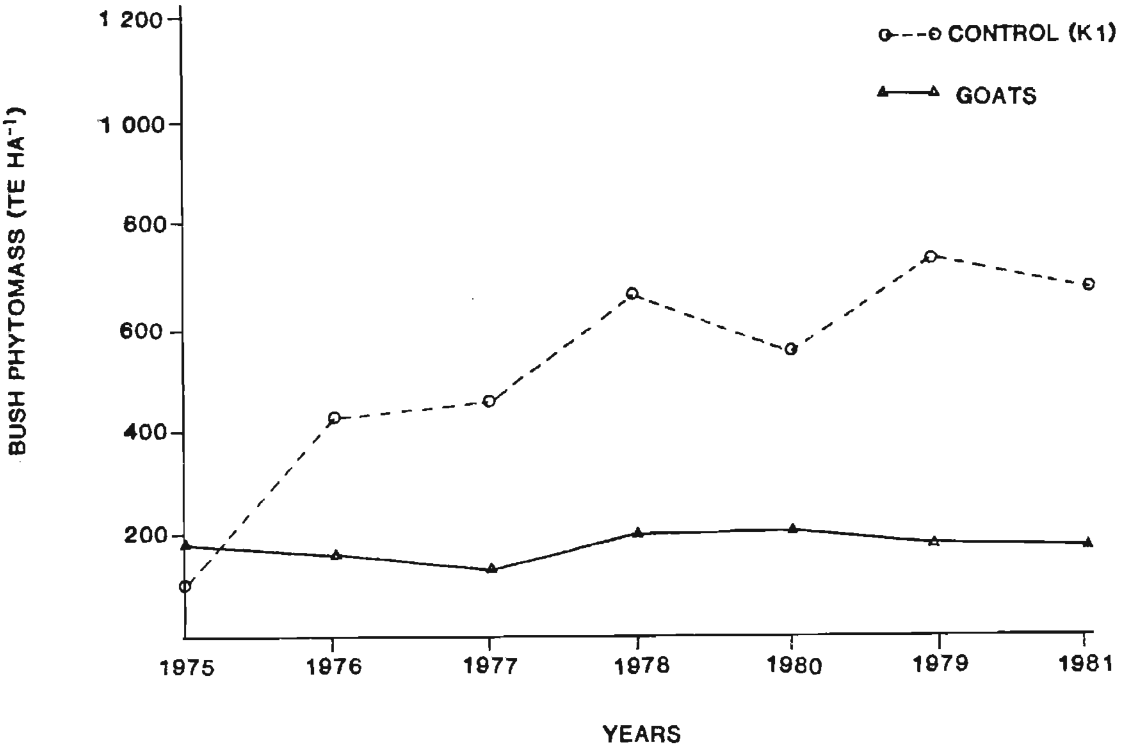

Figure 5.2. The effect of the control (K1) and goat treatments on the phytomass of the acceptable bush species for the period 1975 to 1981 expressed as TE ha^{-1}.

during the study period. This was confirmed by fitting a linear regression line to the data which proved to be non-significant ($r = 0,2114$; DF = 5; NS). The shape of the curve for the control (K1) treatment indicated that there was an initial rapid increase in the phytomass of the bush but that this increase became less pronounced after four years. This relationship fits a logarithmic curve which was highly significant, ($r = 0,9491$; DF = 5; $P \lesssim 0,01$).

The effect of the control (K1) and goat treatment on the phytomass of the unacceptable bush species is presented in Figure 5.3.

The results in Figure 5.3 show that the phytomass of the unacceptable bush species increased significantly in both the control (K1) and goat treatments. However, the bush recovered to a greater degree in the control (K1) treatment than in the goat treatment. At the end of the study period the phytomass of unacceptable bush species had increased by 636,4 per cent in the

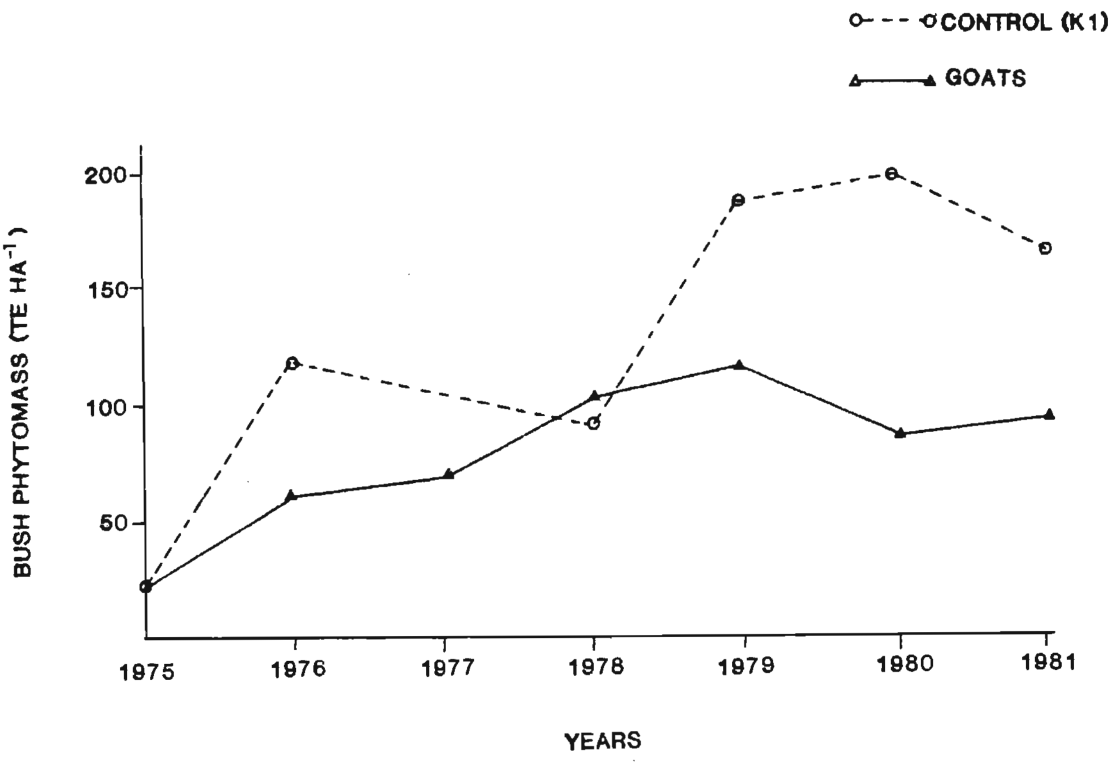

Figure 5.3. The effect of the control (K1) and goat treatments on the phytomass of the unacceptable bush species for the period 1975 to 1981 expressed as TE ha^{-1}.

