DETERMINANTS OF GRASS PRODUCTION AND COMPOSITION IN THE KRUGER NATIONAL PARK

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DECLARATION:

The work reported in this thesis is the result of the author's original work, unless specifically acknowledged and stated in the text.

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ABSTRACT

The dynamics and complexities of climate-soil-vegetation relations in the Kruger National Park are poorly known. Although primary production and composition of the grass layer are very important components of the Park's ecosystem, equally little is known about the determinants of these parameters. A better understanding of these processes and relations will be of value to the management of this Park, as well as providing a better insight into these complex dynamics. A study was consequently undertaken covering a 14-year period to identify the most important determinants of above-ground grass production and composition. At the core of the study is the soil water balance. The use of evapotranspiration data in a study of this nature is however not absolutely essential, provided a variety of rainfall parameters are used, though it has the important advantage of providing a much more detailed and more complete insight into the relations of the grass sward with its environment. Stepwise and tree regression procedures were used to identify the important factors. It is concluded that rainfall in its various forms is the primary determinant of grass production, standing crop, and composition, the latter either as perennials or Decreasers. Secondary determinants, in varying degrees of importance, are the thickness and base status of the A horizon, distance to permanent drinking water, and competition by woody plants. Herbivore utilization is insignificant or at most, plays a relatively minor role. Herbivores appear to exert a negative influence on Decreaser abundance only when soil moisture stress exceeds a threshold level. When this is exceeded, relatively low herbivore densities are apparently sufficient to reduce Decreaser abundance. The definitions of Decreasers and Increasers consequently require revision to take into account the overriding influence of environmental factors, particularly those of soil moisture stress. The calibration of the disc pasture meter was re-evaluated. The relation between mean disc height and standing crop is non-linear. Up to a mean disc pasture meter height of 260 mm, the correlation between this parameter and above-ground standing crop is very strong ($r^2 = 0.95$; $P<0.0005$). Beyond this height, the correlation is very poor ($r^2 = 0.09$; $P<0.0005$), apparently being strongly influenced by the structure of the grass plant, with tall grasses, or grasses with highly lignified culms resulting in a weaker correlation.

DETERMINANTS OF GRASS PRODUCTION AND COMPOSITION IN THE KRUGER NATIONAL PARK

CHAPTER 1

INTRODUCTION, MOTIVATION AND LITERATURE REVIEW

1.1. INTRODUCTION

Veld condition assessment has been undertaken annually in the Kruger National Park (herein after always referred to as the KNP) since 1989 on 533 permanent sample sites using the key-grass species technique of Trollope (1990). Several years after the inception of the veld condition assessment programme (VCA) when trends in standing crop and composition began to emerge, it became apparent even from very basic analyses and comparisons that relations exist between these parameters and rainfall. Furthermore, it became evident (Zambatis 1996) that in certain areas which are known to have a low to very low density of herbivores, Increaser II's consistently remained dominant, in spite of low herbivore pressure.

The Decreaser-Inceaser classification system for grasses (Hardy *et al.* 1999), and which is applied routinely in the annual VCA surveys is controversial, primarily because of apparent inconsistencies in response of the various species to grazing pressure - the basis of the definitions of the main groups and their different sub-categories. This consequently served as a further motivation to undertake this study.

With standing crop, it was very clear from the outset that this is directly correlated with the year's rainfall. Here too, a number of questions arose concerning the dynamics and determinants of annual grass production. This led to the conclusion that there must be factors other than grazing pressure which may be influencing composition 'negatively', in turn raising a number of questions, such as: How important is rainfall in determining annual standing crop and composition in the KNP; What other factors are important determinants of these parameters; Is there a difference in these parameters between the two major geological formations of the KNP; can these parameters be predicted?

These questions thus represent the beginnings of this study. They are in fact incorporated, though in a somewhat oblique manner, in the masterplan for the management of the KNP (Braack 1997).

This study thus deals with climate-soil-grass relations or dynamics in an integrative manner - in a sense, a modelling approach and is shown schematically in Figure 1.1. More specifically, it is an attempt at identifying the most important factors determining grass production and composition in the KNP.

At its core lies the soil water balance; a field which, because of its many complexities, requires not only a huge amount of computational effort, but an equally large volume and variety of on-site data to achieve any level of distinction between sites.

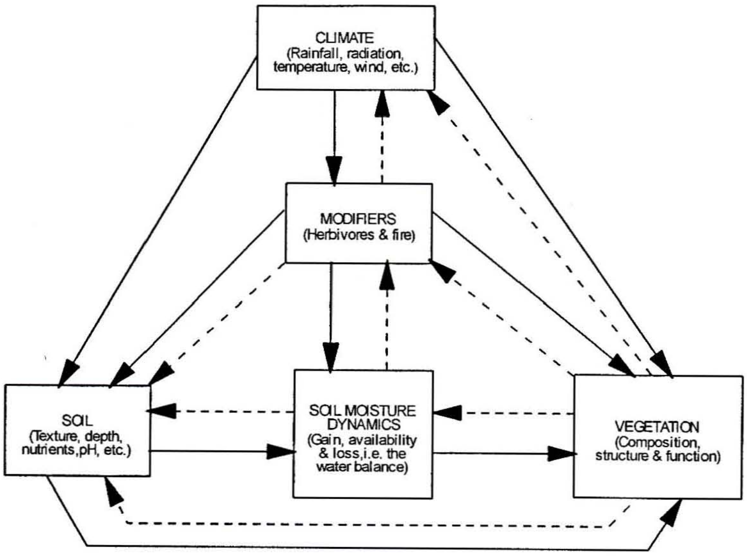

Figure 1.1. Schematic representation of the climate-soil-vegetation links (solid lines) and feedback loops (not dealt with in this study; broken lines).

Essentially, the processes are investigated at two widely-differing scales: the VCA site of 50 x 30 m in size, and the two major geological formations of the KNP, each extending over an area of approximately 260-320 x 30 km (c. 780 000 - 960 000 ha), in keeping with the basic objective of deriving a better understanding at the relatively broad level. To accomplish this successfully however, detailed information at the scale of the site level is essential.

1.2. MOTIVATION AND PURPOSE

1.2.1. OBJECTIVES OF THE MASTERPLAN FOR THE MANAGEMENT OF THE KNP, AND GENERAL BACKGROUND

The revised management plan for the Kruger National Park (Braack 1997) gives the mission statement of the KNP thus: *"To maintain biodiversity in all its natural facets and fluxes"*. The ecosystem objective is *"To manage the KNP as part of the Lowveld savanna... in such a manner as to conserve and restore its varied structure, function and composition over time and space, through an approach integrating all levels of objectives"* while the research objective is *"To promote, through an integrated approach, an understanding of the influences of factors ... affecting ecosystem diversity and dynamics."*

Elsewhere in the document, more specific objectives are given. In the sections dealing with nutrient cycling, and the plant facet of the herbivory objective, *"To understand plant distribution (including patch diversity) and vegetation dynamics in terms of climate, soil nutrients and other soil properties. Collate existing knowledge"*, *"Improve our understanding of changes in vegetation structure...over time"*, and the fire objective: *"Investigate all possible sources to obtain a clearer understanding and insight into fire (of all origins) in the Lowveld..."*

Historically, and as has been the case in many other parts of the country and in many other spheres of biological or ecological work, research has been undertaken on a 'piecemeal' basis in the KNP. Early studies understandably were little more than basic surveys at the species level, followed by broad, descriptive surveys of the vegetation, increasing in detail as time progressed. These then, were inventory or 'stock-taking' surveys and although very basic, were (and still are) the foundation-stones of work which followed.

When ecosystem management was commenced, it became clear that research into the complexities of ecosystem functioning, as well as more specific management problems such as veld burning, artificial provision of drinking water and culling also needed attention. This inevitably led to an increasingly sophisticated research effort that persists to the present day.

Until recently though, and for various reasons, little effort was made at integrating a very substantial diversity and volume of data that has emerged from the KNP over the years. The situation is however changing, with an increasing number of projects integrating data of various types in order to obtain a more holistic picture, but still far from complete. This study is such an undertaking and attempts to bring together and relate a large diversity of variables concerning vegetation, weather, certain soil properties, fire treatment, artificial drinking water and herbivore abundance. This is in accordance with the various objectives of the masterplan for the management of the KNP.

1.2.2. THE NEED FOR A BETTER UNDERSTANDING OF DETERMINANTS OF GRASS PRODUCTION AND COMPOSITION

1.2.2.1. **Production and standing crop**

'Production' is defined as the quantity of grass material produced during the growth season and excludes residual material carried over from previous year(s). It can be sub-divided into gross (GPP) and nett (NPP) production.

Grossman (1982) defines net primary production as GP-R (where GP = gross photosynthesis; R = respiratory loss) and 'standing crop' as the combined sub-components of 'biomass' (the attached live material) and 'necromass' (the attached dead material).

Necromass can either consist of the current season's material which has died, or dead material carried over from the previous season and still attached to plant (residual material), or both. Residual material carried over from the previous to the current growth season is a confounding factor in determining production. In this study, production refers only to above-ground production.

During the practical application of standing crop assessment using the disc pasture meter (and hence in this study as well), it is not possible to determine respiratory loss or consumption by vertebrate or invertebrate herbivores. 'Production' thus implies the nett or residual amount of material remaining after these losses have occurred and can therefore be regarded as a minimum amount or 'nett primary production' (NPP).

The same can be said for 'standing crop', which consists of the NPP material plus the residual carry-over from the previous year(s) and can consequently be termed 'nett standing crop' or NSC.

In the practical application of rangeland management however, these issues are of little consequence, simply because the manager's primary concern is the amount of material available at a particular point in time.

A distinction is made in this study between grass production and grass standing crop. Various techniques can be used for the quantification of production, generally involving the clipping to ground level at the start of the growth period, and subsequent clipping and weighing of material at regular intervals during this period, taking into account senescence and consumption.

In this study the only practical alternative to clipping was to use the VCA standing crop data collected on those sites which were 'clean burnt' (i.e. no material remaining) during the preceding dry season. Although this approach can be expected to be relatively coarse in its results when compared with the more conventional techniques, it should be reasonably accurate in providing a measure of nett primary production for the scale at which this study was conducted.

Although some research work has been done on phytomass production in African savannas, the current state of knowledge is limited, yet this is a key process determining the functioning of these systems. Purely as an academic exercise then, this study should make a contribution towards a greater understanding of phytomass production in the savanna biome in general and should provide a greater insight into the ecosystem dynamics of the KNP in particular.

In a more practical or applied science context, the study should make a contribution towards modelling, both for broader research purposes, but perhaps more importantly, towards rangeland management, both in the wildlife and domestic livestock fields.

Models to estimate phytomass production from simple, easily-measured or easily-calculated parameters can be used to simulate fluctuations in plant and animal production and grazing capacities over time. Such models will facilitate the evaluation of management options, with particular emphasis on the critical seasons in which plant growth is at a minimum. Relating these to animal feeding requirements would facilitate the development of veld management strategies (Barnes & McNeill 1978; Snyman & Fouché 1993), including carrying capacity and stocking rate determinations.

Depending on the determinants identified and on the availability of historic data on these variables as well as their temporal extent, it theoretically would make possible the retrospective determination of grass production and standing crop in the KNP. This could allow the mapping of the historic distribution of standing crop, which in turn can then be related to records of those fires which occurred before the advent of the current monitoring programmes.

By making use of the fire behaviour relationships of Trollope & Potgieter (1985) and of prevailing weather conditions on the day of occurrence of the fire, it should then be possible to determine the intensity of a particular fire as well as its impact on the woody vegetation. This should in turn make possible the retrospective quantification and lengthening of the fire impact record, specifically on the woody vegetation, and particularly when this is combined with an interpretation of the 'early' aerial photographs, the first of which were taken in 1944.

Such a retrospective estimation of standing crop could conceivably also be of some value in reconstructing the ecological histories of other components of the KNP ecosystem, for example herbivore-grass stratum relations, as was undertaken by Coe *et al.* (1976).

Taking this a step further, if present-day correlations between rainfall, grass phytomass, herbivore densities and distribution and *veld condition* can be determined, it may be possible to determine the historic condition of veld since 1977, the beginning of the annual aerial ecological surveys. Due to the fact that veld condition is influenced by a number of factors however, it is doubtful whether this can be done to an acceptable level of accuracy and hence reliability. Nevertheless, this would be a worthwhile exercise.

The revised burning policy (Biggs 2002) requires that at the start of the fire season (normally mid-April to mid-May), section rangers must determine the standing crop and composition (in terms of the Decreaser-Increaser classification) of the fire management units in their sections. This forms the basis for subsequent decisions concerning the extent of area to be burnt, be it due to 'natural' causes, or by illegal immigrants from Mozambique - the latter a very common cause of unintentional fires since the mid-80's until the present (Trollope 1993)

A shortcoming of this approach is that the density of VCA sites (on average, one site per 3 656 hectares) is not necessarily representative of the management areas concerned and can consequently lead to incorrect decisions being taken.

The development of a model (as part of a greater decision-support system) requiring a minimum of information and which would thus be practical to apply by section rangers, should therefore receive consideration. More specifically, what is envisaged is a model which would make use of the available VCA (point) data, as well as the section ranger's knowledge of the standing crop and composition of his section (or sub-section) at a broader scale.

The ability to predict standing crop at an extensive, park-wide scale may also be of value as an early-warning system in the seasonal prediction of fires. By using GIS routines, areas where fire can be expected, the expected fire intensity, and the likely spatial spread of fires could be predicted. Should this be practically possible, it would be a simple matter to expand this predictive ability to provide daily fire danger indices and warnings such as those used in the more humid regions of South Africa (Everson *et al.* 1988).

In view of the frequency of drought in semi-arid grassveld, prediction of grass response to moisture stress is of the utmost importance (Danckwerts & Stuart-Hill 1988).

1.2.2.2. **The calibration of the disc pasture meter**

During the course of this study in the field application of the disc pasture meter (DPM) in the tall-grass veld area of the KNP, it was observed that the instrument frequently settles above the bulk of the grass leaf mass, at times resulting in inflated DPM settling heights. This in turn led to the suspicion that, taking into consideration the relatively heterogeneous nature of the herbaceous stratum, a single calibration equation for the entire KNP is perhaps inappropriate; possibly necessitating that a distinction be made between at least the tall grassveld of the Pretoriuskop area and the rest of the KNP.

The DPM was calibrated for the KNP by Trollope & Potgieter (1986). The scatter diagram of Trollope & Potgieter shows a non-linear (i.e. asymptotic or possibly an optimum) distribution pattern. The original field data used for the calibration are fortunately still available. This allowed the investigation of the data to determine whether they are normally distributed or not, using Maximum Likelihood Estimation (MLE, Version 2.1; J.F. Derry, University of Edinburgh, 1999; Derry *et al.* 1999). Results showed that these are not normally distributed.

It was consequently concluded that the calibration of the disc pasture meter for the KNP should be revised and re-calibrated if necessary. This is dealt with in Chapter 5.

1.2.2.3. **Composition**

The identification of the important determinants of grass sward composition would be of value for reasons similar to those of production and standing crop explained above.

The Decreaser-Increaser classification has been shown to have serious limitations (Janse van Rensberg & Bosch 1990; van Rooyen *et al.* 1991; Bosch & Theunissen 1992).

A shortcoming in the definitions of 'Decreaser' and 'Increaser' is that these are based entirely on the effects of grazing (Trollope *et al.*1990), or fire (Foran *et al.* 1978) with the influence environmental factors not being taken into account. Yet ample evidence exists to show that soil moisture in particular, as well as soil properties, are the primary determinants of grass composition, with grazing treatments being secondary factors overridden by large inter-annual climatic variations (O'Connor 1985, 1991; van Rooyen *et al.* 1993).

Assuming that grazing intensity is in fact the primary cause of change in composition, a further hindrance to the successful application of this classification system remains, especially in large conservation areas such as the KNP. By implication, the defining criterion of this system implies knowledge of the grazing history of an area. In large conservation areas, this is not always known or it is poorly known. This leads to the assumption being made that if Increaser II species are dominant in an area for example, it has been over-utilized. Moreover, and to complicate matters further, a number of studies at the grass species level have shown that the relation between the abundance of a particular species and grazing intensity are not linear but asymptotic (Janse van Rensburg & Bosch 1990; van Rooyen 1991; Bosch & Theunissen 1992; Cauldwell *et al.* 1999).

Without knowledge of the history of grazer density or the type of grazer (e.g. selective grazer, bulk feeder etc.) of an area, the assumption cannot be made that because a species or a group of species is dominant, the area has been over- or under-utilized, particularly if the soil characteristics and the soil moisture history are also not taken into account.

Perhaps the single exception to this is the area surrounding a water-point within a radius of a few hundred meters and which is dominated by Increaser II grasses or forbs for example (Thrash 1993; Thrash *et al.* 1993). In these areas, the herbivore history would be known, though heavy concentration and consequent trampling would probably be the most likely reason for the dominance by these plants, with grazing intensity having an increasing effect further away from the water, but only up to a certain point.

1.2.3. THE RAPID DETERMINATION OF STANDING CROP FOR MANAGEMENT PURPOSES

Annual veld condition assessment surveys are undertaken at the end of the growth stage. Soon after, the veld begins to dry out and the fire season commences. In terms of the revised burning policy, section rangers need to know the composition (in broad terms) and the standing crop of their sections at the start of the fire season so as to be able to calculate what percent of the area can be allowed to burn.

The ability to determine standing crop with the minimum of time and effort and as quickly as possible will consequently be a useful tool for section rangers and can be integrated in their decision-support system for the management of their areas of responsibility. As a consequence, this objective was pursued in an attempt to establish if it is possible to develop a simple management tool for this purpose. Such a tool would allow field managers to predict, prior to the burning season, the areas to be inspected for burning, where this is necessary.

1.3. LITERATURE REVIEW

(In order to avoid repetition, the literature review dealing with the calibration of the disc pasture meter is not included in this review but is dealt with in Chapter 5).

1.3.1. INTRODUCTION

The Kruger National Park extends over only 2% of the southern African savanna biome but within South Africa, it is the largest area of this biome which is conserved (Rutherford & Westfall 1986).

Savannas are one of the most seasonal of the world's major biomes, experiencing strongly contrasting climatic conditions within a year, as well as high variability between years (Frost *et al.* 1985). Southern Africa savanna has a rainfall of between 235 and 530 mm, with moist savanna receiving 650 mm or more per year (Rutherford & Westfall 1986). Savanna with an annual rainfall of between 530 and 650 mm can thus be regarded as being mesic savanna, though Hopkins (1983) regards mesic savanna as receiving from 500 to 1 200 mm per year.

The seasonal nature of the savanna rainfall regime distinguishes this biome from the tropical forests and deserts (Nix 1983; Cole 1986). Arid savanna has six or more rainless months, and generally receives less than 650 mm of rainfall per year with mid-summer droughts a feature of both arid and moist savannas; in the latter, droughts occurring at their lower limit of their moisture range (Huntley 1982).

Twenty years ago, Huntley & Walker (1982) stated that despite their importance as wildlife and agricultural areas, the relations between tropical savanna and environmental conditions are less well understood than those of most other ecosystems. Since then, a great deal of research attention has been focused on the savanna biome, with the large body of work produced by the South African Savanna Ecosystem Programme being synthesised by Huntley & Walker (1982) and Scholes & Walker (1993). The southern African savanna literature is biased towards studies on larger mammals, the tree/grass interaction, fire and production ecology (Scholes 1997).

Until recently, very little was known about the relations between grasses, soil and climatic factors, or the relations between grasses and woody plants in the KNP. A number of research projects have, however, been initiated recently and are aimed at the complex dynamics of the climate-plant-soil interface. In many conservation areas of Africa, including the KNP, these relations are at the core of the veld and herbivore management problems, or deficiencies in knowledge being experienced.

Sustained primary productivity by plants is one of the most important aspects of a landscape that is being managed to maintain stock or wildlife. An understanding of plant growth in response to available moisture is therefore the most basic knowledge that can be used for landscape management decisions (Hobbs *et al.* 1994).

The Masterplan for the management of the KNP specifically mentions the need for the development of an understanding of the functioning and relations of the KNP's components and ecosystem (Joubert 1986; Braack 1997).

The overwhelmingly important factor determining the spatial distribution of forest, savanna and grasslands is soil moisture balance and is the most significant edaphic feature as it overrides all other properties, or influences their effects (Cole 1982; Tinley 1982). Soil moisture is the key variable which synthesizes the action of climate, soil and vegetation on the water balance and the dynamic impact of the water balance of plants (Rodriguez-Iturbe *et al.* 2001).

1.3.2. FACTORS INFLUENCING GRASS PRODUCTION

1.3.2.1. **Abiotic factors**

Of the three major natural patterns that dominate the earth's environment, namely patterns of climate, vegetation and soil, climate is regarded as the principal dynamic component and the obvious independent variable shaping the other two, especially vegetation, on both micro and sub-continental scales (Akin 1991). The vegetation of an area is a reflection of the environmental factors present, amongst which climate occupies a crucial position (Tuhkanen 1980).

The most important climatic factors in vegetation development are light, temperature and moisture, with most major subdivisions of vegetation formations on a sub-continental scale reflecting annual and seasonal soil-moisture balances, rather than gross precipitation (Schulze 1997).

In the savannas, grasslands and deserts, primary production is controlled almost entirely by the incidence of rain (Tuhkanen 1980; Roux 1981; Tinley 1982; Lamotte & Bourlière 1983) and on the availability of nutrients, particularly nitrogen and phosphorus (de Jager *et al.* 1980; Frost *et al.* 1985; Scholes 1990; O'Connor & Bredenkamp 1997). In Africa, a generally positive correlation exists between annual rainfall and above-ground primary production (Coe *et al.* 1976; Deshmukh 1984; Frost *et al.* 1985; Teague & Smit 1992). This relation is however only very general and is affected by factors such as the duration of the wet season, soil type and texture, fire and species composition (Frost *et al.* 1985).

Grass production is linearly related to annual rainfall up to about 900 mm, the slope of this correlation being determined by soil fertility, with the y-intercept being controlled by tree biomass and soil physical properties (Rutherford 1980; Dye & Spear 1982). According to Rutherford, plant production arises from a complex interaction of substrate with climatic and genetic factors. Of these, climate is usually the most variable in the short term; and in an arid area, rainfall is usually one of the most variable of the more important macro-climatic determinants of plant growth.

Rutherford (1980) and Deshmukh & Baig (1983) however caution against attempts to relate only rainfall to plant production for various vegetation types in arid regions, usually with the objective of predicting plant production from available rainfall data. They state that such attempts necessarily remain crude by reason of omission of the many other important determinants of plant growth such as temperature, soil fertility, plant density etc. Precipitation alone is insufficient to indicate the amount of water available to plants, as the effect of a given precipitation is determined by the ambient temperature and other factors affecting evaporation and transpiration (Tuhkanen 1980) and by a diversity of complex soil water relations.

Seasonal variation of primary production is one of the most striking characteristics of savannas, the most extreme seasonality in primary production being found in the most arid savannas, with seasonal changes in production being far less pronounced in more humid savannas (Lamotte & Bourlière 1983).

Phenological patterns also differ between mesic and arid savannas. In mesic areas, the rainfall is relatively predictable. Arid areas on the other hand, have a much less predictable and more variable rainfall so plants are more opportunistic, responding closely to rainfall events (Teague & Smit 1992). No information on the phenological stages of the grasses of the KNP however exists.

Dye (1983) found a poor correlation ($r^2 = 0.54$) between peak grass shoot yield and rainfall, and great changes in species composition over a 16-year period. He ascribes these to a lower soil-water holding capacity due to large quantities of gravel in a shallow soil profile, year-to-year variation in storm sizes, storm distribution through the season and varying evaporative conditions. When the relations between peak shoot yields, transpiration, soil evaporation and deep drainage were investigated, the correlation improved greatly ($r^2 = 0.91$).

The erratic nature of rainfall in the semi-arid savannas of southern Africa results in large and unpredictable fluctuations in basal cover, botanical composition and production, especially in the herbaceous layer (Barnes & McNeill 1978; Snyman *et al.* 1987; and Snyman & Fouché 1991).

The importance of annual carry over of soil moisture is suggested by the results of the Towoomba fertilizer trial in which the control treatment showed a significant correlation between annual rainfall and yield ($r = 0.532$; $P = 0.01$; 28 d.f.). This correlation became more significant when the rainfall of the preceding year was included in the analysis (Donaldson *et al.* 1984).

Using multiple regression, Barnes *et al.* (1991) found that the water content of the whole soil profile, N content of the roots, extractable Ca of the topsoil, H^+ concentration in the topsoil and clay content of the topsoil together accounted for 77.3% of the variation in dry matter yield. Water content of the soil profile on its own accounted for 47.3%. Yields increased slightly with an increased subsoil acidity. No correlation between soil depth and yield was found.

Little information could be found on evapotranspiration under southern African conditions, other than the work undertaken in the Free State (Snyman *et al.* 1980; Snyman & van Rensberg 1986; Snyman 1988, 1989, 1991; Snyman & Fouché 1991; Snyman 1993; Snyman & Fouché 1993; Snyman 1998; 1999).

The soil water balance of savannas is strongly influenced by evapotranspiration (Nix 1983; Cole 1986) as well as evaporation from the soil surface, and water intercepted by the plant canopy and litter layer (Scholes & Walker 1993). Total potential evapotranspiration exceeds the annual rainfall in many savanna areas, with a seasonal water deficit being a characteristic feature of savannas, its severity varying with the length and intensity of the dry period and with edaphic conditions (Cole 1986).

In the False Thornveld of the Eastern Cape, Stuart-Hill & Tainton (1989) found that removal of all vegetation had the greatest effect on soil moisture, increasing it by around 200%. Grass removal had the next most significant effect (100% increase), and the removal of woody plants the least effect (<20%). Although it cannot be generalised from this single study, this indicates that the grass (or surface) vegetation stratum has the greatest consumptive effect on the soil moisture balance.

In southern Africa, an estimated 91-96% of mean annual precipitation is returned to the atmosphere by evaporative losses. In arid and semi-arid rangelands evapotranspiration is a major component of the soil water balance (Schulze 1997; Snyman 1998). The accurate estimation of potential evapotranspiration is thus particularly important (Schulze 1997). The efficiency with which a limited moisture supply is used by plants is dependent on (i) the degree to which surface runoff is minimised and (ii) the transpiration ratio of the veld plants (Opperman & Roberts 1975).

Tinley (1982) identifies the presence or absence of a pan horizon, its distance from the surface and soil permeability to rain (which is a function of texture and relief), as the most important combination of factors governing soil moisture content and thus the spatial distribution of woody cover and grasslands in savannas. The surface texture of soils determines the level of moisture recharge and the amount of water remaining in the soil after rain and subsequent evaporation, and this is far more important that the amount of rain (Tinley 1982). By implication, then, these soil properties also have a strong influence on grass production and composition, be it direct or *via* tree/grass competition.

For similar reasons, but at the other end of the scale, Tinley (1982) states that an excess of soil moisture on a perennial or seasonal basis is a major factor determining the presence of open grasslands. It is not only excessive waterlogging during the growing period (rain season), but also excessive drying out of the soils in the dry season, that kills back any woody plant root development.

He states further that the presence of pan soil horizons in certain situations such as vleis allows for a much longer period of plant growth; in contrast to deep sand areas and soils with a pan horizon close to the surface, or on saline areas. Here, the productivity of shallow-rooted grasslands is totally reliant on amount, distribution and the interval between rains (Tinley 1982).

An interaction between rain and soil nutrients exists, with soil texture and nutrient properties influencing grass production. Texture influences soil water dynamics and availability, the leaching or concentration of nutrients, and the ability of plants to absorb these. High rainfall is generally associated with highly-leached soils. This results in a gradient from arid/eutrophic to mesic/dystrophic savannas (Huntley 1982).

For a given value of rainfall, and a given species of plant, the yield can vary considerably with the structure and nutrient content of the soil. When enough water is available, soil quality becomes a major variable; it depends not only on the nature of the parent material but also on other factors such as leaching and erosion (Lamotte & Bourlière 1983).

Evidence presented by Dye & Spear (1982) suggests that coarse-textured sandy soils allow for a greater infiltration and deeper percolation of rainwater than heavier-textured soils, with a consequent increased moisture storage in the subsoil of the sandveld. Fine-textured soils (high in clay content) are much more xeric. In such soils, water is limiting for much of the year. With the same climatic conditions on sandy soils, moisture is much less limiting to plants (Teague & Smit 1992); these differences being important to productivity (Dye & Spear 1982; O'Connor 1985). The higher fertility on heavier soils results in much greater yields in wet years (Dye & Spear 1982; Frost *et al.* 1985). The result is that in relation to the same fluctuations in rainfall, production on clay soils is much more variable than on sandy soil (Frost *et al.* 1985).

As rainfall and the length of the wet season increase, water becomes less limiting and other factors such as low nutrient availability begin to limit production (Frost *et al.* 1985; Scholes 1990; O'Connor & Bredenkamp 1997).

Grasses growing on inherently fertile soil for example, are much more productive than those growing on infertile soils. The effects are more pronounced when water is not limiting. Improved soil fertility increases the use of water by vegetation and improves water-use efficiencies, thus contributing to higher production. The available soil moisture is however used up more rapidly, thereby shortening the period for active growth and increasing the risk of physiological drought (Frost *et al.* 1985).

The level of production is strongly influenced by the relative availability of nitrogen and phosphorus, though the additions of either of these on their own do not result in significant increases in production, unless the other nutrient is already present in excess. When nitrogen and phosphorus are added simultaneously, however, there is a massive increase in production, particularly of grasses (Mott *et al.* 1985, cited by Frost *et al.* 1985).

Veld condition (composition) also plays an important role in grass production. Snyman & Fouché (1993) report that seventy-eight percent of the variation in above-ground phytomass production may be attributed to the interaction between effects of rainfall and veld condition, with veld in different conditions reacting differently to different amounts of rainfall. In terms of herbage production, the response to increasing rainfall is relatively greater in the case of good condition than with poor condition. The low production of veld in poor condition results in poor utilization of rainfall (Snyman 1991; Snyman & Fouché 1993).

1.3.2.2. **Biotic factors**

Fire and herbivores are the two most important secondary determinants modifying the influences of climate and edaphic factors (Tinley 1982). Protection from fire results in a decrease in grass production and an increase in tree density (Teague & Smit 1992). Ellis & Swift (1988) state that the assumption has been made that herbivores play a major role in the controlling plant biomass through consumption. Using ecosystem-wide estimates of forage production and livestock consumption, they calculated that total offtake in the Turkana region of northern Kenya by livestock is in the order of 10-20% of forage production during a 'good' year. They conclude, in the context of this relatively unconstrained system, that it seems unlikely that livestock exert a major control on plant biomass.

The effect of fire on herbaceous production depends on both the time of burning and on soil moisture availability. Webber (1979) found that on duplex soils of granitic origin in the KNP, increased frequency of burning dramatically decreased soil moisture. In high rainfall areas, fire tends to increase grass production with a short dry season, but in drier areas, production is generally reduced relative to the neighbouring unburnt areas (San José & Medina 1975, cited by Frost *et al.* 1985).

The season of burn has an important bearing on the outcome. Early dry-season fires induce grasses to flush at a time when soil moisture levels are already declining. This re-growth rapidly depletes the remaining soil moisture and the tillers do not survive. The potential stimulus to production is thus not sustained. Growth at the start of the following wet season is initiated simultaneously in both burnt and unburnt plants. Burning at or soon after the first rains generally has the same outcome except where growth in unburnt plants is limited by an accumulation of standing dead matter (Frost *et al.* 1985).

In contrast, defoliation by fire during the latter part of the dry season results in equilibration of plant and soil water potentials, allowing plants to grow. Provided that the soil moisture store is replenished by early wet-season rains before it is again depleted by the grasses, this early start to the growing season results in a higher production by burnt plants (San José & Medina 1975, cited by Frost *et al.* 1985). Depending on the amount of herbivory, the dry season standing crop of grass on regularly burnt areas can be higher than on unburnt plots. This increases the probability of fire, setting up a positive feedback loop that serves to maintain a high fire frequency and high grass production (Frost *et al.* 1985).

Production directly under the canopy of woody plants may be suppressed (Barnes 1982) or enhanced (Bosch & van Wyk 1970). Smit & Swart (1994) however found that given an equal amount of rainfall, potential tree competitiveness was the most important determinant of grass yield on five plots on sandy soil thinned to different tree densities in Mixed Bushveld.

1.3.3. FACTORS INFLUENCING GRASS COMPOSITION

1.3.3.1. **The combined effects of abiotic and biotic factors**

In various studies undertaken in the less mesic areas of southern Africa a considerable amount of evidence has emerged that rainfall generally is the primary or overriding determinant of grass composition, with other factors having modifying or synergistic effects.

O'Connor (1985; 1991) suggests that for the savanna grasslands of southern Africa, rainfall, as affected by soil type and the grass/woody ratio, is the controlling force on compositional changes, with drought having an overriding effect on community change and grazing being a modifying force. The decrease of perennial grasses and an increase of annual grasses and both annual and perennial forbs is characteristic of semi-arid savannas in southern Africa in response to drought events or sustained heavy grazing pressure. He states further that there is no evidence that rainfall patterns alone have caused major change in any system. All species eliminations which have occurred due to drought have been of a temporary nature (O'Connor 1985).

Kennedy *et al.* (2002) found that in the KNP, areas with a low grass species richness were more resistant to drought than those with a high species richness. Species-poor sites also showed a better recovery from perturbation after the drought had passed, suggesting that ecosystem stability may be negatively related to grass species richness, at least in South African savanna.

The processes of change are described by O'Connor (1985) as a continued run of wet and dry years which generate a continued, if small, cumulative change in the composition of the sward. Cumulative compositional changes are overridden by the influence of a singular dry or wet year. These patterns of change are most pronounced at the drier end of the savanna spectrum. In marginal semi-arid areas, the existence, let alone the composition, of the perennial component is directly dependent on the mean annual rainfall.

MacDonald (1982; cited by O'Connor 1985) has a similar explanation of these processes, stating that during a period of below-average rainfall, bare patches develop as a result of mortality of perennial tufts. In the first high-rainfall season following such a dry period, the bare parches are invaded by annual grasses and forbs, as well as pioneer perennial grasses adapted to bare ground. In subsequent seasons of above average or average rainfall the proportion of forbs and annual grasses decrease as perennials assume dominance. O'Connor (1985) feels that MacDonald's explanation is applicable principally to heavy textured soils of mesic savannas, with annual grasses always constituting a major component of the sward in semi-arid regions. In contrast, neither annual grasses nor forbs are recorded as major components of the mesic sandveld areas (O'Connor 1985).

Mentis *et al.* (1989) are of the opinion that moisture and nutrients available to plants are the primary determinants of the plant species composition and production; with herbivory and fire being secondary determinants. These authors state further that most local methods of assessing veld condition arose from succession theory. Arid and semi-arid rangelands however display large spatio-temporal switches in herbaceous species composition and production that are not consistent with simple successional pathways. The fluctuations are associated with episodic events (such as rainfall, herbivory and fire) which themselves vary greatly in space and time. Moisture-limited rangelands in particular might be viewed as event-driven systems.

On the Adelaide Experimental Station in the Eastern Cape, Danckwerts & Stuart-Hill (1988) found that extensive grass mortality occurred during the 1982/83 drought, with post-drought recovery being particularly sensitive to the management treatment applied. Veld that was grazed immediately after the drought recovered at a slower rate than veld that was rested.

In the central Free State, Snyman & van Rensburg (1990) found that Increaser II grasses are better able to survive drought than Decreasers are as the latter have a higher water requirement than Increaser II's. Similar results are reported by O'Connor (1995). Working in a sandveld savanna area of the Lowveld, he found that severe drought in combination with a history of severe grazing transformed grassland of predominantly palatable, perennial grasses to grassland dominated by unpalatable perennial and annual grasses and forbs. The most lightly grazed grassland maintained its character of palatable, perennial grass species but was changed considerably in the relative proportion of these species. After the drought, tuft size of palatable species was smaller than any previously recorded but recovered thereafter (O'Connor 1995). He states that change in community structure in response to grazing occurs both with the onset of drought and during post-drought seasons, due to the influence of grazing on mortality of established tufts and on seedling recruitment.

O'Connor came to the conclusion that grazing management during drought episodes appears to be critical for determining the direction of community change. The notion that savanna grasslands are insensitive to grazing because of their disequilibrium behaviour without any effect of grazing was rejected. Peel *et al.* (1991) found that rainfall of the preceding season and selective grazer stocking rates has a significant effect on veld condition. In mesic savanna, van Rooyen *et al.* (1993) found that the herbaceous vegetation on sandy soil is relatively stable and shows cyclic patterns of floristic and basal cover changes due to fluctuations in rainfall and in reaction to fire.

In the continuous verses fixed season rotational grazing trial at Towoomba, it was concluded by Donaldson & Rootman (1983) that variability and trends in species composition were largely influenced by rainfall variability, in addition to the differential effects of grazing treatments.

After undertaking an analysis of 50 grazing experiments conducted in southern Africa, O'Reagain & Turner (1992) came to the conclusion that stocking rate has a major impact on veld condition in both humid and semi-arid areas. They state further that generally, while veld condition is maintained or improved under conservative stocking, overstocking causes severe veld degradation. Total basal cover and and the abundance of palatable species declines while the proportion of unpalatable perennials, annuals and forbs increase substantially.

In arid Mopani Veld, (O'Connor 1998) reports that perennial grasses of sandveld have consistently shown a tendency to disappear during years of drought and re-appear during runs of wet years. The extent of dieback of perennial grasses, which differ in their susceptibility to drought, apparently depends on the type of substrate.

Smit & Rethman (1999) undertook thinning trials in Mopani Veld. They found that although colonization of bare ground by herbaceous plants increased with increased levels of tree thinning, perennial grasses showed a general lack of successional trends due to the arid nature of the area. Moreover, prior to thinning of the woody layer, perennial grasses were not dominant and occurred at a very low frequency. Annual grasses were the main colonizers, with perennial grasses only constituting a small proportion of the grass species composition. They consider it unlikely that that succession will proceed to the point where perennial grasses will again become dominant.

Soil type seems to have a pronounced influence on the patterns of compositional change. The distribution of arid and moist savannas is closely related to the base status of the soil types in southern Africa. Generally, arid savannas occupy calcareous and eutrophic, non-calcareous soils, while moist savannas occur on dystrophic and some mesotrophic, non-calcareous soils. Calcretes are common in arid savanna while laterites occur over much of the area occupied by moist savannas on fersiallitic and ferralitic soils (Huntley 1982).

Plant species composition in the various vegetation types of southern Africa is influenced by soil properties such as nutrient status, pH, salinity and texture (Cole 1982; Tinley 1982; Scholes 1990). Their structure and function are also highly influenced by nutrient availability, especially nitrogen and phosphorus (Scholes 1990).

Trends are accentuated on heavier textured than sandier soils, but this is dependent on the general climatic regime. Although different perennial species at any one locality respond very differently to a given pattern of rainfall change, the response of an individual species to a specified climatic regime is also dependent on soil type (O'Connor 1985).

These differences in soil are important to vegetation structure and species composition (Dye & Spear 1982; O'Connor 1985). The herbaceous vegetation on heavier soils shows greater sensitivity to the availability of soil moisture and greater changes in species composition during droughts (Dye & Spear 1982).

In attempting to understand the factors and processes controlling grass sward composition, the view of O'Reagain & Turner (1992) that there appears to be a threshold stocking rate above which veld degradation occurs, is of major significance. They cite a study in semi-arid savanna where vegetal cover remained constant at stocking rates of less that "1 beast 6 ha^{-1}" but declined sharply above this level. This may partly explain the controversy surrounding the response of the Decreaser and Increaser groups to grazing on the one hand, and their environment on the other, suggesting that the response of grasses to these variables is possibly non-linear.