control (K1) treatment and 287,5 per cent in the goat treatment. This difference would indicate that the goats had utilised the unacceptable bush species to a certain extent. This is to be expected because the preference ratios for the unacceptable bush species in Table 5.20 are positive. This indicates that a limited quantity of browse was utilised by the goats during the study period. Finally, both sets of data conformed better to a logarithmic curve than a linear regression and the correlation coefficients for the control (K1) and goat treatments were $r = 0,8698$ ($DF = 5$; $P \lessapprox 0,05$) and $r = 0,8775$ ($DF = 5$; $P \lessapprox 0,01$) respectively. This indicates that there had been a statistically significant increase in the phytomass of the unacceptable bush species during the study period.

Having established the effect of the treatments on the recovery of the acceptable and unacceptable bush species it is now necessary to assess these results in the light of their overall effect on the bush component of the vegetation. These results are presented in Figure 5.4.

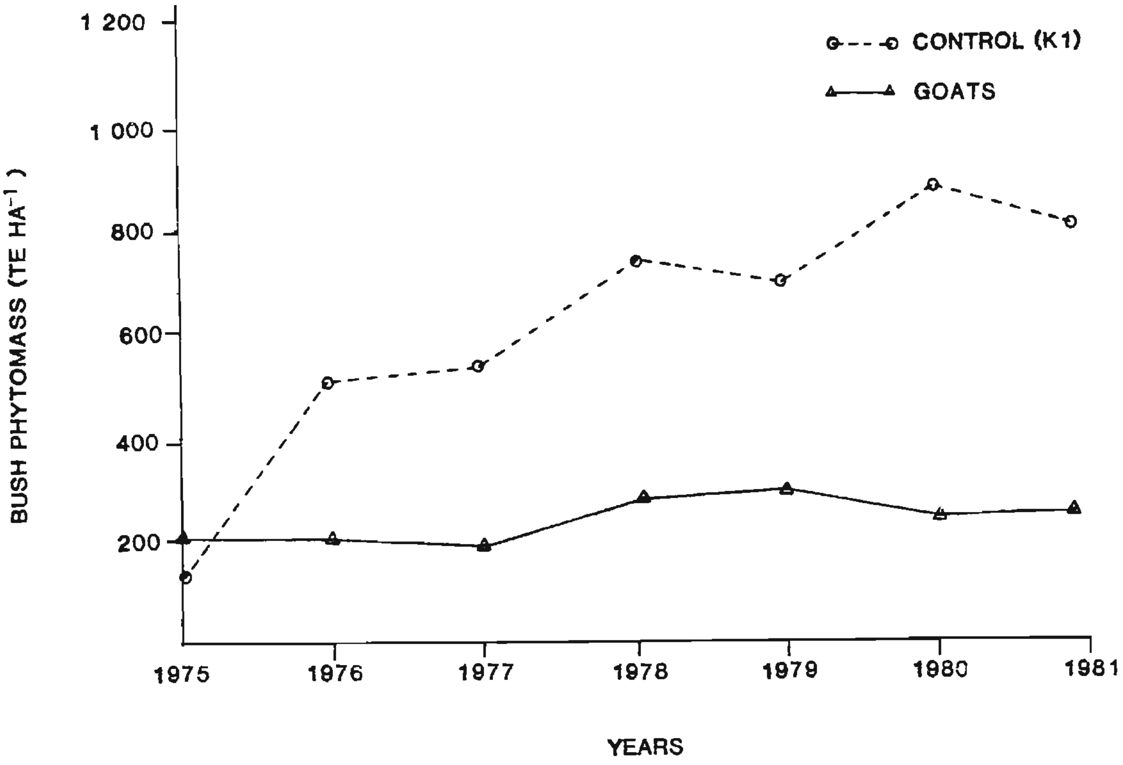

FIGURE 5.4. The effect of the control (K1) and goat treatments on the phytomass of all the bush species for the period 1975 to 1981, expressed as TE ha^{-1}.

The results in Figure 5.4 are very similar to those for the acceptable bush species in Figure 5.2 and indicate that the goats had very effectively controlled the overall regrowth of the bush. The reason for the similarity in the results is that the acceptable bush species in the control (K1) and goat plots made up 86,2 and 90,8 per cent respectively of the total bush component at the beginning of the experiment and still constituted 84,4 and 69,8 per cent respectively at the end of the study. Thus the acceptable bush species made up the major portion of the phytomass of the bush component of the vegetation and the stocking rate of goats used in the experiment would appear to have been effective in controlling the regrowth of the bush after having been initially chopped down.

The effect of the different treatments on the seasonal production of grass is presented in Table 5.21.

TABLE 5.21. The effect of the control (K1), control (K2) and goat treatments on the seasonal production of grass during the period 1975/76 to 1980/81. Data expressed in kg ha^{-1}.

Season	K1	K2	G1	G2	G3	G4
1975/76	5 962	-	6 904	6 067	5 347	5 205
1976/77	5 492	-	4 704	4 590	3 796	3 614
1977/78	3 781	3 562	3 453	3 286	2 702	2 779
1978/79	2 747	3 097	2 437	2 514	2 087	2 320
1979/80	2 165	2 825	1 893	1 660	1 544	1 582
1980/81	4 339	4 767	3 835	3 136	2 708	2 592

Various two way analyses of variance were conducted on the data in Table 5.21 after a ln(x + 1) transformation had been applied to normalise the data. A two way analysis of variance was deemed permissible because instead of the series of treatments being separated by space they were separated by time and therefore met the requirements of a randomised block design (Retief, 1982).

A two way analysis of variance was conducted to determine the effect of the control (K1) and goat treatments on the production of grass at the end of the first growing season. All the data from the control (K1) and goat treatments were used in the analysis and the F-test was highly significant (F = 23,81; DF = 4 and 20). However, the investigation into the differences between treatments was confined to the 1975/76 data for which the Student-Newman-Keuls test for multiple comparisons between means was used (Sokal & Rohlf, 1969). The results are presented in Table 5.22.

The results in Table 5.22 indicate that there were no clear cut differences in the seasonal production of grass in the different treatments at the end of the first growing season at the five

TABLE 5.22. The effect of the control (K1) and goat treatments on the production of grass at the end of the 1975/76 growing season. Data expressed in kg ha^{-1}.

Treatments	Grass Production		Significant Differences*		
	ln(x + 1)	x	$P \leq 0,05$		$P \leq 0,01$
Goats - G1	8,840	6 904	│		│
Goats - G2	8,711	6 067	│	│	│
Control - K1	8,693	5 962	│	│	│
Goats - G3	8,584	5 347	│	│	│
Goats - G4	8,558	5 205		│	│

Note: Standard error of transformed mean = 0,070;

* Lines on the same vertical axis link treatments that are not significantly different from one another.

per cent level of significance and no differences at the one per cent level of significance. This would indicate that at this stage the goats were utilising primarily browse and very little grass.

In 1977 a second control (K2) treatment was included in the experiment to estimate the quantity of grass being utilised by the goats. This was investigated in a two way analysis of variance of all the data for the period 1977/78 to 1980/81. The F-test was highly significant (F = 17,28; DF = 5 and 15). The individual treatment differences were determined with the Student-Newman-Keuls test (Sokal & Rohlf, 1969) and the results are presented in Table 5.23.

The results in Table 5.23 indicate that the production of grass in the control (K2) treatment was significantly greater than in the goat treatments at both levels of significance. This would indicate that the goats were utilising significant quantities of grass during this period i.e. somewhere in the order of 20,0 to 36,9 per cent ($\bar{x}$ = 29,7 per cent). There were also differences in grass production between the various goat treatments but they

TABLE 5.23. The effect of the control (K2) and goat treatments on the seasonal production of grass (kg ha^{-1}) for the period 1977/78 to 1980/81.

Treatment	Mean Grass Production		Significant Differences*					
	ln(x + 1)	x	$P \lesssim 0{,}05$			$P \lesssim 0{,}01$		
Control (K2)	8,159	3 494	│			│		
Goats - G1	7,936	2 795		│			│	
Goats - G2	7,849	2 562		│	│		│	│
Goats - G4	7,727	2 268			│			│
Goats - G3	7,698	2 203			│			│

Note: Standard error transformed mean = 0,0436;
* Lines on the same vertical axis link treatments that are not significantly different from one another.

were not clear cut differences.

In assessing the results presented in Tables 5.22 and 5.23 it is clear that initially the goats were utilising primarily bush and very little grass. However, with time the goats started to utilise significant amounts of grass presumably in response to a decrease in the availability of browse. It is not completely clear why this result should have occurred because it was shown in Figure 5.2 that the phytomass of acceptable bush species remained practically constant in the goat treatments during the study period. It is possible though that the acceptable bush species were not as vigorous at the end of the experiment as they had been immediately after the bush had been chopped down at the commencement of the trial. The results in Figure 5.2 showed that the phytomass of the acceptable bush species increased very rapidly in the control (K1) treatment during the initial stages of the experiment. This would indicate that the bush in the goat treatments was very productive at this stage. However, it is probable that with the effect of continuous browsing over time the vigour of the browsed bushes declined significantly. Consequently less browse was produced and the goats were forced to supplement their diet with grass. Thus it can be concluded that with time the stocking rate of one goat per 2 000 coppicing bushes resulted in a statistically significant, but relatively modest, quantity of grass being used by the goats.

5.3.2.3 Browsing management

The effect of continuous browsing on the coppicing bush species was assessed in terms of the changes that occurred in the density of the bush in the control (K1) and goat treatments. The density of the bush in the different treatments during the period 1975 to 1981 is presented in Table 5.24.

TABLE 5.24. The density of all species of bush in the control (K1) and goat treatments during the period 1975 to 1981 expressed as P ha^{-1}.

Season	K1	G1	G2	G3	G4	$G\bar{x}$
1975	1 424	3 681	2 007	3 111	1 039	2 460
1976	1 444	1 909	1 357	2 323	923	1 628
1977	1 630	2 030	1 650	1 868	956	1 626
1978	2 563	4 977	3 485	3 454	1 297	3 303
1979	2 986	6 265	4 342	4 959	1 647	4 303
1980	3 369	5 659	3 457	3 525	998	3 410
1981	2 170	3 613	2 350	3 101	1 139	2 551

Note: K1 = control treatment;
G1 - G4 = goat treatments;
$G\bar{x}$ = mean of goat treatments.

A perusal of the results in Table 5.24 indicates that a similar trend occurred in the bush density of all the individual treatments during the study period. This is well illustrated in Figure 5.5 where the bush density for the control (K1) and goat treatments as a whole are presented. It was deemed permissible to present a mean value for the goat treatments because they were all replicates of the same treatment and the trends in Table

5.24 are all very similar.

FIGURE 5.5. The mean density of all species of bush in the control (K1) and goat treatments during the period 1975 to 1981, expressed as P ha^{-1}.

Ignoring the minor differences in the changes in the bush density of the two sets of treatments there is a remarkable similarity in the results. Both sets of data increased to a peak bush density during 1979 and 1980 respectively but then decreased at the end of the study period. The overall shape of the two curves would indicate that the treatments had no significant effect on the density of the bush. A two way analysis of variance was conducted on the data in Table 5.24 to determine whether there were any significant differences between the initial and final bush densities in the different treatments. A reciprocal transformation was necessary to normlise the data and the overall F-test was highly significant (F = 70,63; DF = 4 and 24). A t-test was conducted to investigate the individual differences between the initial and final bush densities and the results are presented in Table 5.25.

TABLE 5.25. The initial and final density of all bush species in the control (K1) and goat treatments during the period 1975 to 1981. Data expressed as the reciprocal of the number of plants per hectare ($\frac{1}{x} \times 10^6$).

Treatment	Bush Density				Significant Difference
	Initial		Final		
	$\frac{1}{x} \times 10^6$	x	$\frac{1}{x} \times 10^6$	x	
Control - K1	702	1 424	461	2 170	$P \bar{<} 0,05$
Goats - G1	272	3 681	277	3 613	NS
Goats - G2	498	2 007	426	2 350	NS
Goats - G3	321	3 111	322	3 101	NS
Goats - G4	962	1 039	878	1 139	NS
Goat Mean - $G\bar{x}$	407	2 457	392	2 551	NS

Note: Standard error of transformed mean (K1 - G4) = 76,2;
Standard error of transformed mean ($G\bar{x}$) = 38,1;
Least significant difference (K1 - G4) = 223 (P = 0,05);
= 302 (P = 0,01);
Least significant difference ($G\bar{x}$) = 111 (P = 0,05);
= 151 (P = 0,01).