1.3.4. VELD CONDITION ASSESSMENT USING THE DECREASER-INCREASER CLASSIFICATION

The Decreaser-Increaser classification of grasses (Vorster 1982; Tainton 1988; Trollope *et al.*1990) has been widely applied in South and southern Africa, particularly in agricultural areas to evaluate veld condition (e.g. Vorster 1982; Danckwerts & Stuart-Hill 1988; Friedel 1988; Tainton 1988; Snyman & Grossman 1990; Trollope 1990; van Rooyen *et al.* 1991; Nel *et al.* 1993; van der Westhuizen *et al.* 1999 and Cauldwell *et al.* 1999).

In the past decade, increasing criticism of the technique has been expressed, for example by Mentis (1983), Barnes *et al.* (1984), Janse van Rensberg & Bosch (1990); van Rooyen *et al.* (1991) and Bosch & Theunissen (1992).

Bosch & Janse van Rensburg (1987) and Janse van Rensberg & Bosch (1990) found that the same species often react differently to grazing in different topographic localities as well as between sub-habitats of the same topographic unit. This can be due to ecotype variation. They conclude that broad standardized grouping of species in ecological groups, i.e. Decreasers and Increasers, is scientifically wrong and of little practical value.

van Rooyen *et al.* (1991) state that the grazing history of a plot in a large conservation area is difficult to quantify, an essential requirement for the correct interpretation of survey results in which this classification is used. A non-linear relation between response and the grazing gradient is evident for the majority of grasses classified according to this system (Janse van Rensburg & Bosch 1990; van Rooyen 1991; Bosch & Theunissen 1992; Cauldwell *et al.* (1999).

These two factors in combination therefore make it practically impossible for the manager of an extensive area to accurately assess the causes of the trends in composition, to make the correct deductions, and to take the correct action where this is necessary.

Bosch & Theunissen (1992) undertook a principal components analysis of *Themeda triandra, Eragrostis racemosa and Digitaria eriantha* using morphological, epidermal and chemical characteristics, and dry mass production. Specimens were collected along a moisture gradient at five predetermined locations and in three different habitats, namely shallow soil, relatively deep soil and a watercourse.

Their study clearly showed that distinct morphological, epidermal and chemical compositional differences exist between different habitat groups within the three species. and concluded that the same species often react differently to grazing in different topographic positions, as well as between habitats of the same topographic unit and apart from habitat differences, the above phenomena can possibly be attributed to ecotypic variation.

Bosch & Theunissen (1992) suggest that, without altering their taxonomic classification, ecotypes within a particular species should be included in a functional, special-purpose classification system in order to facilitate the interpretation and understanding of plant community dynamics by rangeland scientists and managers.

Snyman & Grossman (1990) found that during a wet period, Increaser II species increase relatively faster than do species of other ecological classes. This effect results in lower veld condition scores in wet periods even if the increase in Increasers is not accompanied by a decrease in Decreasers. They state further that according to the Dyksterhuis-related classification (Dyksterhuis 1949), species are classified according to their response to grazing, while in fact the greater response is to rainfall.

Similar findings are reported by van der Westhuizen *et al.* (1999), namely that seasonal rainfall apparently plays a noticeable role as a determinant of the variation on the degradation gradient, with habitat differences, especially soil differences, also playing a role.

No publication was found which has the objective of determining the factors (determinants) important in grass production and composition in an African savanna by following a multi-facetted, integrative approach to synthesize available data into a single or a few models. The most likely reason for this is that inadequate data (both in terms of quantity, appropriate diversity and time frame) to attempt this are available, particularly at the scale of the KNP.

Though limited in its scope, the work of Barnes *et al.* (1991) is a step in this direction. Teague & Smit (1992) provide a very valuable synthesis of a diversity of studies dealing with savanna dynamics and determinants. These however are unrelated or integrated by means of mathematical models. These authors in fact make a strong plea for the development of such modelling frameworks within decision-support frameworks in order to enhance problem-solving by managers.

Dealing with the matter in an agricultural context, they state that " ... scientists almost invariably direct research effort at an hierarchical level below that which they are working" and do so "to develop understanding at the level at which they are working. This is a major part of the problem of not relating research to the ranch business level. Very few instances exist in southern Africa of scientists synthesizing material at higher levels in the hierarchy, in particular at the ranch level. Simulation modelling provides a medium for incorporating component models to address questions at these higher levels of integration".

1.4. HYPOTHESES AND OBJECTIVES

1.4.1. HYPOTHESES

Based on the foregoing discussions, several hypotheses can be formulated.

1 *Nett primary production in the KNP is influenced primarily by the rainfall and soil properties, with composition, grazing and fire playing secondary roles.*

This is the primary hypothesis that needs to be tested.

Soil moisture is the fundamental factor influencing grass growth, with soil properties such as texture, fertility and effective depth playing modifying roles. Secondary determinants are woody plant competition, with grazer pressure and woody competition having modifying effects.

2 *A closer correlation can be expected to exist between evapotranspiration and phytomass production, than between total annual rainfall and phytomass production. Evapotranspiration can therefore be expected to be a better predictor of production than rainfall.*

Maximum yield of most agricultural crops is related to conditions where the water supply for transpiration needs is unrestricted. Inadequate soil moisture is therefore regarded as being the most important factor limiting dry-matter production in semi-arid grassveld. The measure, ET_c, records water loss from the plant (and from the soil via the plant) and is thus an important factor in the water balance equation. The use of ET_c is a better indicator of soil moisture dynamics than is total rainfall received during a period e.g. the growing season.

In terms of rainfall only, properties such as the temporal distribution of rainfall during the growth period probably plays a more significant role than the total received during the growth period or year. Briefly, this is because of the temporal spacing and quantity of rainfall, the total of which can be high in a given period, but may have occurred primarily at the beginning or towards the end of the season, with relatively long rainless periods in between. Even though the total amount may be relatively high, this type of temporal distribution is not as effective in phytomass production than a lower amount but spread more evenly during the growing season would be.

3 *Soil moisture and other soil properties, rather than grazer pressure, play dominant roles in determining grass composition, be it in terms of perennials or Decreasers.*

This is because perennials have a lower tolerance of decreased soil moisture than annuals have. Grazing pressure however has a modifying influence on botanical composition, in all likelihood accelerating the decline of perennial grasses under low-rainfall conditions and at the same time enhancing conditions for an increase in annuals, including forbs.

1.4.2. OBJECTIVES

In accordance with the above hypotheses, the objectives of this study are to:

1. Determine which variables are the primary determinants of nett primary production and nett standing crop.
2. Determine which variables are the primary determinants of composition (in terms of perennials and Decreasers).
3. Determine whether it is possible to derive mathematical equations to be able to predict nett primary production, nett standing crop and composition (perennials or Decreasers).

4. Determine whether a simple, easily-applicable model can be developed for use by managers in order to enable them to derive estimations of nett production and nett standing crop for management purposes.
5. Evaluate the calibration of the disc pasture meter and re-calibrate it if this proves necessary.

In order to meet these objectives, a number of essential processes entailing the acquisition and preparation of data had to be undertaken. Because each required a substantial amount of time and effort to be allocated to them, they are regarded as sub-objectives and warrant separate listing here. Details are given in Chapter 3.

1.4.2.1. **Rainfall**

- Calculate rainday statistics for each monitoring point and interpolate by GIS in order to derive values for each VCA site.
- Calculate mean monthly and annual rainfall totals for use in other calculations, and mapping of annual and other rainfall statistics.
- Calculate moisture indices for monitoring stations according to the procedures of Rutherford & Westfall (1986).

1.4.2.2. **Other daily weather parameters**

- Develop procedures for estimates of wind speed and hours of sunshine for stations where these parameters are not recorded, and 'patching' of missing rainfall and temperature data.
- Compile databases of daily weather parameters for 13 weather stations for an 11-year period.
- Calculate daily ET_0 and ET_c values for 13 weather stations for an 11-year period.

1.4.2.3. **Soils**

- For each VCA site used in this study, do fieldwork to collect soil samples, determine thickness of the A horizon and effective depth and determine size and density of woody plants.

- Determine soil texture class & pH and obtain data on nutrient content and other properties.

1.4.2.4. **Herbivores**

- Classify grazers according to the Collinson & Goodman (1982) categories.
- Determine annual concentrations around VCA sites by GIS (Geographic Information System) analyses using annual aerial survey data.

1.4.2.5. **Permanent drinking water**

- Determine distance from each VCA site to nearest permanent water-point by GIS

1.4.2.6. **Fire**

From the fire database, extract information on burn dates and fire effectiveness, and calculate burning frequencies and time since last burn for each VCA site.

CHAPTER 2
THE STUDY AREA

2.1. LOCALITY

The Kruger National Park is situated in the South African Lowveld and straddles the Mpumalanga and Limpopo provinces. Measuring approximately 350 km north to south and 65 km east to west, it extends over a surface area of 1 948 528 ha and is thus one of the largest national parks in the world.

The Lowveld consists mainly of plains with low to moderate relief and has a gentle slope to the east, on average, being some 300 m above sea level. Venter (1990) has identified five major landform types, namely plains with low relief, slightly undulating plains, moderately undulating plains, extremely irregular plains, and low mountains and hills.

2.2. GEOLOGY

Venter (1990) gives a detailed description of the geology of the KNP. In essence, it comprises a diverse assemblage of igneous, sedimentary and metamorphic rocks. This diversity of parent materials is reflected by an equally large diversity in soils, vegetation, and fauna (Venter 1990). Venter lists 21 major geological sub-units and 43 dominant rock types. Basaltic and granitic derivatives are the largest, extending over 29.4% and 39.2% respectively (almost 70% of the KNP). Because of their predominance, this study was concentrated on these formations only.

2.3. SOILS

In broad terms, the distribution of arid and moist savannas is closely related to the base status of the major soil types; arid savanna generally occurring on calcareous and eutrophic non-calcareous soils, while moist savannas occur on dystrophic and some mesotrophic non-calcareous soils (Huntley 1982, Venter 1990).

Venter (1990) gives a detailed description of the soils occurring on the different geological formations. Except for the mountainous areas in the south-western corner and the intensely dissected area along the Olifants river, soils underlain by granite/gneiss are characterized by a very distinctive catenary sequence of soils from crests to valley bottoms: Sandy-hydromorphic-duplex-alluvial. Although this general pattern is found throughout the area, Venter recognizes three major soil zones on granitoid formations, based on differences related to annual rainfall:

In areas with a rainfall range of 600-750 mm, crests consist of deep eutrophic sand, with deep yellow and grey coarse sand on the midslopes. Footslopes are characterized by duplex soils with both gley and primacutanic B horizons.

Areas with a rainfall of 500-600 mm, have crests which are characterized by moderately deep red and yellow eutrophic coarse sand, with moderately deep to shallow yellow and grey coarse sand on the midslopes. Footslopes comprise duplex soils with prismacutanic B horizons.

Areas with less than 500 mm of rainfall have shallow red and yellow eutrophic coarse sand on the crests, shallow yellow grey coarse sand on the midslopes, and duplex soils with prismacutanic B horizons on the foorslopes. Over the entire rainfall range, valley bottoms consist of a complex association of alluvial soils.

The basalt formation (basic igneous rocks) consists primarily of Letaba and Sabie river basalts. On the northern basaltic plains, the Letaba basalt is rich in olivine (picrite) and has formed large areas of shallow to deep black melanic and vertic clay soils which generally contain an excessive amount of calcium carbonate. In some areas, cementation has formed continuous layers of hardpan calcrete in the subsoil (Venter 1990).

In the central district, soils of the Sabie river formation contain less olivine and more quartz than the picrite, producing red structured and pedocutanic sandy clays and clays, which are seldom calcareous (Venter 1990).

Soil texture of the veld condition assessment sites used in this study was determined as described in Chapter 3, section 3.2.1. The number of sites in each texture class on basalt and granite are shown in Table 2.1. Not unexpectedly, this shows that the distribution of sites on basalt is strongly negatively skewed, with a majority of sites having a high to very high clay content. Sites on granite on the other hand are strongly positively skewed, with a low to very low clay content. Typical clay content is according to Schulze (1995).

Table 2.1. Percent of study sites of a particular soil texture class on basalt and granite

	SOIL TEXTURE CLASS (Typical % clay content underneath)							
GEOLOGY	LMSA	SALM	LM	SACLLM	CLLM	SICLLM	SACL	SICL
	7	10	18	27	32	33	40	50
BASALT	0	1.2	2.2	7.2	8.5	10.	21.2	49.7
GRANITE	39.2	36.9	0	6.7	5.4	0	11.8	0

2.4. CLIMATE

The locality of weather and rainfall monitoring stations, and other places discussed in this dissertation, are shown in Figure 2.1.

As in many other areas, climate plays a major role in the bio-ecological composition, structure and functioning of the KNP ecosystem. Herbivores and fire, sometimes erroneously regarded as drivers of the KNP's ecosystem, are in fact *modifiers*, whereas climate, via two of its constituents, namely energy and moisture, can be regarded as being a *driver* of the KNP's ecosystem. Energy in the form of solar radiation, occurs in abundance; even during winter. Moisture however, is a key element, and its presence or absence, as well as its abundance or scarcity, has many profound and complex effects on the entire ecosystem.

The Lowveld's climate is related to the regional climate of the sub-continent as a whole, in that it is influenced by anti-cyclonic systems which move over southern Africa from west to east in a semi-rhythmical manner (Venter 1990), particularly in the northern areas of the KNP. Over the southern part of the KNP sub-Antarctic systems sweeping over the Indian Ocean then swinging inland seem to have a greater influence.

During summer months, the presence of anti-cyclonic conditions (related to the sub-tropical high-pressure belt) in the north-eastern interior of the country, give rise to very hot and dry conditions over the Lowveld, often persisting for two weeks at a time (Venter 1990). These conditions are normally followed by the development of cyclonic (low pressure) conditions

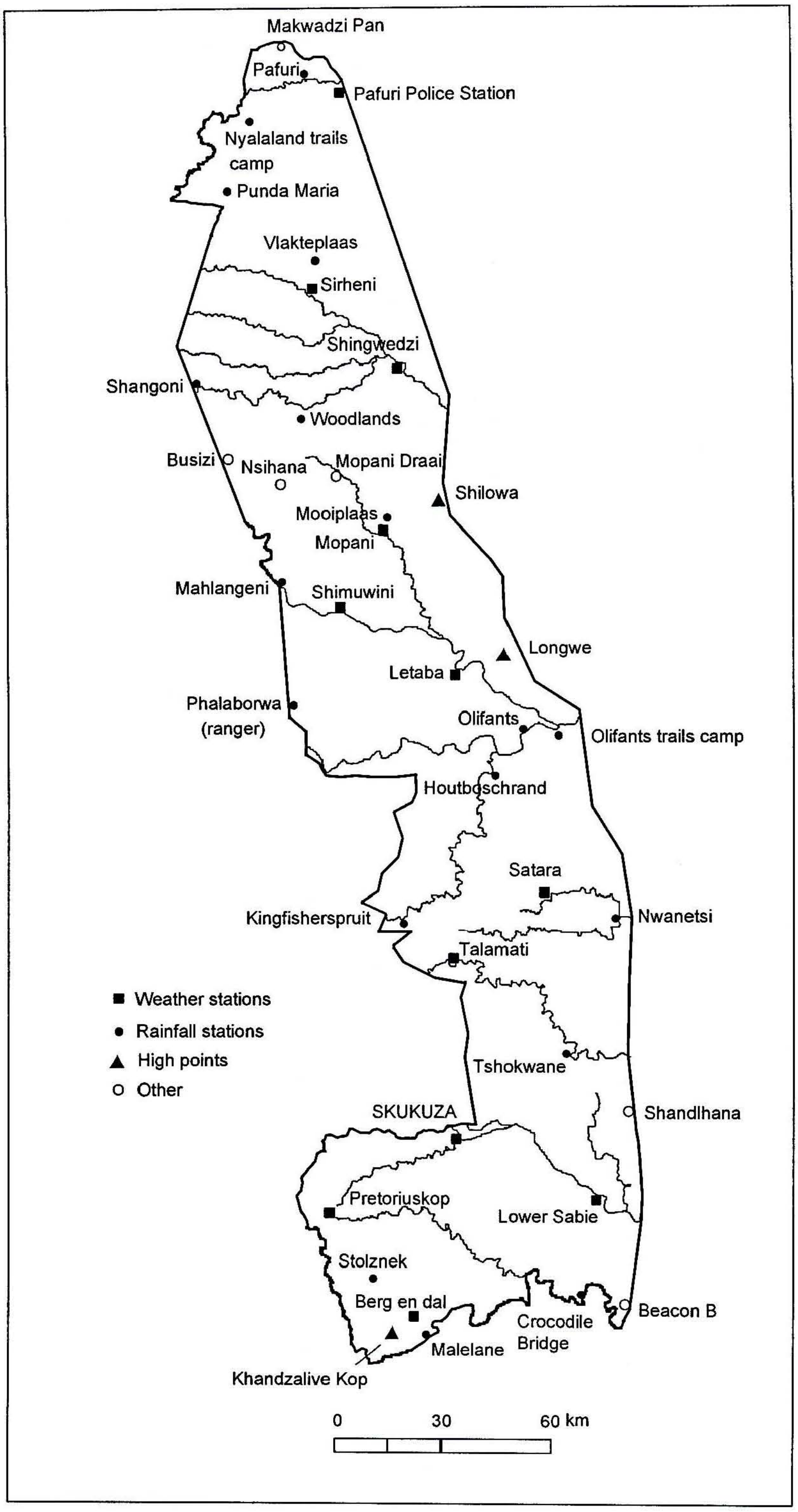

Figure 2.1. Localities of weather and rainfall monitoring stations, and other places discussed in the text.

over the interior, resulting in an influx of warm, moist air from the north and north-east, and the subsequent development of thunderstorms. The development of an equatorial low-pressure trough over the sub-continent normally gives rise to extensive and continuous rain over the Lowveld, seldom characterized by thunder (Schulze 1965; Venter 1990). Tropical cyclones occasionally enter the Lowveld during the late summer months from the Indian Ocean, often causing flooding and widespread damage (Venter 1990).

Winter is generally characterized by fine and relatively mild conditions over the Lowveld, with only a few localities experiencing minimum temperatures of below 0°C, this in fact being a rare occasion when it happens.

2.4.1. RAINFALL

Because of its importance in this study, the rainfall of the KNP is discussed in some detail. Records show that rainfall has been recorded during all months. Most of it however occurs during the summer months, on average, approximately 78.5% of the season's total occurring between November and March (Table 2.2). Summary statistics of annual rainfall are given in Table 2.3.

Mean annual rainfall (MAR) of the KNP as a whole is 537.4 mm. It is a well-known phenomenon though, that a 'two-way' gradient in MAR exists. This ranges from a mean of 466 mm at Pafuri in the far north, to 737 mm at Pretoriuskop in the south-west. An east-west gradient is also evident, particularly in the southern half of the KNP.

The rainfall extremes unfortunately occur in unmonitored areas - the Limpopo River valley in the extreme far north (with an estimated MAR of 350 mm), and on Khandzalive Kop in the south-western corner (with an estimated MAR of 950 mm). The coefficient of variation is equally great, ranging from 30% in the wetter south to 55-60% in the drier north. Seasonal concentration of rainfall varies in temporal extent from a relatively short period in the north to a longer period in the south.

Another well-known phenomenon about the rainfall of the KNP is that it fluctuates between periods (cycles) of generally above-average rainfall, to periods of below-average rainfall (Figure 2.2).

The rainfall categories are defined as follows:

Abundant rain:	>25% above the long-term mean
Above average:	>0 to 25% above the long-term mean
Below average:	>0 to 25% below the long-term mean
Drought:	>25% below the long-term mean

The graph showing these cyclic trends in MAR (extending over a 92-year period) was produced by applying a simple moving average procedure using a three-year term (Manugistics 1995). The number of stations' data used to produce Figure 2.2 is given at the bottom of the figure just above the X axis under the heading 'Number of stations with complete data'. For years without a figure, the last number to the left is the number of stations. The decrease in the number of stations in certain years does not always imply that the number of monitoring stations decreased but rather, it is a reflection of the number of stations with a complete rainfall record which were used to determine that particular year's average. Incomplete data are primarily due to periods of no observations being made during part of a year, obviously resulting in the entire year's total being incomplete.

It must also be noted that until 1918/19, only one monitoring station existed (Malelane town just outside the KNP) and the bars for the preceding period thus represent the rainfall trend of one station only. Rainfall records at Skukuza commenced in 1908 though until 1917/18, these are incomplete and were thus not used in the compilation of Figure 2.2. Several aspects in this figure are noteworthy and need to be pointed out:

Excluding the incomplete cycles at both ends of Figure 2.2 wet and dry cycles have an average duration of 10.25 years, ranging from eight to 14 years. It is interesting to note that in the 92-year period, 'abundant rain' occurred 15 times (on average, once every 6.13 years) and 'drought' 12 times (once in every 7.7 years); yet 'above average' rain occurred once in every 3.2 years and 'below average' rain, once every 2.6 years. There is thus a slight overall tendency towards below average and drought conditions (48 years total), whereas above average and abundant rain occurred during a total of 44 years.

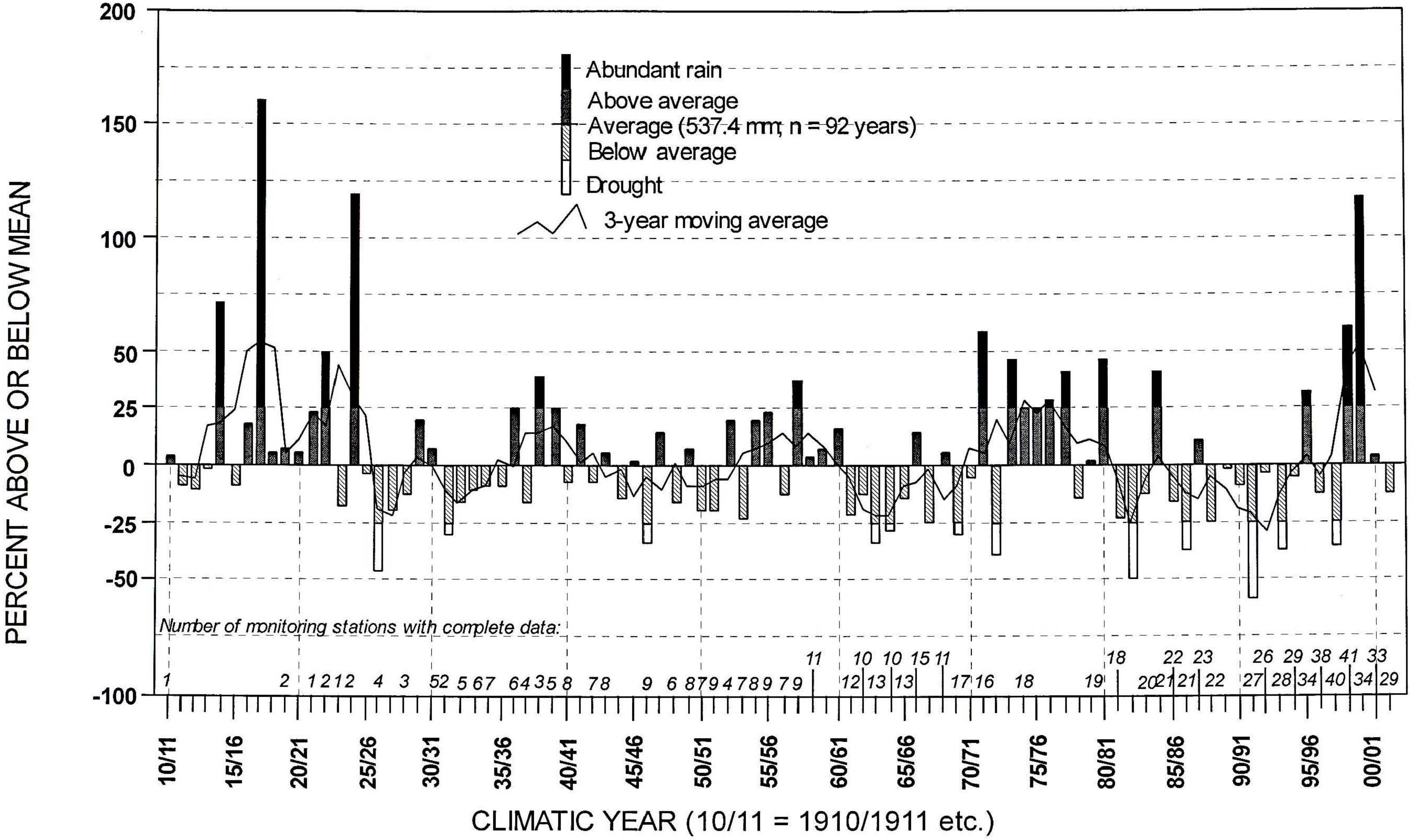

Figure 2.2. Annual rainfall deviations from the long-term mean annual total since 1910/11.

Table 2.2. Mean monthly rainfall totals of monitoring stations 15 years and older. Figures in parentheses are the number of years of observations. Figures in italics are the mean percentages of the mean annual total for that month

MONITORING STATION	**MEAN MONTHLY RAINFALL (mm)**												**ANNUAL**	
	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	MEAN	MEDIAN
Crocodile Bridge (55)	9.7	9.1	24.4	45.8	84.3	90.6	115.6	107.9	70.3	39.7	14.7	7.9	620.0	607.0
	1.6	*1.5*	*3.9*	*7.4*	*13.6*	*14.6*	*18.6*	*17.4*	*11.3*	*6.4*	*2.4*	*1.3*		
Houtboschrand (19)	7.3	7.6	8.2	31.1	77.1	76.1	79.0	79.8	43.7	19.4	6.2	3.4	438.9	419.0
	1.7	*1.7*	*1.8*	*7.1*	*17.6*	*17.3*	*18.0*	*18.2*	*10.0*	*4.4*	*1.4*	*0.8*		
Kingfisherspruit (41)	8.0	7.7	20.1	39.4	77.5	98.0	89.2	114.1	62.4	38.7	10.0	6.7	571.8	566.5
	1.4	*1.3*	*3.4*	*6.9*	*13.6*	*17.2*	*15.6*	*20.0*	*10.9*	*6.8*	*1.7*	*1.2*		
Letaba (45)	6.5	5.9	14.8	31.0	67.2	86.9	85.1	77.2	42.1	26.5	9.8	3.7	456.7	453.0
	1.4	*1.3*	*3.2*	*6.8*	*14.7*	*19.0*	*18.6*	*17.0*	*9.2*	*5.8*	*2.2*	*0.8*		
Lower Sabie (33)	9.6	8.6	21.4	43.4	68.2	94.6	117.1	112.8	67.2	34.5	15.8	9.4	602.6	566.0
	1.6	*1.4*	*3.6*	*7.2*	*11.3*	*15.7*	*19.5*	*18.8*	*11.2*	*5.7*	*2.6*	*1.6*		
Mahlangeni (42)	6.1	5.5	14.0	33.9	61.3	86.2	74.4	95.6	46.9	23.1	12.3	3.4	462.7	465.0
	1.3	*1.2*	*3.0*	*7.3*	*13.3*	*18.6*	*16.0*	*20.7*	*10.1*	*5.0*	*2.7*	*0.8*		
Malelane (85)	7.5	8.4	21.8	50.7	91.3	93.6	112.2	104.5	85.3	39.2	17.5	7.3	639.3	589.0
	1.2	*1.3*	*3.4*	*7.9*	*14.3*	*14.6*	*17.6*	*16.4*	*13.3*	*6.1*	*2.8*	*1.1*		
Mooiplaas (28)	5.9	5.0	13.4	31.3	66.3	77.4	89.4	118.5	44.1	27.2	13.6	4.2	496.3	433.0
	1.2	*1.0*	*2.7*	*6.3*	*13.4*	*15.6*	*18.0*	*23.8*	*8.9*	*5.5*	*2.7*	*0.9*		
Nwanetsi (33)	6.9	9.0	21.5	37.9	62.5	97.8	99.0	98.8	62.4	26.5	12.8	6.3	541.4	538.0
	1.3	*1.7*	*4.0*	*7.0*	*11.5*	*18.0*	*18.3*	*18.2*	*11.5*	*4.9*	*2.4*	*1.2*		
Olifants (27)	7.4	6.8	13.2	34.7	79.4	89.7	88.9	94.7	44.2	22.6	12.5	2.4	496.5	471.0
	1.5	*1.4*	*2.7*	*7.0*	*16.0*	*18.1*	*17.8*	*19.0*	*8.9*	*4.6*	*2.5*	*0.5*		
Pafuri (18)	7.0	3.6	7.8	29.7	47.3	91.1	99.2	103.0	50.9	14.8	8.8	2.9	466.1	426.0
	1.5	*0.8*	*1.7*	*6.4*	*10.1*	*19.6*	*21.3*	*22.0*	*10.9*	*3.2*	*1.9*	*0.6*		
Pafuri Police Station (69)	2.5	3.9	11.6	20.3	56.9	79.7	82.1	87.2	46.1	20.6	8.2	4.5	423.6	406.0
	0.6	*0.9*	*2.7*	*4.9*	*13.4*	*18.8*	*19.3*	*20.6*	*10.9*	*4.9*	*1.9*	*1.1*		

Table 2.2. (continued)

MONITORING STATION	**MEAN MONTHLY RAINFALL (mm)**												**ANNUAL**	
	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	MEAN	MEDIAN
Phalaborwa (63)	8.5	5.1	14.2	31.5	72.0	86.9	86.7	90.2	58.9	28.8	10.4	7.1	500.3	470.0
	1.7	*1.0*	*2.8*	*6.3*	*14.4*	*17.4*	*17.3*	*18.0*	*11.8*	*5.8*	*2.1*	*1.4*		
Pretoriuskop (60)	9.7	12.4	28.3	55.0	100.4	118.5	129.4	111.1	92.3	52.0	19.0	9.1	737.2	681.0
	1.3	*1.7*	*3.8*	*7.5*	*13.6*	*16.1*	*17.5*	*15.1*	*12.5*	*7.1*	*2.6*	*1.2*		
Punda Maria (72)	4.9	4.2	12.9	28.6	68.2	91.5	111.8	100.7	59.1	32.8	9.7	6.2	530.6	471.0
	0.9	*0.8*	*2.4*	*5.4*	*12.9*	*17.2*	*21.1*	*19.0*	*11.1*	*6.2*	*1.8*	*1.2*		
Satara (54)	6.6	7.3	17.8	36.5	74.5	94.2	91.6	99.8	69.6	27.5	11.5	6.8	543.7	525.0
	1.2	*1.3*	*3.3*	*6.7*	*13.7*	*17.3*	*16.8*	*18.4*	*12.8*	*5.1*	*2.1*	*1.3*		
Shangoni (43)	7.2	3.9	16.5	36.6	70.6	94.0	103.4	113.3	57.6	26.1	13.1	5.9	548.2	524.0
	1.3	*0.7*	*3.0*	*6.7*	*12.9*	*17.1*	*18.8*	*20.7*	*10.5*	*4.8*	*2.4*	*1.1*		
Shingwedzi (40)	4.7	5.3	20.1	36.0	63.7	91.9	93.3	97.0	47.3	28.7	11.1	4.9	504.0	450.0
	0.9	*1.1*	*4.0*	*7.1*	*12.6*	*18.2*	*18.5*	*19.3*	*9.4*	*5.7*	*2.2*	*1.0*		
Skukuza (76)	9.3	6.8	23.9	35.1	74.7	85.5	95.6	92.0	71.6	34.5	13.5	7.9	550.4	524.5
	1.7	*1.2*	*4.3*	*6.4*	*13.6*	*15.5*	*17.4*	*16.7*	*13.0*	*6.3*	*2.5*	*1.4*		
Stolznek (20)	9.3	9.3	19.2	50.0	90.8	115.1	99.2	123.9	99.1	39.2	11.0	6.8	672.9	585.0
	1.4	*1.4*	*2.9*	*7.4*	*13.5*	*17.2*	*14.7*	*18.4*	*14.7*	*5.8*	*1.6*	*1.0*		
Tshokwane (60)	7.3	8.4	19.7	39.5	72.4	102.3	92.1	100.1	70.3	30.9	11.3	8.0	562.3	526.5
	1.3	*1.5*	*3.5*	*7.0*	*12.9*	*18.2*	*16.4*	*17.8*	*12.5*	*5.5*	*2.0*	*1.4*		
Vlakteplaas (18)	8.1	5.4	19.2	40.7	71.2	78.4	104.4	112.7	38.8	21.4	9.2	5.6	515.1	472.5
	1.6	*1.0*	*3.7*	*7.9*	*13.8*	*15.2*	*20.3*	*21.9*	*7.5*	*4.2*	*1.8*	*1.1*		
Woodlands (19)	7.9	5.1	15.0	30.9	79.8	87.9	80.5	97.5	30.0	25.9	10.2	8.2	478.9	391.0
	1.7	*1.1*	*3.1*	*6.5*	*16.7*	*18.3*	*16.8*	*20.3*	*6.3*	*5.4*	*2.1*	*1.7*		
Means for KNP (44.3)	7.3	6.7	17.3	36.9	72.9	91.7	96.5	101.4	59.1	29.6	11.8	6.0	537.2	520.5
	1.4	*1.2*	*3.2*	*6.9*	*13.6*	*17.1*	*18.0*	*18.8*	*11.0*	*5.5*	*2.2*	*1.1*		

Table 2.3. Summary statistics of annual rainfall up to and including the 2001/2002 climatic year

STATION	n	MEAN	MEDIAN	VARIANCE	STD DEV.	SE	MINIMUM	MAXIMUM	STD SKEW	STD KURT	CV
Crocodile Bridge	55	619.6	607.0	35170.50	187.50	25.24	317	1224	2.521	1.745	30.270
Houtboschrand	19	439.0	419.0	34508.11	185.76	42.62	190	818	1.133	-0.533	42.315
Kingfisherspruit	42	565.8	566.5	37350.06	193.60	29.82	253	1178	1.693	1.019	34.157
Letaba	39	458.4	453.0	31416.45	177.25	28.38	198	935	1.289	-0.232	38.670
Lower Sabie	33	604.5	566.0	36536.20	191.10	33.27	139	1041	0.874	0.816	31.621
Mahlangeni	42	462.6	465.0	38963.18	197.39	30.46	133	1087	1.691	1.370	42.673
Malelane	85	639.3	589.0	53971.94	232.32	25.20	204	1409	4.877	3.836	36.341
Mooiplaas	28	496.4	433.0	67571.94	259.95	49.13	151	1364	3.078	3.506	52.371
Nwanetsi	33	539.6	538.0	41439.05	203.57	35.44	234	883	0.604	-1.315	37.723
Olifants	27	496.7	471.0	32266.23	179.63	34.57	168	881	0.457	-0.220	36.167
Pafuri	18	466.1	426.0	59785.35	244.51	57.63	121	1092	1.988	1.524	52.464
Pafuri Police Stn	69	423.6	406.0	27666.89	166.33	20.02	98	987	3.389	3.199	39.266
Phalabowra	64	499.6	470.0	34274.37	185.10	23.14	133	1174	2.547	2.250	37.057
Pretoriuskop	60	737.2	681.0	48605.36	220.47	28.46	342	1530	2.877	2.827	29.907
Punda Maria	69	549.3	471.0	55544.94	235.68	28.37	133	1323	3.109	1.656	42.907
Satara	54	543.6	525.0	31687.98	178.01	24.22	248	1043	1.654	-0.081	32.747
Shangoni	43	548.3	524.0	54346.00	233.12	35.55	172	1321	2.335	2.102	42.521
Shingwedzi	40	502.6	450.0	52781.79	229.74	36.33	162	1262	2.972	2.514	45.716
Skukuza	76	549.7	524.5	29827.95	172.71	19.81	237	1123	3.334	2.122	31.419
Stolznek	20	672.7	585.0	85481.40	292.37	65.38	341	1564	2.901	3.127	43.466
Tshokwane	60	562.3	526.5	33303.54	182.49	23.56	256	1179	2.772	1.859	32.455
Vlakteplaas	18	515.0	472.5	60881.41	246.74	58.16	242	1126	2.236	1.289	47.911
Woodlands	19	479.0	391.0	75296.72	274.40	62.95	144	1299	3.252	3.425	57.293
KNP (Overall)	1130	554.6	520.5	52542.02	229.22	6.82	98	1600	13.702	11.690	41.329

Since 1971/72, the inter-annual variability in rainfall has increased and is considerably greater than the preceding 45 years. Mason (1996) states that there has been a 38% decrease in expected rainfall totals over the Lowveld during the last two decades, with rainfall variability over the Lowveld increasing since the 1950s, though the increase in variability appears to be slowing down in more recent years. The rainfall trend post-1996 however does not confirm this. Mason states further that "significant changes in frequencies of extreme drought events and of heavy rains in the Lowveld are likely to occur even with only small changes in the rainfall climatology of the region". This has indeed been the case, with the worst drought in the KNP's history occurring during 1991/92 when the KNP received an average of 235.6 mm (0.4 times the long-term mean annual total; Zambatis & Biggs 1995), and the floods of February 2000 when the KNP as a whole received 1 173.5 mm (2.2 times the long-term mean annual total).

Dent *et al.* (1989) estimated MAR at a 1' x 1' grid square level for the entire country. This was determined by the use of an adjusted regression surface in which MAR was regressed against factors such as altitude, latitude, longitude, continentality (distance from the sea) and aspect. A close inspection of the MAR map of the KNP however shows that in certain areas, MAR is underestimated whilst in others, overestimated. A revised map of MAR was consequently produced, details of which are given in Chapter 3, section 3.2.6. The revised map of mean annual rainfall was re-classified according to the major rainfall regions of the KNP and is dealt in Chapter 4. The classification of the rainfall stations of the KNP according to the procedures of Rutherford & Westfall (1986) is described in Chapter 3, section 3.4.

2.5. **VEGETATION**

The KNP is situated in the savanna biome (Low & Rebelo 1998). Most of the KNP receives less that 650 mm rainfall per anumn and thus falls within the arid savanna, while a minor proportion, approximately 20%, has a mean annual rainfall of over 650 mm and is thus situated in the moist savanna (Huntley 1982).

Gertenbach (1983) identified and mapped thirty-five landscapes in the KNP and gives a detailed description of the soils and vegetation of each. This study extends over the following landscapes, all on basalt or granite (the figure preceding the landscape name is the landscape number):

2: Low granitoid mountains with *Combretum apiculatum* bushveld
3: Moderately undulating granitoid plains with *C. apiculatum* woodland
4: Granitoid lowlands with *Acacia grandicornuta* tree savanna
5: Granitoid plains with *C. apiculatum* bush savanna
7: Granitoid hills with *Colophospermum mopane* tree savanna
8: Granitoid plains with *C. mopane* bush savanna
11: Granitoid plains with *C. mopane* shrub savanna
17: Basaltic plains with *Sclerocarya birrea* tree savanna
18: Basaltic plains with *Acacia nigrescens* shrub savanna
20: Basaltic plains with *A. nigrescens* tree savanna
22: Basaltic plains with *C. mopane* bush savanna
23: Basaltic plains with *C. mopane* shrub savanna
24: Basaltic plains with *C. mopane* tree savanna
27: Basaltic plains with *C. apiculatum* bush savanna.

The herbaceous stratum comprises approximately 235 grass species and a large variety of other herbaceous plants and forbs. Ground cover ranges from sparse in the Very Arid and Arid regions, to dense in the Mesic and Moist regions, particularly on basalt-derived soils. Rainfall regions are described in Chapter 4, section 4.2.

2.6. STUDY SITES

In order to limit the extent of this study to a manageable level, it was decided to restrict it to the two major geological formations of the KNP, namely basalt and granite, extending over 29% and 39% of the KNP respectively. It is further restricted by using only 160 of the 365 sample sites located on these two geological formations (Figure 2.3).