The results in Table 5.25 show that the bush density had increased significantly only in the control (K1) treatment (52,4%). While this is a logical result because of the absence of the effect of browsing in the control (K1) treatment the shape of the graph in Figure 5.5 indicates that not too much significance should be attached to this result, since the bush density in both the control (K1) and goat treatments was decreasing during the final stages of the experiment.

Separate analyses of variance were also conducted on the data for the acceptable and unacceptable bush species. The results from both sets of data showed that there were no significant differences between the initial and final bush densities in the control (K1) and goat treatments. Thus the selective browsing habit of the goats was apparently having no significant effect on the population dynamics of the bush. It would therefore appear that continuous browsing had no significant effect on the density of the bush.

Finally it was also necessary to assess the effect of continuous stocking with goats on the condition of the grass sward. This was done by calculating the veld composition score using the data from the grass surveys conducted in the plots during the different seasons. The results are presented in Table 5.26.

TABLE 5.26. The effect of the control (K1) and goat treatments on the condition of the veld as represented by the veld composition score. Data expressed as a percentage.

	Treatments						
Season	K1	K2	G1	G2	G3	G4	$G\bar{x}$
1975/76	45,7	-	73,2	61,1	62,3	57,5	63,5
1976/77	54,1	-	71,1	71,1	63,0	73,2	69,8
1979/80	51,0	63,0	53,0	68,0	68,5	64,0	63,4
1981/82	48,5	73,5	61,0	60,5	67,5	73,5	65,6

Note: K1 and K2 = control treatments;
G1 to G4 = goat treatments;
$G\bar{x}$ = mean of goat treatments.

A two way analysis of variance was conducted using data from the control (K1) and goat treatments. The F-test was significant (F = 5,15; DF = 4 and 12) and showed that there were significant differences in the condition of the veld in the different plots but that these differences could not be ascribed to treatment effects. A t-test showed that there were no significant differences within the control (K1) treatment and in the mean of the goat treatments during the study period. Thus it can be concluded that these treatments had no statistically significant effects on the condition of the grass sward.

The condition of the veld in the control (K2) treatment appeared to improve after the eradication of the bush but this could not be determined statistically because of a lack of data.

5.3.3 Discussion and conclusions

It can be concluded from the results that a good indication has been obtained of the acceptability to goats of the majority of the different bush species occurring in the arid savannas of southeastern Africa. The results accord well with field experience in this region and can serve as a practical guide for assessing the browsing potential of the veld.

The hypothesis that a stocking rate of one mature goat per 2 000 coppicing bushes would result in the goats utilising primarily bush and only negligible amounts of grass has been tested and generally not disproved. It was clearly shown in Figure 5.4 that the goats had very effectively controlled the regrowth of the coppicing bush. It was also shown in Table 5.22 and 5.23 that initially the goats did not utilise significant quantities of grass but with time were forced to supplement their diet with significant but modest amounts of grass. This was ascribed to a decline in the productivity of the coppicing bush because of the deleterious effect of continuous browsing. The fact that the goats had utilised approximately 29,7 per cent of the seasonal production of grass is in itself not a major reduction in the amount of grazing available. It indicates that even with a set stocking rate of goats that has not been adjusted to a declining browsing capacity, there can still be a considerable lack of competition between grazers and browsers for the available forage. It is also probable that with rotational browsing based on the physiological requirements of the key bush species, the vigour and productivity of the bushes could be maintained at a level where goats would not have to supplement their diet with significant amounts of grass when stocked at a rate of one mature goat per 2 000 coppicing bushes.

From this discussion it is clear that further research is required to estimate the browsing capacity of bush. Nevertheless, the current findings indicate that a stocking rate of one mature goat per 2 000 coppicing and acceptable bushes is a useful guideline for estimating the browsing capacity of veld. Arising from this result Teague, Trollope & Aucamp (1981) have suggested the concept of a browsing unit for use in the estimation of the browsing capacity of veld. Such a unit is defined as a tree or shrub species 1,5m high, that is acceptable to goats. It is also proposed that the browsing capacity of the thornveld areas of the arid savannas be estimated on the basis of 2 000 browsing units per mature goat. Obviously this guideline needs to be tested under experimental conditions because 2 000 browsing units are not necessarily equivalent to 2 000 coppicing bushes. Nevertheless, field experience indicates that a stocking rate based on 2 000 browsing units per mature goat gives a realistic estimation of the browsing capacity of veld in this region.

The hypothesis that continuous browsing results in the gradual mortality of bush was tested and disproved. The results showed that continuous browsing with goats had very little effect on the density of the bush. This is in contrast to the earlier findings presented in chapter 3 where continuous browsing drastically reduced the density of the bush. The main difference between the two experiments was that the bush in the former was dominated by Acacia karroo, whereas in the latter the bush comprised a wide range of species. This would indicate that the different species of bush probably reacted differently to continuous browsing. However, an investigation of the reaction of Acacia karroo to continuous browsing in this experiment showed that there had not been an overall statistically significant decrease in the density of this species during the study period.

Thus a contradictory state of affairs exists regarding the effect of continuous browsing on the density of the bush. In attempting to come to some conclusion it is clear from Table 3.4 that even in the first experiment, continuous browsing did not result in the complete eradication of the bush. Considerable numbers of juvenile bushes were still present in the plot after nine years of continuous browsing. Similarly, in this experiment, the bush was not eradicated and therefore the difference in the results of the two experiments are more a matter of degree than effect. In both cases the removal of the goats would have resulted in the recovery of the bush albeit at different rates because of the different densities of bush in the two experiments. On reflection this conclusion is supported by what has occurred in the thornveld areas of the Ciskei where bush encroachment has taken place. Prior to the introduction of the rotational grazing/browsing and resting programs in the rural areas, the bush was maintained in a short and severly cropped state by heavy continuous stocking. However, when this form of management was replaced by rotational stocking at more realistic stocking rates, together with a reduction in the number of goats, the bush responded immediately and began to encroach (Trollope, 1976). Thus the bush had been present all the time and had not succumbed to the heavy continuous stocking that had been applied for generations.