The study period extends over the 11-year period 1989 to 1999. During this relatively short period, extremes in rainfall have occurred, ranging from the severest drought in the recorded history of the KNP (1991/92), to a year with abnormally high rainfall (1995/96). These events present an ideal opportunity to include extremes in rainfall in the study and consequently, to determine their effects on grass phytomass production and composition.

During the annual surveys of the sites, a record is made as to whether the site was burnt during the preceding dry season or not. If burnt, the effectiveness of the fire must also be indicated, namely 'Clean burn' (no or very little unburnt grass material remaining), 'Moderate burn' (some grass material or tufts unburnt or partly burnt), and 'Poor burn' (very little or no material burnt, fire largely ineffective).

Only sites burnt clean at least once during the 11-year study period were chosen. This ensured that adequate samples were available to investigate the determinants of grass *production*, as opposed to *peak standing crop*. The latter includes carry-over of unutilized material from the previous year(s) and would thus not be a true reflection of a specific year’s production.

This approach resulted in a total of 160 sites being selected, with basalt and granite each having 80 (Figure 2.3). These represent a total of 227 clean burns on basalt and 245 on granite. For standing crop analyses, a total of 1 681 samples, burnt and unburnt, resulted (829 on basalt and 852 on granite).

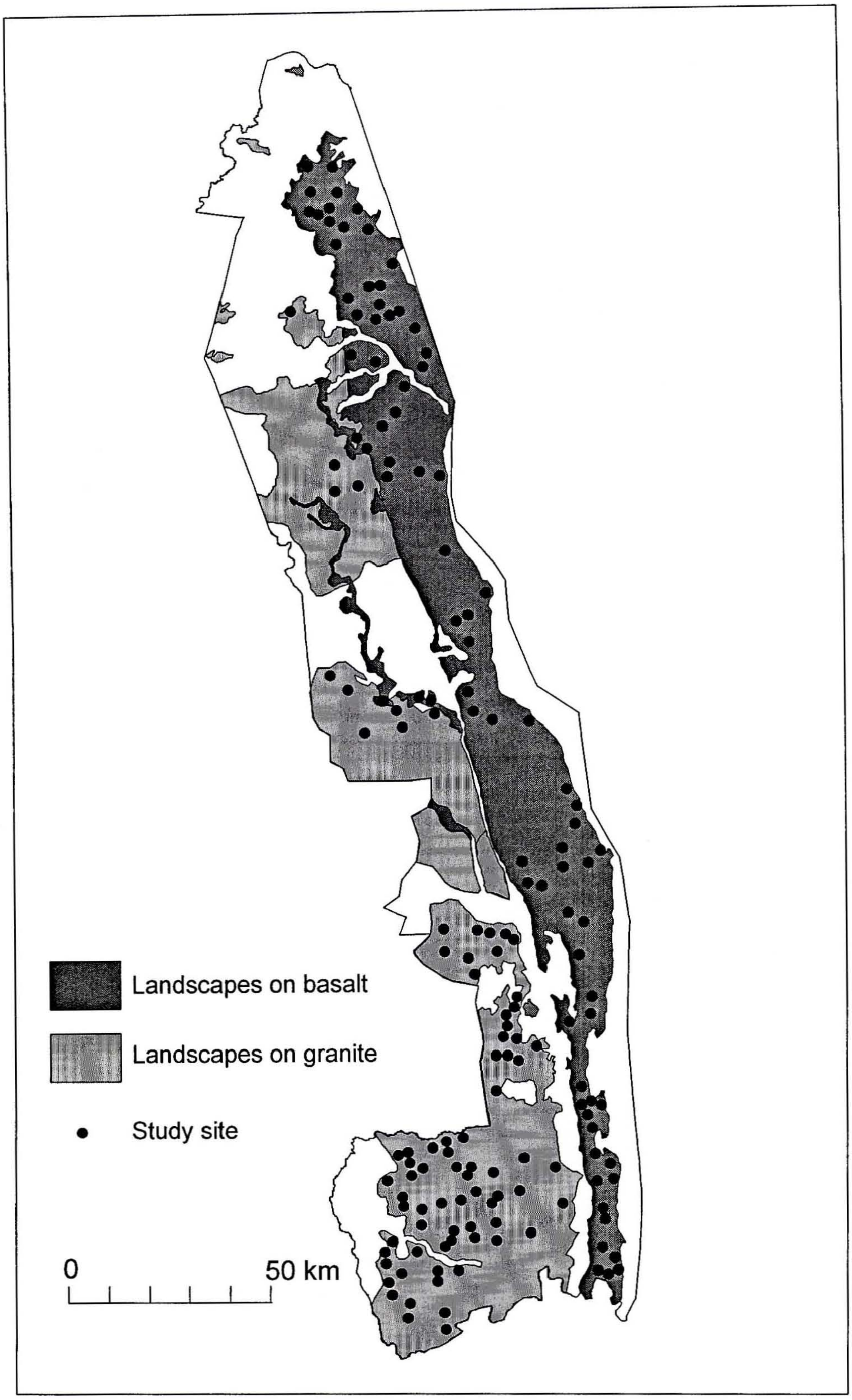

Figure 2.3. The distribution of the study sites on basalt and granite.

CHAPTER 3

METHODS

3.1. INTRODUCTION

The nature of this study is such that a very wide diversity and quantity of data were required. This was not apparent from the outset but became so as the study progressed. The only field-work undertaken specifically for this study was to collect grass samples for the re-evaluation of the disc pasture meter calibration, obtain soil samples from all the study sites and undertake a subjective evaluation of woody plant density on these sites. For the rest, existing data and information originally obtained for other purposes was used or had to be estimated as no data on many of the required parameters exist. This was particularly the case with the determination of crop evapotranspiration. This, together with the need to process the data to an appropriate level for use in analyses required a disproportionate amount of time and effort to be allocated to this task and to methodology in general.

In accordance with the objectives of this study and for reasons that are explained in greater detail in this chapter, the following major abiotic and biotic criteria were used in sub-setting the data:

- Geology (basalt or granite)
- Acocks veld types (Lowveld, Arid Lowveld and Mopani Veld)
- Veld condition classes (Good, Moderate or Poor)
- Soil texture classes (eight classes)
- Fire treatment (unburnt or burnt)

Relations at a finer scale, i.e. the landscape and terrain or land unit levels, were not investigated.

These relatively few criteria produce 288 possible combinations, consequently requiring a very large amount of computation. In all, approximately 3.373 million 'pieces' of data resulted and represent both basic (source) data and data resulting from processing. The latter required over 41 000 lines of computer programming (dBase IV).

3.2. DATA ACQUISITION AND PREPARATION

3.2.1. SOIL

Soil samples of the A and B horizons were collected at five points on each veld condition assessment site by means of an auger. A sub-sample of each horizon was taken at each hole and placed in a plastic bag for that horizon, thereby mixing the sub-samples of each horizon (but not the samples of the different horizons). The thickness of each horizon, as well as total depth of the hole was also measured.

Financial constraints prevented detailed analyses of soil samples by a soil laboratory. Instead, soil texture of each horizon was determined by the 'finger assessment' technique of Rowell (1996) and placed in one of 12 soil texture classes. A total of eight classes were identified: loam, loamy sand, sandy loam, sandy clay loam, clay loam, silty clay loam, sandy clay and silty clay.

The presence or absence of $CaCO_3$ in each horizon was determined using a 10% solution of HCl, while pH (KCl) of each horizon was determined using the procedure of the Soil Science Society of SA (1990).

Soil properties were determined by Kiker (1998) using data from Venter (1990) for each land type, terrain unit and topsoil. Subsoil horizons were added to the soil database file. These include soil water content at the drained upper limit; permanent wilting point; saturation; fraction of saturated soil water to be re-distributed daily from the topsoil and subsoil, to the subsoil and intermediate/groundwater store when the topsoil or subsoil respectively is above its drained upper limit, and fertility indices based on base status and clay content.

Typical percentage values of clay, silt and sand for the different soil texture classes were derived from Schulze (1995). In the analyses however, only clay and silt content values were used due to the premature termination of some of the analyses as a result of all three groups totalling 100%.

3.2.2. VEGETATION

3.2.2.1. **Veld condition assessment data**

Veld condition is assessed annually on 533 permanent sites, each measuring 50 X 30 m. Surveys are generally undertaken between mid-March to mid-April by the section rangers. Surveys are undertaken according to the key grass species technique of Trollope (1990). A stratified sampling technique using 100 sample points is applied in which the nearest key grass to a vertically-held rod is recorded. Non-key grasses are grouped as 'Others'. Non-graminoid, broad-leaved herbaceous plants or small semi-woody shrublets, generally termed 'forbs', are grouped collectively in the 'Forbs' category. Where no representatives of these categories are present and the soil is bare for a radius of up to 250 mm from the rod, a record of 'Bare ground' is made. Percentage composition in terms of Decreaser, Increaser I and Increaser II; as well as perennials and annuals, and forage and fuel scores are calculated for each site. An assessment of the standing crop is also undertaken simultaneously on the 100 points using the disc pasture meter (Bransby & Tainton 1977).

Data is routinely analysed to determine percentage composition (frequency) of each species, as well as of the categories Decreaser, Increaser I, Increaser II, Forbs and Bare Ground. Forage and fuel production potential scores are calculated for each site.

In terms of their definitions (Trollope *et al.* 1990), the Decreaser/Increaser categories reflect the condition of the grass sward in terms of grazing pressure. The abundance of perennial and annual grasses, regardless of their response to grazing (Decreaser/Increaser classification), as well as the abundance of forbs and bare ground, are however considered to better indicators of the overall condition of the herbaceous stratum as a whole, particularly in terms of soil stability and resistance to erosion. Key species are therefore also classified as perennials and annuals, and percentage frequency for these groups is also determined on a routine basis.

In this study, three condition classes are used to describe the overall condition of each site, namely 'Good' (>60% perennials), 'Moderate' (>30-60% perennials) and 'Poor' (≤30% perennials). This classification was brought about primarily by the necessity of the ACRU model (Shulze 1995) to categorize veld condition in these three broad terms for the purposes of determining crop coefficients and the determination of reference and crop evapotranspiration. These are discussed in greater detail elsewhere in this chapter.

The percentage of Decreaser and Increaser species or 'forage scores' (Trollope *et al.* 1990) is commonly used to reflect veld condition in terms of its grazing value or grazing potential. Although a close relation commonly exists between Decreasers and perennials, this is not necessarily always the case.

3.2.2.2. **Woody plant competition**

As an index of woody plant competition, the total estimated canopy and root surface areas of woody plants (trees, bushes and shrubs) was determined. Trees were defined as woody plants >2 m tall, bushes >2-3 m tall and shrubs ≤2 m tall. In all three cases, they could be either single- or multi-stemmed.

Using previous woody survey data, the mean crown diameters (rounded off to the nearest 0.05 m) were determined for each of the height classes defined above as follows: Tree: 3.70 m (n = 386); Bush: 2.15 m (n = 690); Shrub: 0.95 m (n = 4 164).

During fieldwork, the inter-canopy gaps (canopy diameters) of the tree, bush and shrub strata were estimated. These were recorded according to the following classes:

Density class	**Estimated mean canopy diameter between individuals**
Absent	None present
Very open	≥5
Open	4
Moderate	3
Dense	2
Very dense	≤1

For each VCA site, the number of plants in each of the five density classes was then determined using the estimated crown diameter spacing, and the mean crown diameters. For each density category and growth form, a factor was determined as follows:

Example

Mean crown diameter of tree = 3.70 m

Very open = $\geq$5 diameters + 1 diameter (of the tree)

= 6 X 3.70 = 22.2

The number of trees along the length of the site is thus 50 m /22.2 = 2.25, and along the side is 30 m /22.2 = 1.35. Therefore the total number of trees on the site is 2.25 X 1.35 = 3.0.

According to Scholes and Walker (1993) the root radius of a tree extends “up to” seven times its radius. This was reduced to 5 m, on the assumption that this would be the approximate mean. Root surface area, i.e. the surface area of the 'root skirt' around a plant, was then calculated: Tree: 268.8 m^{-2}; Bush: 91.6 m^{-2}; and Shrub: 18.1 m^{-2}. Consequently, a 'Very open' tree stratum for example, would have a root surface area extent of 3.0 X 268.8 = 806.4 m^{-2}

Using this procedure, a table of estimated woody plant density and canopy and root skirt surface areas was constructed for each density class (Appendix 1; Table A1). The total canopy and root skirt surface areas of each site were then calculated. In many cases, this is greater than the surface area of the site itself. As is frequently the case with canopy cover, this is due to overlapping canopies and root skirts.

3.2.2.3. **Data required for the computation of reference and crop evapotranspiration**

In this study, the determination of reference and crop evaporation was undertaken according to the FAO procedures (Allen *et al.* 1998). These are very complex and time-consuming, and require data on a large variety of parameters. Most of this information does not exist for extensive, natural areas such as the KNP and thus has to be estimated. Estimations in the majority of cases are based on knowledge gained from personal experience; in a few cases, they are purely guesses. This however holds the inherent risk of substantial errors in their estimation, which in turn can have a significant 'knock-on' effect on the accuracy of subsequent calculations. The calculation of reference and crop evapotranspiration under these circumstances is consequently a reasonable estimate (at best), and can in fact be grossly incorrect.

3.2.2.4. **Phenological stages**

One of the basic requirements for the computation of reference and crop evapotranspiration using the procedures of Allen *et al.* (1998) is information on the various phenological stages. These however have not been determined for the grass stratum in the KNP and were consequently estimated, using personal field experience and knowledge of the area. Rainfall concentration and its geographic distribution (Table 3.1) was also taken into account. The shortest period is approximately a fortnight.

The phenological stages for the grass sward are defined as follows:

Dormant:	The 'rest' period, when the plant is not photosynthesising (perennials), or perennates as a dormant seed (annuals).
Crop initiation:	The stage when germination or new shoot production takes place, i.e. establishment. Defined by Allen *et al.* (1998) as the time when approximately 10% of the ground surface is covered by green vegetation; for perennial plants, the time when the initiation of new leaves occurs.
Development:	The stage when maximum growth and flowering occurs. According to Allen *et al.* (1998), from 10% ground cover to effective full cover - in many plants the initiation of flowering.
Mid season:	Seeding - the stage when seed is produced. From full cover to the start of maturity, often indicated by the beginning of aging, yellowing or senescence of leaves (Allen *et al.* 1998).
Late season:	Maturity - leaf senescence and drop and seed ripening and drop. From the start of maturity to full senescence, when the plant dries out naturally, or experiences leaf drop (Allen *et al.* 1998).

Details of the phenological stages are given in Appendix 1, Table A2 'Climyear' refers to the climatic year, starting on 1 July (climyear day 1) and ending on 30 June (climyear day 365 or 366). The mean duration of the phenological periods is given in Table 3.1.

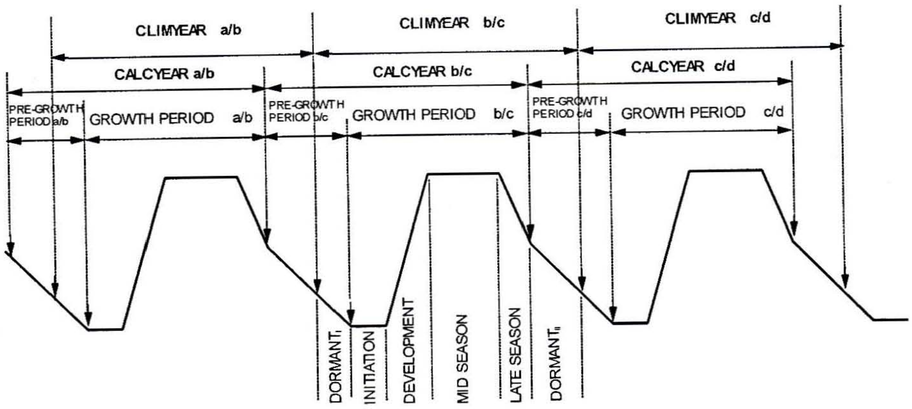

Figure 3.1. Schematic layout of the phenological stages of a year in relation to the 'calcyear' and 'climyear'. Climyear or calcyear 'a/b' extends from year 'a' to year 'b', etc.

The pre-growth period of a particular year includes the dormant period preceding the initial stage, as well as the dormant period following the late season phenological stage of the preceding climyear (Figure 3.1). It is also collectively referred to in this work as the 'dormant' period.

The growth period includes the initial, development, mid season and late season stages of the 'current' climatic year. Together, the pre-growth and growth periods constitute the 'calcyear' (i.e. calculation year), this being the period for which a series of calculations and analyses were subsequently undertaken.

Table 3.1. Mean number of days' duration of the various phenological stages for veld in good, moderate and poor condition

VELD CONDITION	PHENOLOGICAL STAGE					GROWTH PERIOD
	INITIATION	DEVELOPMENT	MID SEASON	LATE	DORMANT	(Initiation, Development, Mid season, Late season)
GOOD	16	30	98.5	38.5	183	173
MODERATE	15.5	22.5	83.5	23	221.5	144.5
POOR	15	15	69	14.5	252.5	113.5

The effect of this re-alignment of the climyear is thus the re-definition of a year to better reflect the phenological stages, taking into account the differing dates of commencement and termination of each stage, depending on the overall condition of the grass stratum.

3.2.2.5. **Cover**

Information on percentage cover is required for crop evapotranspiration calculations (Allen *et al.*1998). Cover is defined as the percent of the soil surface which would be obscured when viewed directly from above, the obscurity being due to grass material (attached or detached), and detached material from woody plants such as leaf litter, seed pods, thin twigs, etc.

Aerial cover

As with numerous other parameters, no detailed information on this is available for the KNP and consequently had to be estimated. The basis for this was estimates of peak cover at the end of the growing season and minimum cover at the end of the dry season, for both unburnt and burnt veld. Separate estimates were made for each of the three Acocks veld types included in this study, namely Lowveld, Arid Lowveld and Mopani Veld (Acocks 1988), and for basalt and granite in good, moderate and poor condition (Appendix 1; Table A3).

Estimates correspond with the phenological stages. The cover curves shown in Figure 3.2 are simplified and not an accurate representation of actual trends during a typical year. It was however decided that as these values are estimates and could differ markedly from the true situation, there was no point in attempting to estimate annual trends in greater detail. The shape of the curve is in fact based on that of crop coefficients, as given by Allen *et al.* (1998).

Cover curves were drawn on graph paper and from these, straight-line equations were developed. The equations were then used to calculate daily values, required for crop evaporation computations. Equation statistics are given in Appendix 1, Table A4.

In general terms, cover is directly related to rainfall – the greater the rainfall, the greater the cover. Values produced by the equations in Table A4 are for an 'average' year, i.e. a year having a total annual rainfall close to the long-term mean. To compensate for years when rainfall differs markedly from the mean, adjustment factors were estimated on a logarithmic scale.

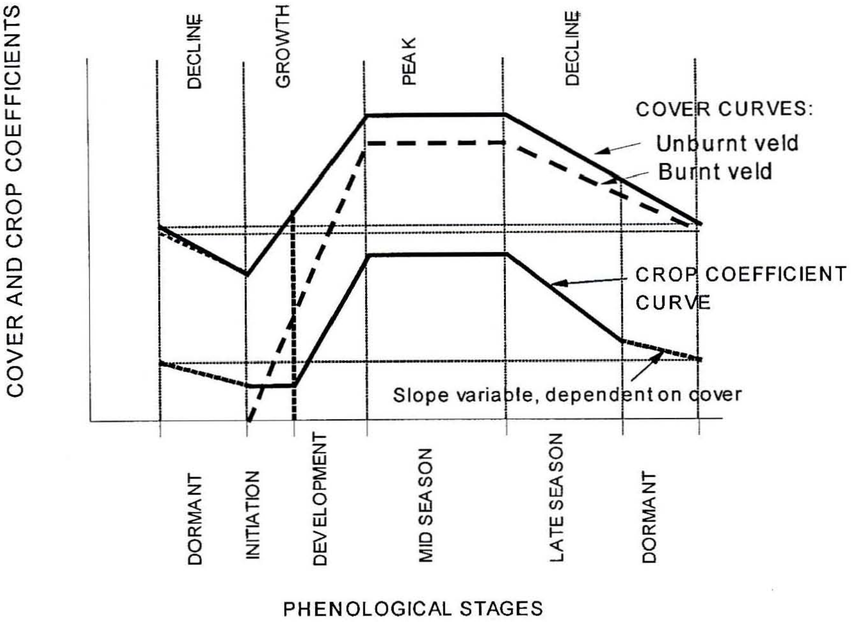

Figure 3.2. Cover and crop coefficient curves in relation to the phenological stages.