This is an extremely important result and leads to the conclusion that goats can be used to control bush encroachment but cannot be used to eradicate bush. Therefore, as was mentioned earlier, the re-encroachment of bush from either seedlings or coppice growth will always be a problem that will necessitate either a resident population of goats or some other means of controlling the continuous re-encroachment of bush.

Finally, lack of any statistically significant effect of the treatments on the condition of the veld deserves comment. Normally, when bush density is decreased, there is a dramatic improvement in the condition of the grass sward. However, it would appear that the repeated heavy grazing of the veld at the end of autumn prevented an improvement taking place. This is probably because this treatment caused a severe depletion of plant reserves at a time when they could not be restored, and removed shoot apices that would have developed into tillers during spring. The seedlings of species like Themeda triandra would also have been adversely affected. Therefore it is highly likely that, with the application of a proper rotational grazing and resting program, the grass sward would have responded more positively.

CHAPTER 6

GENERAL DISCUSSION AND CONCLUSIONS

A fundamental aspect that was investigated in this research program was the testing of the hypothesis that the role fire can play in controlling bush encroachment in the arid savannas is to maintain bush at an available height and in an acceptable state for utilisation by browsing animals. This hypothesis was tested in the experiment reported upon in chapter 3 and the results did not disprove the hypothesis. Therefore it can be concluded that when considering the use of fire in controlling bush encroachment in the arid savannas it must be combined with the introduction of a browsing animal to control the coppice growth of the bush. Failure to do this merely compounds the problem because the coppicing bush develops into multi-stemmed plants that result in a greater thickening up of the bush in the encroached areas. The effectiveness of introducing a browsing animal to control the coppicing bush is well illustrated by the results from the goat treatment described in chapter 3. Conversely the effect of using fire alone is clearly shown by the results from the control (K1) treatment in the same experiment where the bush fully recovered within a period of four years after the initial intense fire and exceeded the original phytomass of the bush by 278 per cent after five years.

The key questions that arose from the establishment of the role fire can play in the control of bush encroachment in the arid savannas were stated in chapter 3 and certain general conclusions can be drawn from the results in response to these questions. Firstly the results clearly showed that surface head fires should be used in preference to back fires. This is because they caused least damage to the grass sward but were found to cause a significant topkill of bush when applied under appropriate fuel and environmental conditions. Crown fires can also be used but are difficult to apply in practice because they will develop only under extreme atmospheric conditions which makes them dangerous to life and property. In view of their effectiveness though it is believed that a research effort should be made to identify these burning conditions because there are situations when crown fires can be safely applied. Crown fires could be particularly useful when bush encroachment has developed to the bush clump stage, when it has been found to be particularly resistant to surface fires.

The topkill of bush was found to be closely related to fire intensity. The results lead to the conclusions that an intensity of approximately 2 500kJ s^{-1} m^{-1} is necessary for a significant topkill of bush. The results also indicated, however, that bush is only susceptible when its height is approximately two metres or less. This is therefore the upper limit to which fire can be used in controlling encroached bush in the arid savannas. Initially this would appear to be a serious limitation to the use of fire. However, an assessment of the physiognomy of the encroaching bush communities in the Eastern Cape, Ciskei and Transkei indicates that the majority of the trees and shrubs are less than 2m tall.

The situation is complicated though, by the fact that the ability of the grass sward to produce sufficient fuel to support an intense enough fire to cause a significant topkill of bush decreases with an increase in the size and density of the bush. Fuel accumulation is also influenced by the condition of the grass sward and the amount of rainfall that has fallen. Unfortunately no comprehensive model has been developed for predicting the fuel dynamics of the arid savannas of southeastern Africa. Suffice it to say that burning should only be attempted in situations where the fuel load is at least 0,4 kg m^{-2} (4 000 kg ha^{-1}). It can also be concluded that the fuel dynamics of veld in which burning can be an important veld management tool should be investigated.

The aforementioned problem is further compounded by the phenomenon mentioned in chapter 2 that once the plant succession in the bush community has progressed from the Acacia karroo stage to the bush clump stage, the fires skirt around the edges of the clumps, leaving the centres unburnt. All these conflicting factors lead to the conclusion that fire can only be effectively used during the initial stages of bush encroachment when there is still a dense enough grass sward to support an intense fire. Bush clumps will not have developed at this stage so that an effective topkill of bush can be expected. Of course fire could also be used in situations where the original bush community has been chopped down or eradicated where it can be used to maintain coppice or invading seedlings at an available height for browsing animals.

The most appropriate season for burning, when using fire to control bush encroachment, is at the end of winter when the grass sward is dormant and dry. The results have shown that burning at this time enables the application of intense fires necessary to cause a significant topkill of bush while having no deleterious effects on the recovery of the grass sward. It is deemed permissible to draw this firm conclusion about the effect of the season of burning on the grass sward because of the similar findings of Tainton et al (1977) and Dillon (1980) in Natal.

The conclusion that late winter burns are most effective for controlling bush encroachment is a significant deviation from previous recommendations made in South Africa. Scott (1971) stated that burns should be applied after the first spring rains when fire is used to control bush encroachment. However, experience gained during this study showed that burning at this time resulted in significantly lower fire intensities in response to higher fuel moisture contents and relative humidities associated with the more humid atmospheric conditions that prevail after the first spring rains. Therefore, as was found and recommended by West (1965), burns for controlling bush encroachment should be applied when the grass is dry and dormant at the end of winter. Care should be taken though to ensure that the veld is not unnecessarily exposed to the elements after the burn in order to minimise the soil erosion hazard. With these factors in mind it is recommended that the general burning season should be limited to one month before the normal commencement of the growing season in spring. Furthermore, it must not be extended for longer than two weeks after the first signs of growth in the grass sward in spring in response to either rising temperatures and/or the first spring rains. This recommendation will ensure that burning can be conducted when an intense fire is necessary while simultaneously ensuring that the least damage is done to the grass sward by burning when it is dormant.

Tainton (1981) states, however, that burning under these extreme conditions should be viewed with caution. This is because of the considerable fire hazard and the possible damage to the veld through drought and incorrect veld management after the burn. While recognizing the danger of the fire hazard, personal field experience has shown that the probability of wild fires occurring can be greatly reduced by having adequate fire breaks and applying the burns according to the procedure illustrated in Figure 4.1. Secondly, the possibility of damage being caused by intense fires to the veld is not a potential threat. Fire intensity has had no significant effect on the recovery of the grass sward when veld was subjected to fire intensities ranging from 925 to 3326kJ s^{-1} m^{-1} i.e. cool fires to extremely hot fires. It must also be remembered that burning can only be used in situations where the grass sward is in a satisfactory condition since only such veld accumulates an adequate fuel load if it is to be effective in causing a topkill of bush. This study indicates that veld is highly resistant to fire when in this condition.

Finally grazing the grass before it has fully recovered after a burn in response to either drought or wilful incorrect management are problems to which there are no easy answers. The decision to burn and the size of the area to be burnt must be considered carefully and weighed against the possibilities of drought and the ability to allow the veld to recover fully if it does not rain. Wilfully applied incorrect veld management after a burn is a problem that exists in all farming communities and can only be minimised through vigorous extension efforts and resorting to legal measures.

The response of the bush to the season of burning was not specifically investigated in this study. An assessment of the data did not show any tendency for the bush to react differently when burnt when it was dormant or when it was actively growing. Therefore it was not possible to test the hypothesis postulated by West (1965) that bush is more susceptible to fire when it has produced a flush of spring growth and its plant reserves are in a depleted state. The overall results indicate that bush is very resistant to a total kill and that the topkill of stems and branches is primarily a function of fire intensity rather than the physiological state of the bush at the time of the fire.

As mentioned earlier the frequency of burning was not investigated because of the opportunistic role fire plays in the control of bush encroachment in the arid savannas. Burning to maintain bush at an available height for goats will depend upon the effect of the stocking rate and browsing management on the regrowth of the bush. The frequency will also be influenced by the occurrence of above average rainfall conditions that will permit enough grass fuel to be produced to permit an intense fire. The objective should be to burn as infrequently as possible because the arid savannas of southeastern Africa comprise very sweet veld where the grass forage remains highly nutritious to livestock even when in a mature state. Experience with using goats to control bush encroachment on the research farm of the University of Fort Hare indicates that it should not be necessary to have to reduce the height of the bush to make it available to goats more frequently than once every 10 to 15 years, provided that an appropriate stocking rate and browsing management program is applied.

The research on the browsing of coppice growth of bush with goats has lead to the conclusion that the majority of the bush species in the arid savannas of the Eastern Cape, Ciskei and Transkei are acceptable to goats. These results support the views of du Toit (1972a) and Aucamp (1976) that the goat can and should play an important role in utilising the vegetation of this region.

The conclusion that a stocking rate of one goat per 2 000 coppicing and acceptable bushes is necessary to control the regrowth of bush is a useful rule of thumb. However, it is clear that more detailed research is necessary to determine the browsing capacity of the different bush species that are acceptable to goats.

The investigation into the effects of continuous browsing on the regrowth of coppicing bush showed that this treatment successfully controlled the regrowth and caused varying degrees of mortality amongst the different bush species. Therefore, continuous browsing with goats can be used to control bush encroachment but it cannot be used for eradicating bush. It is interesting to note that the original objective of this investigation revolved around developing a method for eradicating encroaching bush. However, in recent years the economics of goat farming in South Africa have completely changed. Both meat and mohair production from goats have become very lucrative forms of livestock farming. In addition, results presented by Aucamp et al (1983) showed that in the thornveld areas of the Eastern Cape the highest total animal production per unit area was obtained when there was a mixture of grass and bush vegetation being utilised by grazers and browsers in the form of cattle and goats. Thus bush has been recognised as an important source of animal forage. Therefore instead of eradicating it there is now the point of view that it should be retained but at a density and size which does not compete severely with the grass sward. It should then be managed to produce maximum quantities of browseable forage for utilisation by goats.

Thus while continuous browsing may have a role to play in controlling bush encroachment in certain situations, rotational browsing has become an equally or more important management practice in the arid savannas of south eastern Africa. The key question that must now be answered through research is what intensity and frequency of defoliation is necessary to maximise the production of forage from the key browse species in the veld?

A major portion of the research reported upon in this thesis involved the characterization of fire behaviour. This stemmed from the recognition that the type and intensity of fires are important components of the fire regime, and that the effect of fire depends upon the amount, rate and vertical level at which heat energy is released during a fire. The results of the effects of type and intensity of fire on the grass and bush components of the vegetation clearly illustrate the importance of these factors in the fire regime.

The significant effects of the amount, rate and vertical level at which the heat energy is released during a fire were well illustrated by the response of the bush to the burns. The topkill of bush was highly significantly correlated with the amount of heat energy released, as represented by the fuel load. Similarly, there was a highly significant correlation between the topkill of bush and fire intensity. Finally flame height, representing the vertical distribution of heat energy, became increasingly correlated with the topkill of bush as the height of the trees and shrubs increased.

The response of the grass sward to the effects of these three parameters was not as clearly evident as with the bush. Some evidence is provided though by the different effects of head and back fires on the grass sward. The slower recovery of the grass sward when burnt with a back fire was apparently due to the higher temperatures that occurred at ground level. Also, the duration of critical threshold temperatures was greater in back fires than in head fires. Thus the effects of the elements of the amount, rate and vertical level at which the heat energy was being released on the grass plants are evident in these results.

A significant result of the fire behaviour studies was the fact that fire intensity can be used for describing the general behaviour of fires and their effects on the vegetation. This is a particularly useful result because it enables comparisons to be made between different fires and their effects on the ecosystem. Experience gained during the course of this study indicates that fires can be classified into the following catagories according to their intensity:

Fire Intensity (kJ s^{-1} m^{-1})	Description
< 500	Very cool
500 - 1 000	Cool
1 001 - 2 000	Moderately hot
2 001 - 3 000	Hot
> 3 000	Extremely hot

This classification will assist in conceptualizing what different fire intensities mean in practice. For example back fires which are generally very cool fires never exceeded 268 kJ s^{-1} m^{-1} in this study. Conversely the intensity of head fires varied widely and a hot fire of approximately 2 500 kJ s^{-1} m^{-1} was found necessary to cause a significant topkill of bush to a height of 2m.

The successful development of a fire intensity model also greatly facilitates deciding upon when to burn and when not to burn. These results indicate the desirability of extending this type of fire research to other ecological areas where burning is an important veld management practice. The minimum characterization of fires that should be undertaken in such studies is recording the fuel load, fuel moisture, air temperature, relative humidity, wind speed and the rate of spread of the fire front. Using these data together with an appropriate heat yield of the available fuel, the fire intensity can be calculated and once sufficient data have been collected a fire intensity model can be developed.