Although growth of the grass sward is assumed to be linearly related to rainfall amount, this is probably true only up to a certain amount of rainfall, after which the amount of material produced levels off with increasing rainfall. Cover can be expected to also follow a similar trend. The adjustment factors were thus designed to reflect this trend (Appendix 1, Table A5).

For the purposes of evapotranspiration calculation, maximum cover must be restricted to 99% (Allen *et al.* 1998). The highest value of the correction factors of 1.10 is based on an estimated cover of 90% for Lowveld on basalt (the highest for all the veld types), during a year with average rainfall. An adjustment of 1.10 will thus result in a cover of 99%.

Litter cover

In this study, 'litter' is defined as detached, dead plant material and animal dung lying on the ground surface. It consists of dicotyledonous and monocotyledonous material such as leaves, stems, woody twigs, bark, fruit, etc. By implication, plant basal cover is not included though its contribution (approximately 4-10%) was taken into consideration when estimating overall ground cover.

Cover values used in this study are estimations based on cursory field inspections. Litter cover is estimated to reach a maximum of approximately 20% for the three Acocks veld types, decreasing to approximately 15% in summer.

In reality, litter cover is spatially heterogeneous and varies greatly across the ground surface. Directly under woody plants, cover is high, particularly in the case of deciduous plants - approximately 70-90% at its peak, the bulk of it consisting of leaves. In the inter-canopy spaces litter cover consists of a few scattered wind-blown leaves, dead grass leaves, dung, etc.

The assumption was made that the abundance of litter cover follows an annual cycle. Although litter is deposited throughout the year, the bulk of it occurs during the dry season, the actual time of deposition varying greatly and is dependent on the amount of rainfall received and the extent or persistence of the rain season. Persistence of leaves appears to be strongly influenced by the capacity of the soil to retain water, i.e. soil texture.

In the case of the Lowveld and Arid Lowveld veld types, deposition starts in mid-April to mid-May, the rate of deposition accelerating from about the beginning of July and reaches a peak in about mid-September. It remains at this peak (approximately 20%) until December when, due to increased moisture and temperature, decomposition starts and continues during the wet (rain) season until mid-February, leveling off at about 15%. From here onwards until mid-April to mid-May, new material is produced by actively-growing plants.

In the case of Mopani Veld, the sequence and time intervals are similar, except that the rate of deposition initially is slower (i.e. mopani leaves are more persistent than those of other deciduous plants), extending until mid-October when the majority of leaves are dropped in a relatively short period.

Should a fire occur at the start of the dry season while mopani leaves are still green, the latter are scorched and fall after the fire has occurred. This results in a considerable litter cover being deposited on the otherwise burnt veld, the percentage cover being directly proportional to the canopy cover of the woody plants. This phenomenon was however ignored in the computations as it would have introduced several complexities. Nevertheless, the importance of this is to reduce evaporation from the otherwise bare soil surface, though to what extent this is effective in preserving soil moisture in this vegetation type is unknown.

In order to simplify calculations, where veld was burnt, litter cover was set at zero from day 46 onwards; the default day for fire occurrence. It largely remains at this level until the shedding of the subsequent season's leaf production commences in April or May, when the cycle 'reverts to normal'.

In reality, fire intensity (dependent on the amount and moisture content of the material and weather conditions at the time of the fire), influences the amount of unburnt litter remaining after the fire - the greater the intensity, the greater the consumption of this material by the fire. The contribution of basal cover on burnt veld in reducing soil evaporation was assumed to be negligible and was therefore ignored.

The amount of litter deposition (and hence cover) is greatly influenced by the species and abundance of plants, both woody and herbaceous. This is directly related to leaf size and overall 'leafiness' of plants. Comparing two plants of similar canopy diameters for example, a fine-leaved *Acacia* species will produce a much smaller amount of leaf litter than a *Colophospermum mopani* or a *Combretum* species. A similar variation is also evident in the case of grasses and overall veld condition - the greater the proportion of perennial grasses, the greater the quantity of grass leaf litter and hence coverage.

The type and abundance of herbivores, in combination with plant species composition, and the proximity of drinking water, also influence the amount of litter on the ground surface. Where preferred browse or graze species are present, coupled to a relatively high number of herbivores, the amount of litter available is obviously reduced, sometimes greatly so. Concentration of herbivores around a water-point further enhances the removal of plant material before it is deposited as litter. Furthermore, trampling in the vicinity of a water-point accelerates the breakdown and decomposition of any litter that may be on the ground surface.

On the other hand, a concentration of herbivores in the vicinity of drinking water leads to a higher density of dung deposition, which also contributes to ground cover, though this is probably negligible.

In terms of ground cover therefore, the overall effect of water-points, and permanent water-points in particular, is a reduced ground cover, which in turn enhances evaporation from the soil surface.

Equation statistics for calculating estimated daily values of litter cover are given in Appendix 1, Table A6.

3.2.2.6. **Crop coefficients (K_c)**

A 'crop coefficient' is defined by Allen *et al.* (1996) as the ratio of evapotranspiration occurring with a specific crop at a specific stage of growth to reference crop evapotranspiration at that time. They state further that because estimating ET in hydrological studies goes beyond agricultural crops and extends to various natural vegetation types under rain-fed conditions (including bare soil), the term might be more appropriately referred to as a 'cover coefficient', rather than as a 'crop coefficient'.

Schulze *et al.* (1995) define the crop coefficient as the ratio of maximum evaporation from a plant at a given stage of plant growth, to a reference potential evaporation. The term 'maximum' is used to describe the evaporation from the plant under 'well watered' conditions when the effects of soil water shortages are negligible. Green (1985) refers to this ratio as the 'crop factor' of a particular plant species.

The term 'crop' ("produce of cultivated plants, especially cereals") is of agricultural origin. The work of Allen *et al.* (1998) is also based on, and primarily aimed at the agricultural sector, hence the very frequent use of the term 'crop'. In this study, it is used in a broader context, to imply or mean 'grass sward' or 'plant'.

Data on crop coefficients for savanna vegetation are very limited (Schulze *et al.* 1995). The values for the different veld types contained in the 'Compoveg' file of the ACRU model (Appendix 1, Table A7) were therefore used, most of these apparently being based on the work of Green (1985). Schulze *et al.* (1995) further state that the major shortcoming in using K_c in estimations of plant evaporative losses is this lack of information on natural vegetative surfaces such as bushveld and grassveld, use then having to be made of those few lysimeter-based values derived by Snyman, Opperman & van den Berg (1980) for different succession stadia of veld.

Other shortcomings of fixed, generalized crop coefficients which Schulze *et al.* (1995a) point out are that they fail to account for the differences in a plant's growing environment: inter-seasonal differences in plants' climatic environments affect their growth rates, and hence water requirements. Plant water loss is dependent on daily weather patterns, differences between seasons for any one locality (or between localities), and variability in soil properties.

To a degree, these shortcomings are mitigated by the computational procedures of Allen *et al.* (1998). The cost of this however is the computational complexity and time-consuming nature of these procedures.

When the ACRU K_c values were plotted, it became evident that for all veld types, their temporal distribution during the year differed markedly from the estimated phenological periods of the KNP, indicating a longer growth period than is the case in the KNP. It was therefore decided to produce new curves using the basic ACRU values as guidelines, especially for the upper (maximum) values, using the procedures of Allen *et al.* (1998). This was done by estimating maximum K_c values for each phenological stage for the three veld types, each on basalt and granite, and in good, moderate and poor condition (Figure 3.3 and Appendix 1, Table A8). Graphs of each were then plotted on graph paper and straight-line equations determined from these, in order to be able to calculate daily values for every day of a year (Appendix 1, Table A10).

The fact that the ACRU coefficients are given for different Acocks veld types and for veld in different conditions necessitated that all subsequent computations in which these coefficients were used, were sub-set accordingly. No distinction between basalt and granite is however made in the 'Compoveg' data, nor was any made in this study as far as K_c values are concerned. Although procedures would have been significantly simplified if veld condition was ignored and mean values used instead, it was assumed that this would introduce unacceptably large errors in the K_c values, which are already of a general nature for each veld type as a whole.

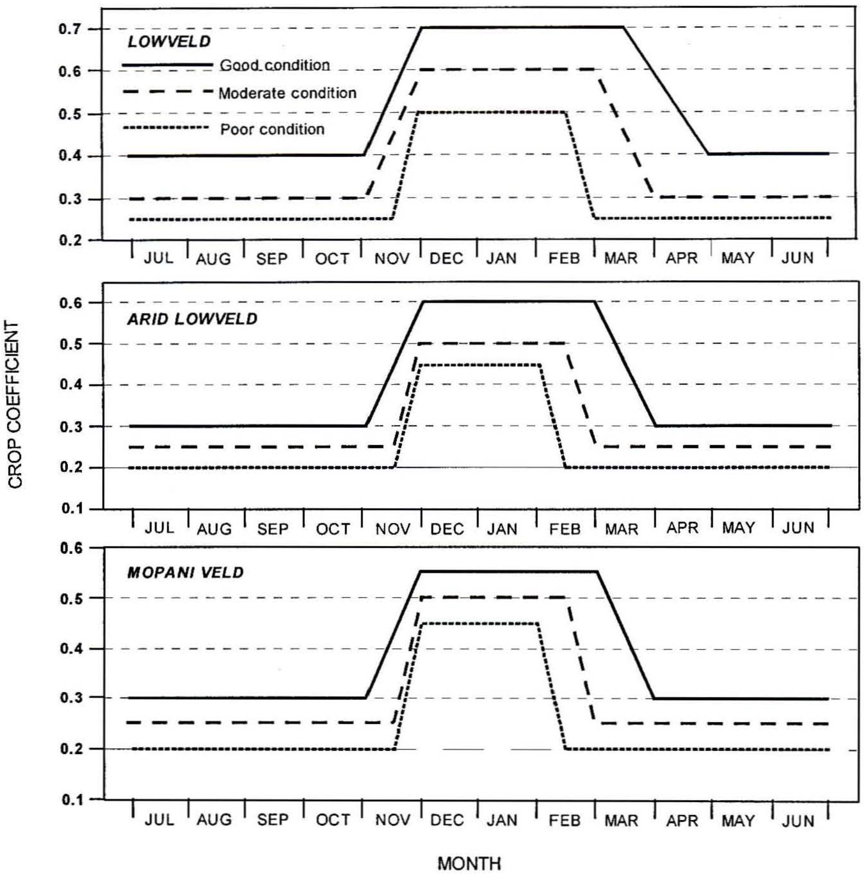

Figure 3.3. Estimated basal crop coefficients (K_c) for Acocks' Lowveld, Arid Lowveld and Mopaniveld in good, moderate and poor condition.

3.2.3. HERBIVORES

In a study of this nature, it is essential to take into account the important modifying effect which mammalian herbivores, particularly grazers, have on grass composition and primary production. Data on those species classified by Collinson & Goodman (1982) as concentrate, mixed and bulk feeders were extracted from the annual aerial censuses.

Before the advent of the Global Positioning System (GPS), herbivores were recorded during flight on a map overlain with a 2′ x 2′ (2.1 x 2.3 km) grid square and then digitized. Species and number recorded however are a 'snapshot' of only one day in the year. Consequently, in order to obtain a more representative value of the broader grazing pressure situation around each VCA site, data were extracted for the 'grazing zone' with the VCA site in is centre, i.e. 9 census grid squares (3 x 3); Figure 3.4. This extends over an area of 6.3 x 6.9 km (4 347 ha).

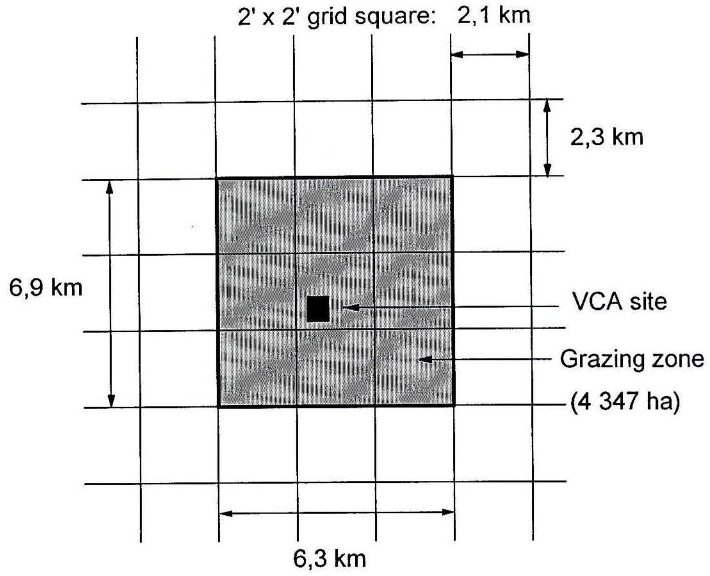

Figure 3.4. Schematic layout of the grazing zone associated with each sample site based on the 2' x 2' census grid.

Total biomass (tonnes) for each feeder category and for each grazing zone was then calculated using the species' mean mass of Bothma (1996) and Meissner *et al.* 1990; Table 3.2).

The alternative to using biomass would be to use the metabolic mass (Grossman *et al.* 1999) and from this, to calculate stocking rates in terms of hectares per large stock unit (ha LSU^{-1}). A large stock unit (or AU, animal unit) is defined by Trollope *et al.* (1990) as an animal with a mass of 450 kg and which gains 0.5 kg per day on forage with a digestible energy percentage of 55%.

The latter procedure appears to be at least reasonably well suited to agricultural systems dealing with one or two types (classes) of herbivore feeders, and where relatively small and homogenous systems, are generally in a relatively stable state. The LSU's are also applied in situations of relatively small-sized land units covering nearly uniform vegetation and climatic zones.

The LSU is however based on a heavy-bodied grazing ruminant and does not take into account the feeding patterns, which in some cases overlap, and the digestive systems of different herbivores (Peel *et al.* 1998). Where the herbivore species mix increases however, metabolic mass is suited to similar types of feeders in terms of energy requirements but does not reflect their impact on vegetation. This can (and does) vary greatly, for example the localized impact of wildebeest - a concentrate grazer. Mixed or bulk feeders or browsers (Collinson & Goodman 1982) on the other hand have a very different impact on the vegetation.

The model developed by Coe *et al.* (1976) relates animal biomass to long-term annual rainfall and has proved to be satisfactory for areas receiving rainfall of up to 700 mm (Peel *et al.* 1998). A shortcoming of this approach, however, is that the broad relation between biomass and rainfall does not take into account local temporal and spatial variations in savanna ecosystems (Peel *et al.* 1998). Nevertheless, Peel *et al.* (1998) consider the herbivore biomass method of expressing stocking density to be more useful that the animal-based approach as it provides a basis for coarse-scale, medium to long-term 'stocking density map' for an area at a regional scale of 1:250 000. It was thus concluded that this approach would be more appropriate for this study.

Table 3.2. Herbivore feeder categories, species, and mean unit mass per species

FEEDER TYPE CATEGORY & SPECIES	**[1]MEAN UNIT MASS (kg)**
[2]CONCENTRATE GRAZERS	
Reedbuck	70
Warthog	70
Tsessebe	125
Wildebeest	180
[2]MIXED FEEDERS	
Impala	50
Eland	500
Elephant	[3]4 500
[3]BULK GRAZERS	
Waterbuck	180
Sable	210
Roan	250
Zebra	260
Buffalo	495
Hippopotamus	1 340
White rhino	1 800

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[1] Bothma (1996)
[2] Collinson & Goodman (1982)
[3] Meissner *et al.* (1990)

3.2.4. DISTANCE FROM PERMANENT DRINKING WATER

The distance of each VCA site from permanent drinking water was determined by Geographic Information System (GIS) analysis. These distances are regarded as maximum distances as they were measured to water points of various kinds (mostly artificial structures such as catchment dams and borehole-fed troughs).

In reality however, the distance to drinking water varies from year to year and is dependent primarily on the amount and temporal distribution of rainfall: the greater the rainfall towards the end of the rain season, the greater the likelihood that drinking water will be available until the start of the following rain season at specific points such as natural pans and river pools. The effect of this is thus a reduction of the distance between a VCA site and drinking water.

Although the presence of drinking water is recorded during the aerial surveys, the size of the water body is not recorded. This would at least provide some indication, albeit a coarse one, of the permanency of the water. The distances derived by GIS analysis can consequently be regarded as approximate. There are however no alternative, more reliable data available.

A broad insight into the general relations between distance from water and mean DPM height on the one hand, and distance from water and perennials and Decreasers on the other, would be of value in better understanding the role which herbivore concentrations play in influencing NPP and NSC, and composition. A cursory investigation using regression statistics (CurveExpert 1.3 software http://www.ebicom.net/)) was consequently undertaken using data from all the VCA sites on basalt and granite for the period 1989-1999 to investigate this relation.

3.2.5. FIRE HISTORY

The choice of VCA sites to be used in this study was firstly on the basis of the two major geological formations (granite and basalt), and secondly, on the basis of their fire treatment. More specifically, a site had to have been 'clean-burnt' at least once in the 10-year period during which VCA surveys have been undertaken. This would ensure that samples were adequate for statistical analyses. The fire history of each block on which a VCA site is situated was also consulted and information on burning frequency and time since last burn calculated.

In this study, reference to 'burnt' and 'unburnt' in some of the tables and figures (abbreviated in some cases as 'BNT' and "UBNT' respectively), is synonymous with NPP and NSC respectively.

3.2.6. DAILY WEATHER DATA

Allen *et al.* (1998) recommend that for research purposes, a daily time step interval should be used in the calculation of evapotranspiration. This consequently requires the use of daily values for a variety of weather and other parameters, and although a great deal more intense computationally, has the advantage of greater accuracy in the output.

Daily weather observations are undertaken at 13 weather stations according to standard SA Weather Services procedures. Observations are made at least twice per day, at 08:00 and 14:00. Besides the weather stations, rainfall is also recorded at a number of rainfall monitoring stations and is measured and recorded for a 24-hour period (08:00 to 08:00 of the next day) using a standard 'copper bucket' raingauge.

One daily data file per station was compiled and extends from July 1986 to June 1999, i.e. the 1986/87 to 1998/99 climatic years; a climatic year extending from 1 July to 30 June of the following year. Each file contains the following parameters: Temperatures (dry and wet bulb, maximum and minimum); cloud cover; wind direction; windrun; and rainfall. A total of 128 196 records of either basic or calculated daily weather data are consequently contained in each file; 1 666 548 records for all the weather stations combined.

3.2.6.1. **Rainfall**

Daily rainfall

It is a well-known phenomenon that the total annual rainfall received by savanna vegetation has a direct influence on a specific year's production. This correlation can however can be regarded as being of a gross or a general nature: in broad terms, the greater the total, the greater the production. It was suspected that perhaps of even greater and more direct importance is a combination of the amount received per rainfall event or 'rainday' (in this work, defined as a 24-hour period with a total of ≥0.5 mm of rain) and the distribution of the rainfall as a whole during the growing period, i.e. the skewness and kurtosis of the season's rainfall distribution.

The distribution and other descriptive statistics of *raindays*, rather than rainfall amounts, were determined. These include the variance, standard deviation, standardised skewness, standardised kurtosis, coefficient of variation, total rainfall, and total number of raindays.