An aspect that requires further investigation with the current fire intensity model is to determine whether it is possible to eliminate fuel moisture as an independent variable in situations where the grass sward is dry and dormant. The results showed that fuel moisture does not have a significant effect on fire intensity when less than 45 per cent. Unfortunately there were insufficient data to develop a fire intensity model for situations where fuel moisture does not play a role. The elimination of this variable would greatly facilitate the use of the fire intensity model because the quantitative estimation of fuel moisture is a slow and tedious process.

Finally, the calibration of the disc pasture meter using mean values deserves further attention. Results to date indicate that it is possible to develop a standard calibration for a wide variety of veld conditions within one ecological region. This would greatly enhance the usefulness of this method of estimating the standing crop of herbaceous material as it has great potential for use in agricultural extension and practical farming.

CHAPTER 7

SUMMARY

The arid savannas of southeastern Africa comprise the thornveld and valley bushveld areas of the Eastern Cape, Ciskei and Transkei that receive less than 650mm of rain per annum. Bush encroachment has become a serious problem in the thornveld areas where it has drastically reduced the grazing capacity of the veld. The encroachment has occurred from the valley bushveld of the dissecting river valleys and from the scrub forest that is marginal to the high forest of the Winterberg, Katberg and Amatole mountain ranges. The principal encroaching species is Acacia karroo but other important associated species are Scutia myrtina, Maytenus heterophylla Rhus spp., Diospyros lycioides, Xeromphis rudis, Azima tetracantha and Ziziphus mucronata.

The two most important factors to be considered when formulating a program for controlling bush encroachment are the ecological and economic consequences of applying the control methods. Fire was chosen as a possible method of controlling bush encroachment because it is a non-capital intensive technique which makes it compatible with the inherent low economic potential of veld. From the ecological point of view fire is recognized as being a natural factor of the environment in savanna areas of Africa and has been occurring since time immemorial.

Consequently it was decided to conduct a research program on the use of fire in controlling bush encroachment. The initial key question that was investigated was the role fire can play in controlling bush encroachment in the arid savannas. A review of the literature and personal experience led to the postulation of an hypothesis that the role fire can play in controlling bush encroachment in these areas is to maintain bush at an available height and in an acceptable state for browsing animals. Generally the tree and shrub species of the savanna areas are very resistant to fire alone due to the presence of dormant buds at the base of the stem, from which coppicing occurs. In the arid savannas the rainfall is too low and erratic

to support frequent enough fires under grazing conditions to prevent the regeneration of bush from coppice and seedling growth.

This hypothesis was tested in an experiment on the research farm of the University of Fort Hare. It comprised applying an intense surface head fire to an area of sweet grassveld moderately encroached with Acacia karroo and other woody species. The burn resulted in 80,8 per cent of the trees and shrubs suffering a topkill of stems and branches, of which 71,5 per cent coppiced and only 9,3 per cent were killed. Subsequent follow-up treatments were superimposed on the burnt area in contiguous plots and comprised continuous browsing with goats, annual spring burning and a control treatment without browsing or burning. Continuous browsing with goats caused a marked reduction in the density and phytomass of the bush. The annual spring burn caused an initial decrease in the density of the bush but thereafter it again increased and eventually surpassed the original density of the bush in this treatment. However, this treatment caused a marked reduction in the phytomass of the bush which has been maintained at a low level over the years. The control treatment resulted in a complete recovery of the bush after the initial intense fire and both the density and phytomass of the bush have far surpassed their original pre-treatment levels.

These results led to the conclusion that the hypothesis concerning the role of fire in the arid savannas has not been disproved. The results also indicate that the program of burning and browsing with goats can be used to control bush encroachment under veld conditions where a sufficiently intense fire can be obtained to cause a significant topkill of bush.

Arising from these results and conclusions the following key questions were posed and investigated in order to provide the technology necessary for the practical application of a system of burning and browsing to control bush encroachment.

(i) what type and intensity of fire are required to burn down bush of a particular size and species?
(ii) during what season should burning be applied to reduce bush to an available height for browsing animals?

(iii) What is the acceptability of different bush species to goats?

(iv) What stocking rate of goats must be applied to control bush that has been reduced to an available height? and

(v) what type of browsing management must be applied to control bush that has been reduced to an available height?

In attempting to answer the first question it was necessary to determine the characteristics of fire behaviour in the arid savannas of southeastern Africa. The investigation was limited to identifying and quantitatively describing those fire behaviour parameters pertinent to the effect of fire on the vegetation. Basically the effect of fire on plants depends upon the amount, rate and vertical level at which the heat energy is released during a fire. The amount of heat energy released during a fire is represented by the product of the fuel load and the heat yield of the plant fuel. In the arid savannas of the Eastern Cape, Ciskei and Transkei the fuel load comprises primarily surface fuels in the form of the standing grass sward. It was found that the most efficient method of estimating the fuel load was with a disc pasture meter using the following regression equation:

$$y = (340 + 388{,}3x) \div 10\ 000$$

where:

y = mean fuel load - kg m^{-2};
x = mean disc height - cm.

The regression equation is based on the following statistics:

Number of paired data = 43;
Correlation coefficient (r) = 0,9126;
Coefficient of determination (r^2) = 0,833;
Residual standard deviation = 0,0826.

This was a particularly valuable result because it was found that the regression equation was applicable to a wide variety of grass communities in markedly different stages of growth.

The heat yield of the grass fuel burning as surface head and back fires was determined with a bomb calorimeter and found to be 16 890kJ kg^{-1} and 17 781kJ kg^{-1} respectively. These values represent the amount of heat energy available for release during a fire per unit mass of fuel. The rate of release of heat energy during a fire is represented by the intensity of a fire, which is defined as the amount of heat energy released per unit time per unit length of fire front. Numerically it is the product of the available heat energy and the rate of spread of the fire front. It can be written as the following equation:

$$I = Hwr$$

where:

I = fire intensity - kJ s^{-1} m^{-1};
H = heat yield - kJ kg^{-1};
w = mass of available fuel - kg m^{-2};
r = rate of spread - m s^{-1}.

Fire behaviour studies led to the development of the following statistical model for predicting the fire intensity of surface head fires:

$$FI = 4\ 782 + 3\ 341x_1 - 550\ \sqrt{x}_2 - 0{,}2620x_3^2 - 797x_4^1$$

where:

FI = fire intensity - kJ s^{-1} m^{-1};
x_1 = fuel load - kg m^{-2}
x_2 = fuel moisture - %;
x_3 = relative humidity - %;
x_4 = wind speed - m s^{-1}.

The model is based on the following statistics:

Number of cases = 70;
Multiple correlation coefficient (R) = 0,7394 ($P \gtrsim 0{,}01$);
Coefficient of determination (R^2) = 0,547.

This model can be used under a wide range of fuel and atmospheric conditions.

A reliable indicator of the vertical distribution of heat energy released during a fire is the perpendicular height of the flames from ground level i.e. flame height. The following statistical model was developed for predicting flame height:

$$FH = -5,60 + 6,32\ \sqrt{x_1} + 78,68\overset{1}{x}_2 + 0,0795x_3$$

where:

FH = flame height - m;
x_1 = fuel load - kg m^{-2};
x_2 = fuel moisture - %;
x_3 = air temperature - °C.

The model is based on the following statistics:

Number of cases = 46;
Multiple correlation coefficient = 0,7461 ($P \lesssim 0,01$);
Coefficient of determination = 0,557.

This flame height model can be used under the same conditions as the fire intensity model.

The fire behaviour studies included a comparison of the behaviour of surface head and back fires, the most common types of fire in the savannas. The results showed that head fires were potentially more intense above ground level while back fires were generally more intense at ground level. It was also found that the rate of spread of head fires was significantly greater than that of back fires. These differences in rate of spread were found to be associated with the duration of temperatures at ground level. The main difference occurred at temperatures $\gtrsim$ 60°C and $\gtrsim$ 80°C where head fires had significantly lower duration periods than back fires. This was apparently caused by the greater rate of spread of head fires where the process of combustion occurs for shorter periods of time at any one point. The relationships between the different fire behaviour parameters showed that fire intensity was significantly correlated with all of them. This led to the conclusion that fire intensity is well suited to quantitatively describing the general behaviour of surface head fires.

Turning to the effect of fire on the vegetation the results led to the conclusion that surface head fires should be used to reduce bush to an available height for browsing by goats. This is because, in contrast to back fires, head fires caused the least damage to the grass sward but were capable of causing a significant topkill of bush to a height of two metres if applied under the appropriate fuel and atmospheric conditions. Crown fires can also be used for reducing the bush to an available height for goats but are difficult to apply and are a danger to life and property.

The topkill of bush is closely related to the intensity of a fire. It was found that an intensity of approximately 2 500kJ s^{-1} m^{-1} caused a significant topkill of stems and branches and that the different bush species reacted similarly to different fire intensities. The results also showed that the topkill of bush can be predicted directly using the following statistical models:

$$\text{TK } 1{,}01 - 1{,}50\text{m} = 105 - 19{,}3x_1^1 - 23{,}8x_2^1 + 0{,}04x_3^2$$

where:

TK = topkill of bush - %;
x_1 = fuel load - kg m^{-2};
x_2 = wind speed - m s^{-1};
x_3 = air temperatures - °C.

$$\text{TK } 1{,}51 - 2{,}00\text{m} = 75{,}2 - 16{,}7x_1^1 - 23{,}8x_2^1 + 493x_3^1$$

where:

TK = topkill of buh - %;
x_1 = fuel load - kg m^{-2};
x_2 = wind speed - m s^{-1};
x_3 = relative humidity - %.

The models are based on the following statistics:

TK 1,01 - 1,50m: Number of cases = 46;
Multiple correlation coefficient (R) = 0,7504 ($P \lesssim 0{,}01$);
Coefficient of determination (R^2) = 0,563.

TK 1,51 - 2,00m: Number of cases = 46;
Multiple correlation coefficient (R) = 0,6026 ($P \lesssim 0,01$)
Coefficient of determination (R^2) = 0,363.

Field experience indicates that these models should be used when the grass sward is dry and dormant i.e. fuel moisture 45 per cent.

Besides using the preceeding methods for predicting the topkill of bush the following general guidelines can also be used for ensuring a significant topkill of stems and branches to a height of 2,00m while still being reasonably safe to apply:

Fuel load $\gtrsim$ 0,4kg m^{-2};
Fuel moisture $\lesssim$ 45%;
Air temperature = 25 - 30°C;
Relative humidity $\lesssim$ 30%;
Wind speed $\lesssim$ 5,6m s^{-1}.

The investigation into the effects of season of burning indicated that the burns should be applied at the end of winter when the grass sward is dry and dormant. Burning at this time enables the application of intense fires necessary to cause a significant topkill of bush while having no deleterious effects on the grass sward.

The frequency of burning was not investigated because of the opportunistic role fire plays in the control of bush encroachment in the arid savannas. The objective should be to burn as infrequently as possible. Of course this will depend upon the recovery rate of the bush in response to browsing management and the occurrence of above average rainfall conditions that will produce sufficient grass fuel to support an intense fire.

The results clearly showed the effects of fire on the vegetation as described by the amount, rate and vertical level at which heat energy is released during a burn. Fuel load, fire intensity and flame height were all significantly correlated with the topkill of bush, with flame height having a better relationship in the taller height classes.

The effect of stocking with goats on the coppice growth of bush showed that a stocking rate of one goat per 2 000 coppicing and acceptable bushes controlled the regrowth of the bush and resulted in limited amounts of grass being utilised.

An overwhelming majority of the bush species in the arid savannas of south-eastern Africa are readily acceptable to goats. Continuous browsing of coppice growth of bush with goats caused varying degrees of mortality amongst the different bush species. However, it did not result in the complete eradication of all the bush that was present. Therefore continuous browsing with goats can be used to control bush encroachment but it cannot be used for eradicating bush.

Finally, a significant result of the fire behaviour studies was that fire intensity can be used for describing the general behaviour of fires and their effects on the vegetation. Experience gained during the course of this study indicates that fires can be classified into the following catagories according to fire intensity:

Fire Intensity (kJ s^{-1} m^{-1})	Description
< 500	Very cool
501 - 1 000	Cool
1 000 - 2 000	Moderately hot
2 001 - 3 000	Hot
> 3 000	Extremely hot

This classification will assist in conceptualizing what different fire intensities mean in practice. For example back fires which are generally very cool fires never exceed 268 kJ s^{-1} m^{-1} in this study. Conversely the intensity of head fires varied widely and a hot fire of 2 500 kJ s^{-1} m^{-1} was found to cause a significant topkill of bush to a height of 2m.

CHAPTER 8

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CHAPTER 9

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