Daily rainfall amounts and rainfall characteristics are very closely related to a variety of geomorphological criteria (Dent *et al.* 1989) and can vary markedly over relatively small distances. On the other hand, other daily weather parameters such as temperatures, wind speed and direction, and cloud cover appear to be 'robust' in a spatial sense and vary little over relatively large distances.

Consequently, in order to obtain more accurate estimates for each VCA site, these were interpolated by GIS (Arcview) in which a TIN ('Triangular Irregular Network') surface model fitted with Quintic interpolation with a neighbourhood of 50 km and a decay of 30 km was used. This type of interpolation considers the surface model to be continuous and produces more realistic results from sparse sampling data sets where surface information was obtained at arbitrary locations (Jessica Redfern, University of California, Berkley, USA; *pers comm.*)

Monthly and annual rainfall

It was decided that because of the major role which rainfall plays in grass production and composition, the spatial and temporal nature of annual rainfall should be investigated in some detail, in order to derive a more complete background of this parameter to better understand its role in grass sward dynamics. It was also consequently also concluded that some measure or index of aridity would further serve as an aid in better understanding the role that this key climatic element plays in grass dynamics.

In order to determine mean annual rainfall, monthly rainfall had to be determined. Only those stations with data extending over a period of at least 15 years were used for this purpose. Mean monthly and annual rainfall values are given in Chapter 2 (Table 2.2).

Mean annual rainfall (MAR) of the KNP over the period 1910/11 to 2001/02 was calculated and the annual percentage deviation from the mean plotted (Figure 2.2). For each station, only years with a complete rainfall record were used. Moreover, according to Dent *et al.* (1989), data covering a period of 15 years is required in order to derive an annual mean at the 90% confidence level with ≤11.5% error and 20 years with ≤9.5% error. Since the mean duration of the monitoring stations is 44.3 years, the error according to Dent *et al.* (1989) is <5.5%.

A smoothing function (simple moving average using a three-year term) was then applied to identify wet and dry cycles.

Mapping mean annual rainfall

A map of mean annual rainfall is a basic essential for practically any work dealing with the biology or ecology of an area, of whatever size. Such a map becomes even more versatile and hence valuable when it is available in a digital form in a GIS system on the computer.

Mean annual rainfall was determined by Dent *et al.* (1989) for a 1' x 1' grid of South Africa. The electronic version of this map was obtained from the CCWR and mapped by GIS. A careful inspection of this map showed that for certain regions of the KNP, MAR is under-estimated whilst in others, it is over-estimated. This was done by comparing the true MAR of monitoring stations with the estimations of Dent *et al.* (1989). In certain cases, where no rainfall monitoring station exists, the estimations of section rangers familiar with these areas was obtained.

The greatest discrepancies are in the extreme far north of the KNP (the Limpopo river valley, also referred to as the Limpopo-Levuvhu area); the areas to the north-west and east of Letaba (Shilowa-Longwe region in the Lebombo mountains); south-east of Tshokwane (Shandlana); and south-east of Crocodile Bridge (Beacon B area).

Mean annual rainfall for the Limpopo river valley is estimated by Dent *et al.* (1989) to range between 200 and 300 mm in the vicinity of Makwadzi Pan on the Banyini Plains at an altitude of approximately 180 m asl, yet according to Schulze (1997), this ranges between 200 and 400 mm. Section rangers who are familiar with area estimate it at approximately 350 mm.

Comparing MAR for Messina (Macuville Agricultural Station at 522 m asl) of 339 mm (SA Weather Bureau (undated) and the estimate for the Makwadzi Pan area, it appears that the mapping procedures of Dent *et al.* (1989) are not sensitive enough to the altitudinal differences and the effects of the Soutpansberg mountains to the south-west of Makwadzi Pan on the rainfall of the latter area, resulting in an under-estimation of MAR for both areas.

More specifically, the fact that the high points of the Soutpansberg end some 40 km to the south-west of the Limpopo valley appears to 'allow' the relatively high aridity to the west to extend down the Limpopo valley and into the KNP. Yet, a variety of plants species occur in the Pafuri-Limpopo area which do not occur in the Messina area and which otherwise have a more tropical distribution outside the country's borders. This alludes to the likelihood that the Makwadzi Pan area has a rainfall regime and general climate considerably different to that of the western side of the Soutpansberg, which in all likelihood also has a rain-shadow effect on the rainfall of the Messina area.

It is thus concluded that although the Limpopo valley, in the context of the savanna biome, has a very arid climate, it is not as arid as the western side of the Soutpansberg. Mean annual rainfall for this area within the KNP is thus estimated to be approximately 350 mm.

In the Shilowa-Longwe area of the Lebombo mountains to the east of Letaba rest camp (Figure 2.1), the MAR for this area is estimated by Dent *et al.* (1989) at 808 and 831 mm respectively. Yet careful field investigation of the plant species occurring here as indicators of a relatively high rainfall, as well as the possible presence of any other geo-physical features such as fountains and vleis, failed to confirm this. Experienced section rangers familiar with the area estimate the true MAR to be not more that 650 mm: 154 mm higher than at Mooiplaas 17 km to the west and the closest monitoring station to Shilowa; and 192 mm higher than Letaba, 11 km west of Longwe.

On the high ground between Mopani Draai and Nsihana windmills to the north-west of Mooiplaas ("Middel Voorbrand" vicinity), and the Busizi area on the western boundary, MAR is given as 650-700 mm. This is however estimated to be in the 600-650 mm range.

A statistical analysis using non-linear regression showed that a very strong relation exists between the percentage difference in MAR determined by Dent *et al.* (1989) and the true values, and distance from the sea. This has the form of a 4th Degree Polynomial ($r = 0.9061$; r^2 (adj.) = 0.781; SEE = 11.223; n = 24; Figure 3.5). Generally, those stations furthest from the sea show the greatest difference between true and estimated values. The relation has the form:

$$y = a + bx + cx^2 + dx^3 + \ldots$$

where

a	60.567848	d	-6.0021539e-005
b	-1.6174224	e	7.929199e-008
c	0.015452058	x	distance from the sea

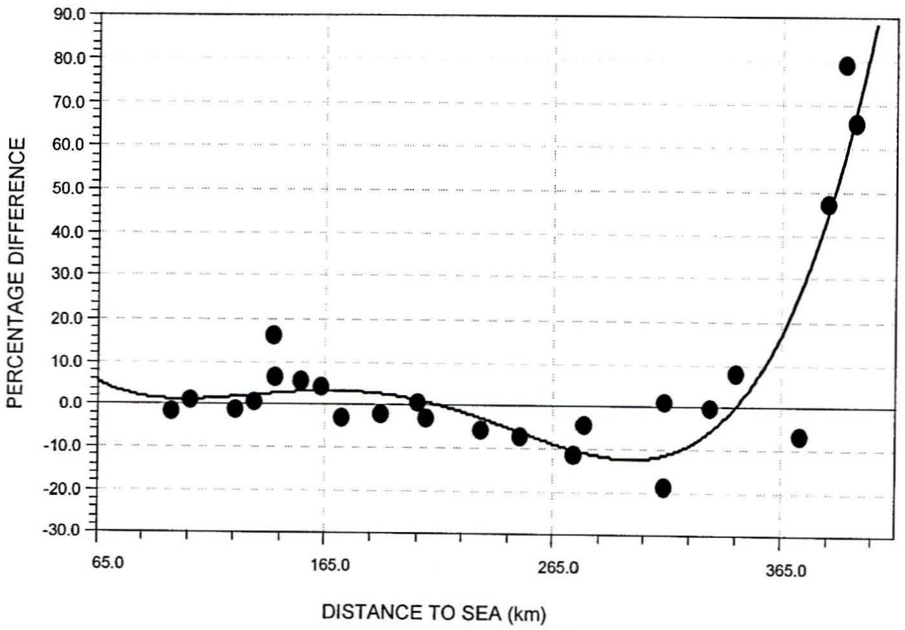


Figure 3.5. Fourth-degree polynomial relation between the percentage difference between mean annual rainfall and distance from the sea.

A similar analysis with altitude above sea level as the independent variable produced a poor relation ($r = 0.2198$; $r^2 = 0.695$; SEE = 11.494; $n = 37$).

This indicates that, at least for the Lowveld, the procedures of Dent *et al.* (1989) may possibly be over-sensitive to continentality, or under-estimate the influence of rain-bearing systems originating north of the country's borders, particularly on the eastern side of the Drakensberg Escarpment and by extension, the Soutpansberg mountains.

With a rather poor coefficient of determination however, the application of this equation in many cases did not have the desired effect, namely to increase MAR values in the Limpopo-Levuvhu area, and to decrease it in the Shilowa-Longwe and Khandzalive Kop areas. Consequently, where MAR was not increased to above the estimated minimum of 300 mm for the Limpopo-Levuvhu area and reduced to an estimated maximum of 650 mm in the Shilowa-Longwe area, this was done by visual inspection and changed manually. In all, a total of only 3.3% of all the 1' x 1' blocks were adjusted by these two means. The 300-400 mm class was adjusted slightly by this means to include Pafuri (ranger) and Pafuri Police Station (Figure 2.1). A smoothing function was then applied. A result of this was that approximately 35 very small (<100 ha) polygons were produced, scattered over the surface of the KNP. In order to reduce cluttering, as well as to improve the overall graphic quality of the map with the application of different black-and-white polygon fills, these were incorporated in the majority rainfall class surrounding or touching them. An additional 0.05% of the surface area of the KNP was consequently altered by this means, bringing the total to 3.35%.

In the Khandzalive Kop area, only two blocks had an estimated MAR value of > 1 000 mm Dent *et al.* (1989) and were reduced to 950 mm. Values for all the other blocks were not altered.

Coefficient of variation of annual rainfall

It is reasonable to assume that the greater the annual variation in rainfall, the greater the fluctuation in grass production and composition. An investigation of the coefficient of variation (CV) of annual rainfall was consequently undertaken. This was plotted against the long-term MAR for each station and mapped by GIS simply using the inverse distance procedure.

Concentration of annual rainfall

The temporal distribution of rainfall in the KNP was suspected not to be the same everywhere during a rain season but to grade from a relatively short duration in the extreme far north (Pafuri area), to a longer duration in the south. Although on average, rainfall has been recorded for every month at every monitoring station, at least 80% of a year's total occurs between the months of October to March (inclusive), with the wettest months generally being December to February. Confirmation of the existence of such a phenomenon would in turn be an important consideration in estimating the phenological stages for the different regions and veld types of the KNP.

To determine if there is indeed a concentration of rainfall during a 'typical' rain season, the mean monthly rainfall and mean percent of the total rainfall occurring in each month were calculated for each of the monitoring stations which have been in existence for at least 15 years (Chapter 2, Table 2.2). A sub-total for the period December to February was then calculated for each station. The greater this sub-total, the greater the concentration of annual rainfall. Stations were then arranged in a geographical sequence according to their longitude and tabulated in this sequence, together with the December-February percentage rainfall sub-total.

3.2.6.2. **Temperatures, relative humidity, wind and cloud cover**

Thermometers are housed in a Stevenson screen at a height of 1.2 m above ground. Daily mean temperature was calculated according to the standard procedure, namely (maximum temperature + minimum temperature)/2. Using dry and wet bulb temperatures, dew point temperature and percent relative humidity were determined from hygrometric tables (Weather Bureau, undated). As this is a somewhat tedious procedure, the hygrometric tables were computerised and a programme complied to automate the determination of relative humidity.

Cloud cover is estimated and recorded daily at 08:00 and 14:00 in octaves.

3.2.6.3. **Missing weather data**

In cases where data were missing, they were replaced with estimates or with data from the nearest station as described below.

Temperatures

Simple linear regression was used to establish the relations between a particular station and other, surrounding or nearest stations ('surrogate' stations) for dry bulb, wet bulb, maximum and minimum temperatures. The strongest correlation was then used to calculate estimates using data from a particular surrogate station. Equations are listed in Appendix 1, Table A11.

In the rare case where data from a surrogate station was also missing for a particular day, the mean between the two days immediately before and after the day with the missing record was used to 'patch' the missing record by using this mean. This was then used in the equations to calculate an estimate for the other station. These equations were also used to impute data in the case of new stations which commenced with observations during the course of this study.

Cloud cover and wind direction

By inspection of the weather records, in the great majority of cases in the KNP, there is generally little difference in cloud cover and wind direction between one area and another, even though they may be relatively far apart (50-60 km). Over larger distances however, gradients in these phenomena are evident and common. Values of the nearest station with data were therefore used to 'patch' missing data, without these being adjusted in any way.

Rainfall

Missing daily rainfall cannot be patched by using the same procedures as was done for the other parameters. Daily rainfall (including localised thunderstorms) is strongly dependent on a variety of geomorphological features (Dent *et al.* 1989). Fortunately, however, there were very few records of missing daily rainfall data. In the few cases where daily rainfall data were missing, these were 'patched' with estimates using data from surrounding stations. Data from the latter points were compared, taking into account the differences and direction of change in the amounts, and the distances between stations. A subjective estimate of the missing value was then made by inspection.

It is recognised that this approach is at best crude and was only applied for periods of one or two days, to prevent large errors being introduced. In the case of those weather stations that commenced with observations in 1990 or 1991, daily rainfall was interpolated by the University of Natal's School of Bioresources Engineering and Environmental Hydrology using the ACRU programme (Schulze 1995).

3.3. PREPARATION OF DATA FOR THE CALCULATION OF REFERENCE AND CROP EVAPOTRANSPIRATION

Before reference and crop evapotranspiration could be calculated, certain daily weather parameters had to be calculated. These include daylength, daily hours of sunshine duration and wind speed.

3.3.1. DAYLENGTH (N) [hour]

Daylength was calculated using the equation of Allen *et al.* (1998):

$$N = \frac{24}{\pi} \omega_S$$

where ω_S = **sunset hour angle** [radians]

$$\omega_S = \arccos[-\tan(\varphi)\tan(\delta)]$$

φ = **latitude** [radians]

$$\varphi = \frac{\pi}{180}(\text{decimal } \mathit{degrees})$$

δ = **solar declination** [radians]

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right)$$

J = Number of day in the year, i.e. the *nth* day of the year. [-]

3.3.2. DAILY HOURS OF SUNSHINE DURATION

Data on this parameter are essential for the calculation of evapotranspiration, but they are only recorded at Skukuza using a Campbell-Stokes sunshine recorder. In order to be able to determine evapotranspiration at the other weather stations, it was essential to devise a procedure whereby daily estimates of sunshine duration could also be determined for the other weather stations as well. This had to be done within the bounds of existing data of other parameters recorded daily at the weather stations. It then had to be decided which factors are likely to either have a direct influence on sunshine duration, or are indicators of the likelihood that sunshine will vary (upwards or downwards) relative to these factors, either directly or indirectly. Skukuza weather data were used for this analysis.

The factor which has the strongest and most direct influence on sunshine is obviously cloud cover. Unfortunately however, cloud cover can often vary greatly during daylight hours in the KNP. Using the values from either the 08:00 or 14:00 observations would therefore not necessarily be typical of the 'average' cloud cover on a particular day. The only data available for cloud cover is that of these two observation times.

Daily weather parameters used in the initial regression analysis were:

Daylength
Mean cloud cover
Dry bulb temperature at 08:00 and 14:00
Wet bulb temperature at 08:00 and 14:00
Dew point temperature at 08:00 and 14:00
Mean dew point temperature
Maximum temperature
Mean temperature
Percent relative humidity at 08:00 and 14:00
Mean relative humidity
Wind speed at 08:00 and 14:00
Wind direction at 08:00 and 14:00
Weighted wind direction at 08:00 and 14:00
Mean wind direction weight

(Means are of 08:00 and 14:00 values).

Weighted wind direction

An analysis of wind direction and the occurrence of rainfall (i.e. cloudy conditions) showed that at all stations, the predominant rain-bearing wind is from a south-easterly or easterly direction. Conversely, wind blowing from the north-west, west or north ('berg-wind' conditions) are the least likely to bring rain and hence cloud. Wind direction was consequently weighted to reflect these phenomena.

Dent *et al.* (1989) applied a weighting to wind direction in their determination of factors influencing rainfall. The same weight categories as used by Dent *et al.* (1989) were used, except that in this study, in contrast to Dent *et al.* (1989), they were rotated 180° so that winds *not* bearing clouds were weighted the highest. In addition, a different set of weights was used for calm conditions (i.e. no wind), and are based on the amount of cloud cover present. These are listed in Appendix 1, Table A9.

A regression best-model selection using 3 095 observations of the above parameters showed that mean cloud cover, daylength, percent relative humidity at 14:00, mean dew point temperature and mean wind weight were the best parameters. A stepwise multiple regression of these parameters produced the following results ($P<0.0001$ for all independent variables).

	r^2	% contribution
(Mean cloud cover)^2	0.75	75.12
Daylength	0.79	3.70
Relative humidity at 14:00	0.81	2.00
Mean dewpoint temperature	0.82	1.07
Mean wind weight	0.82	0.20
		82.09 %

By means of multiple regression, an equation was produced and used to estimate the daily sunshine hours total. Estimates of <0 were corrected to 0.

Estimated daily hours of sunshine (n):

$$n = 7.9879 - \left(0.1195 * Cc_{mean}{}^{2}\right) - \left(0.0560 * \%RH_{1400}\right) + \left(0.1105 * T_{dew\ mean}\right) - \left(0.0639 * WD_{mean}\right) + \left(0.2838 * N\right)$$

Cc_{mean}	mean cloud cover
RH_{1400}	percent relative humidity at 14:00
$T_{dew\ mean}$	mean dewpoint temperature

WD_{mean} mean wind direction weight
N daylength

r^2 (adjusted) = 0.820; Standard Error = 1.416; Mean Absolute Error = 1.060; DurbWat = 1.676; n = 3 095 observations.

Equation statistics:

Parameter	Standard error	t-value	Significance level
Constant	0.4081	19.5718	<0.0001
(Mean cloud cover)^2	0.0019	-63.7000	<0.0001
% RH_{1400}	0.0026	-23.0245	<0.0001
Mean dewpoint temp.	0.0086	12.9303	<0.0001
Mean wind weight	0.0111	-5.7518	<0.0001
Daylength	0.0360	7.8764	<0.0001

The data are not normally distributed (Standardised skewness = –30.69 for actual hours of sunshine, and –23.41 for predicted hours of sunshine). The Kolmogorov-Smirnov test showed that the two populations are different, though the Mann-Whitney test showed that the means do not differ significantly from each other.

A simple linear regression to test actual vs predicted hours of sunshine for Phalaborwa (an independent data set and on the central western border of the study area) showed a strong correlation (r = 0.88; $r^2 = 0.765$; Standard Error of Estimate = 1.46; n = 7 608 observations). Mean daily hours of sunshine for different mean cloud cover amounts is shown in Figure 3.6. This shows a surprisingly close correlation, except for cloud cover amounts of five to seven octaves and may possibly be an indication of observer error (over-estimation) in estimating cloud cover in this range.

A multiple regression to predict daily total hours of sunshine using mean cloud cover, daylength, maximum temperature and radiation determined by the Hargreaves equation (Allen *et al.* 1998) produced a poorer result than the above equation and was therefore not used ($r^2 = 0.750$; $P<0.0001$ for all parameters).

Although the equation developed here can be refined, its performance was considered to be satisfactory for the purposes of this study and was therefore used to estimate total daily hours of sunshine for those stations where this parameter is not recorded.

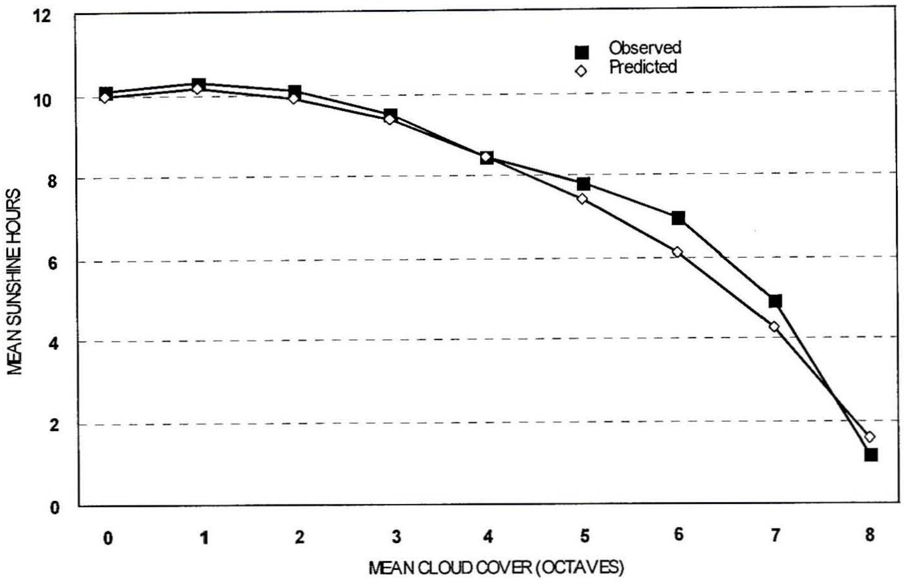


Figure 3.6. Comparison between observed and predicted mean total daily hours of sunshine for different mean cloud cover amounts.

3.3.3. WIND SPEED

Although wind speed (indicated by a pressure plate anemometer) is recorded at 08:00 and 14:00, these values are not representative of the mean wind speed during a longer period. An investigation of mean speed (the latter determined from the 'windrun') and wind speed indicated by the anemometer during the above observation times showed a very poor correlation. This is to be expected as wind seldom blows at a constant speed for any length of time. Speed recorded at the observation times is thus at best, a 'snap-shot' for that point in time.

Within the KNP, windrun, the amount of wind passing a specific point at 2 m above ground level and measured in kilometres, is recorded only at Skukuza using a 'wind totalisator'. From this, the mean speed can be calculated for a period of any length, if the beginning and end times are known.

Windrun is also recorded at the Levubu agricultural research station, approximately 50 km west of Shangoni ranger post. A means to estimate windrun and mean wind speed at the other weather stations therefore had to be devised.

The procedure followed determines a proportional amount of wind at a point, relative to that measured at Skukuza and Levubu. It was assumed that a gradient in windrun between Skukuza and Levubu exists, and that the rate of change in wind speed between these two monitoring stations is constant. The amount of wind at a particular point is thus dependent on its position on the gradient, i.e. its distance from Skukuza or Levubu, whichever is the nearest (Figure 3.7).

A number of equations were consequently developed to determine estimated mean wind speed for those weather stations where this parameter is not recorded by means of a wind totalisator. In only four cases (out of a total of 61 724 calculations), the estimated windrun for stations north or south of Levubu and Skukuza respectively was negative and were corrected to 0.

A. Stations between Skukuza and Levubu, distance a > distance b; $WR_{LEV} < WR_{SKZ}$ (Figure 3.7A):

$$WR_{STN} = WR_{LEV} + \left[b\left(\frac{WR_{SKZ} - WR_{LEV}}{a+b} \right) \right]$$

B. Stations between Skukuza and Levubu, distance a > distance b; $WR_{LEV} > WR_{SKZ}$ (Figure 3.7B):

$$WR_{STN} = WR_{LEV} - \left[b\left(\frac{WR_{LEV} - WR_{SKZ}}{a+b} \right) \right]$$

C. Stations between Skukuza and Levubu, distance a < distance b; $WR_{LEV} < WR_{SKZ}$ (Figure 3.7C):

$$WR_{STN} = WR_{SKZ} - \left[a \left(\frac{WR_{SKZ} - WR_{LEV}}{a+b} \right) \right]$$

D. Stations between Skukuza and Levubu, distance a < distance b; $WR_{LEV} > WR_{SKZ}$ (Figure 3.7D):

$$WR_{STN} = WR_{SKZ} + \left[a \left(\frac{WR_{LEV} - WR_{SKZ}}{a+b} \right) \right]$$

E. Stations north of Levubu, distance a > distance b; $WR_{LEV} < WR_{SKZ}$ (Figure 3.7E):

$$WR_{STN} = WR_{LEV} - \left[b \left(\frac{WR_{SKZ} - WR_{LEV}}{a} \right) \right]$$

F Stations north of Levubu, distance a > distance b; $WR_{LEV} > WR_{SKZ}$ (Figure 3.7F):

$$WR_{STN} = WR_{LEV} + \left[b \left(\frac{WR_{LEV} - WR_{SKZ}}{a} \right) \right]$$

G. Stations south of Skukuza, distance a < distance b; $WR_{LEV} < WR_{SKZ}$ (Figure 3.7G):

$$WR_{STN} = WR_{SKZ} + \left[a \left(\frac{WR_{SKZ} - WR_{LEV}}{b} \right) \right]$$

H. Stations south of Skukuza, distance a < distance b; $WR_{LEV} > WR_{SKZ}$ (Figure 3.7H):

$$WR_{STN} = WR_{SKZ} - \left[a \left(\frac{WR_{LEV} - WR_{SKZ}}{b} \right) \right]$$

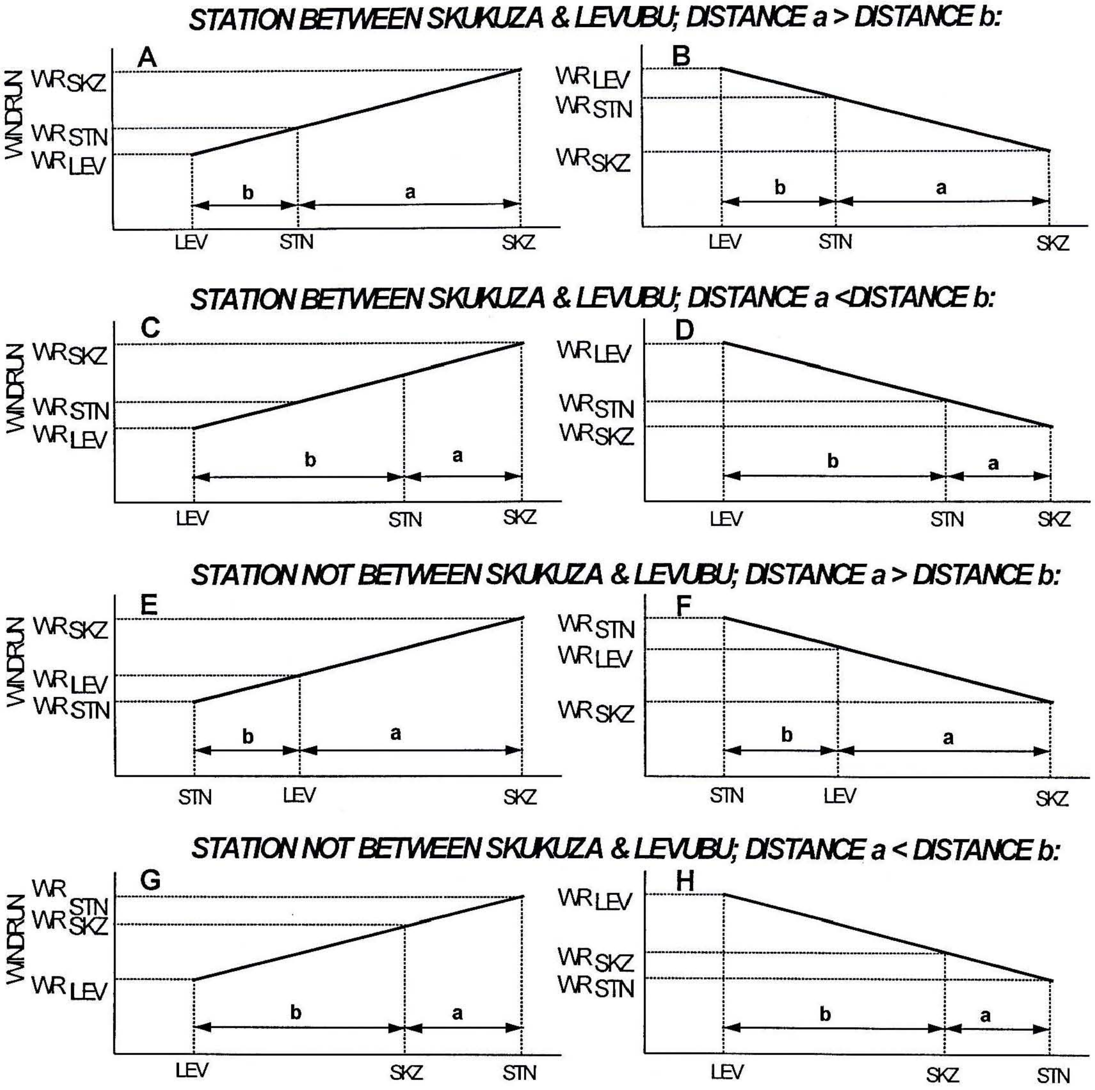


Figure 3.7. Diagrammatic representation of weather station positions relative to windrun gradients. LEV = Levubu; SKZ = Skukuza; STN = station; WR_{LEV} = windrun value at Levubu, etc.

3.4. CLASSIFICATION OF THE KNP ACCORDING TO THE MOISTURE MATRIX OF RUTHERFORD AND WESTFALL

The procedures of Rutherford & Westfall (1986) were used to determine the position of some of the rainfall monitoring stations in a moisture matrix consisting of a Summer Aridity Index (SAI) and the Percentage winter half year rainfall (winter concentration of precipitation). The SAI is an aridity index that refers to mean moisture conditions and is not a drought index, the latter reflecting irregular periods of sub-normal rainfall. Essentially, it is a measure of moisture stress for the period which is potentially well-suited to optimum plant physiological performance (Rutherford & Westfall 1986).

In its original form, the SAI incorporates the mean summer half year rainfall (October to March inclusive) and was designed for application where summer drought is more important and where the hottest four-month period is markedly hotter than that of adjacent months, reflecting a period of maximum potential water stress to plants (Rutherford & Westfall 1986). These authors state further that in the pronounced summer rainfall regions, the amount of rainfall in the wet season is physiologically important and in these areas, the four hottest months overlap to a large extent with the four wettest months.

The SAI was thus modified by using the four wettest months in the moister inland areas of southern Africa, including the "Transvaal" as maximum rainfall quantities are more important than the four hottest months which may not contain the rainfall maxima (Rutherford & Westfall 1986). This modified form was consequently applied in the determination of the moisture regions of the KNP (Figure 4.5).

$$\mathrm{SAI} = 9 - \ln\left[\sum_{i=1}^{4} \mathrm{P}i\right]_{t_{max}}$$

where

P_i mean monthly precipitation [mm]

t_{max} the wettest four months

Winter half year rainfall (R)

The winter half-year rainfall reflects the seasonality of rainfall in the form of winter concentration of precipitation (Bailey 1979), using the rainfall for April to September (Rutherford & Westfall 1986). These authors state that the winter concentration of precipitation is a proportion and is not regarded as a particularly sensitive index on its own, but, combined in a matrix with the SAI, it assumes a much greater significance for correlation with vegetation elements.

$$R = \frac{100(\sum winter\ \text{half precipitation})}{\text{Mean annual precipitation}}$$

According to Rutherford & Westfall (1986), the 'R' factor is fully applicable to southern Africa since all five of Bailey's (1979) classes are present, namely strong winter ($\geq 81\%$), winter (61-80%), even (41-60%), summer (21-40%) and strong summer ($\leq 20\%$).

No rainfall monitoring stations exist in the mountainous area of the south-western corner of the KNP (the highest part of the KNP, with Khandzalive Kop at 839 m asl). Nevertheless, annual rainfall in these areas almost certainly is a great deal higher than that of Pretoriuskop and thus, according to the above criteria, probably has a summer rainfall regime.

3.5. CALCULATION OF REFERENCE AND CROP EVAPOTRANSPIRATION

Note: Whilst particular care was taken with the interpretation and application of the various procedures and calculations of Allen et al. (1998)*, due to their complexity, no guarantee can be given that errors did not occur. The procedures below are thus listed merely to document them as used in this study. Reference to the original work of* Allen et al. (1998) *is consequently recommended for studies similar to this but in other locations.*

The various parameters and procedures described below are presented in the sequence in which they must be calculated. All are derived from Allen *et al.* (1998). The runoff procedures and equations are from Allen *et al.* (1996). Equations, and their symbols or acronyms are given and explained in Appendix 1, Tables A12 and A13 respectively. The calculated or estimated 'default' input data required for these calculations are given in the other tables of this appendix.

3.5.1. REFERENCE EVAPOTRANSPIRATION (ET_o)

Reference crop evaporation was calculated using the FAO Penman-Monteith equation (Allen *et al.* 1998). The reference crop is a hypothetical crop with an assumed height of 0.12 m, closely resembling the evaporation of an extensive surface of green grass of uniform height, actively growing and adequately watered (Allen *et al.* 1998).

The only factors affecting evapotranspiration are climatic parameters and is consequently itself a climatic parameter. It expresses the evaporative power of the atmosphere at a specific location and time of the year, and does not take into account the crop or plant characteristics and soil factors (Allen *et al.* 1998).

In May 1990, a consultation of experts and researchers organised by the FAO in collaboration with the International Commission for Irrigation and Drainage, and the World Meteorological Organisation (1885) recommended the adoption of the Penman-Monteith combination method as the new standard for reference evapotranspiration (Allen *et al.* 1998).

The method overcomes shortcomings of the previous FAO Penman method and provides values more consistent with actual crop water use data world-wide (Allen *et al.* 1998). Mean daily air temperature and wind speed values used in the equation are for 2 m above ground.

Note: in the above equation, a factor of 965 for wind speed measured at 2 m and temperatures at 1.2 m above ground level was used instead of the standard 900 (M. Smith, FAO; pers comm.*).*

The calculation of the following five parameters is essential for the calculation of solar radiation.

Sunset hour angle (ω_s)
Latitude (φ)
Solar declination (δ)
Daylength (N)
Inverse relative distance Earth-Sun (d_r)

The calculation of the remaining 13 parameters is essential for the calculation of reference crop evapotranspiration, ET_o.

Extraterrestrial radiation (R_a)
Solar or (shortwave) radiation (R_s)
Net solar or net shortwave radiation (R_{ns})

Clear-sky solar radiation (R_{so})

Actual vapour pressure (e_a)

Net outgoing longwave radiation (R_{nl})

Net radiation (R_n)

Maximum and minimum saturation vapour pressure ($e^{\circ}T$)

Mean vapour pressure (e_s)

Atmospheric pressure (P)

Psychrometric constant (γ)

Slope of the saturation vapour pressure curve (Δ)

Soil heat flux (G)

The soil heat flux is the energy that is utilised in heating the soil. As the magnitude of the day or ten-day soil heat flux beneath the grass reference surface is relatively small, it may be ignored and $G \approx 0$ (Allen *et al.* 1998).

3.5.2. CALCULATION AND ADJUSTMENT OF CROP COEFFICIENTS AND CALCULATION OF CROP EVAPOTRANSPIRATION (ET_c)

Steps and procedures for calculating ET_c per veld type, in good, moderate and poor condition, and on different soil texture classes are described below and are according to Allen *et al.* (1998). In this study, the 'dual crop coefficient' procedure was used, whereby K_c, the crop coefficient, is split into two separate coefficients: one for crop transpiration; i.e. the basal crop coefficient (K_{cb}), and one for soil evaporation (K_e).

In the 'single crop coefficient' approach, the effect of crop transpiration and soil evaporation are combined into a single K_c coefficient, the latter integrating differences in the soil evaporation and plant transpiration rate between the plant and the grass reference surface (Allen *et al.* 1998).

Allen *et al.* (1998) recommend the dual crop coefficient procedure over the single crop coefficient procedure for research purposes and where detailed soil and hydrologic water balance studies must be undertaken. The time step for this procedure is daily, whereas for the single crop coefficient, this generally is weekly or monthly (although calculations may also be undertaken on a daily basis). Consequently, all calculations were undertaken on a daily basis for 13 weather stations, each for 14 years.

1. Determine phenological stages

Phenological stages were determined as described earlier (Table A2).

2. Estimate basal crop coefficients (K_{cb})

Basal crop coefficients were determined as described earlier (Tables A8 & A10).

3. Potential rate of evapotranspiration (E_{so})

The value 1.5 represents increased evaporation potential due to low albedo of wet soil and heat possibly stored in the surface layer during previous dry periods.

4. Time when stage 1 drying is completed (t_1)

Evaporation from bare soil can be characterized as occurring in two distinct stages; stage 1 being the 'energy limited' stage during which moisture is transported to the soil surface at a rate sufficient to supply the potential rate of evaporation (E_{so}); the later in turn being governed by energy availability at the soil surface (Allen *et al.* 1998).

The maximum total depth of water that can be evaporated during stage 1 is termed 'readily evaporable water' (REW; Appendix 1, Table A14).

5. **Total evaporable water** (TEW; Appendix 1, Table A14); i.e. maximum depth of water that can be evaporated from the soil when the topsoil has initially been completely wetted.

Some degree of protection from evaporation loss is provided to the soil by dead mulch or vegetation. Total evaporation loss will therefore be less than the TEW calculated by the above equation and can be accounted for by reducing TEW by 5% for every 10% of soil surface effectively covered by organic mulch (Allen *et al.* 1998).

6. Mean interval between wetting events (t_w)

Values in Appendix 1, Table A15 were determined from daily rainfall data.

7. Fraction of the soil surface covered by vegetation, as observed from overhead (f_c);

According to Allen *et al.* (1998), in vegetation with incomplete ground cover, evaporation from the soil often does not occur uniformly over the entire surface, but is greater between plants where exposure to sunlight occurs and where more air ventilation is able to transport vapour from the soil surface to above the canopy.

Where the complete soil surface is wetted, then the fraction of the soil surface from which most evaporation occurs (i.e. the exposed and wetted soil fraction), f_{ew}, is essentially defined as ($1-f_c$), where f_c is the average fraction of the soil surface covered by vegetation and ($1-f_c$) is the approximate fraction of the soil surface that is exposed. Where only a fraction of the ground surface is wetted, f_{ew} must be limited to f_w, the fraction of the soil surface wetted by precipitation (Allen *et al.*1998). These concepts are illustrated in Figure 3.8.

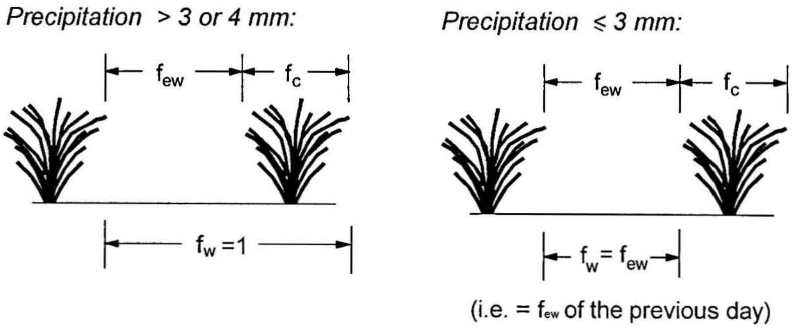


Figure 3.8. The concepts of soil surface covered by vegetation, and exposed soil (adapted from Allen *et al.* 1998).

Maximum and minimum percentage cover was estimated for an 'average' year (a year with mean annual rainfall as defined in Appendix 1, Table A3), according to the various phenological stages and plotted on graph paper for the three veld types, each on basalt and granite; in good, moderate and poor condition; and unburnt and burnt veld. Straight-line equations (Appendix 1, Table A4) were then determined for each stage and used to calculate daily values of f_c and f_{ew}.

Cover of burnt veld was adjusted to 6%, 4% and 2% for veld in good, moderate and good condition respectively to reflect basal cover stubble, unburnt litter, etc. The adjustment periods are the same as for grass height adjustments (Appendix 1, Table A18).

The following rules are applied in determining f_w (Allen *et al.*1998):

- Surface is wetted by significant rain (>3 to 4 mm), with no irrigation: $f_w = 1$.
- Where there is neither significant precipitation nor irrigation: f_w is the f_w of the previous day.

8. Crop coefficient during the initial growth stage (stage 2) ($K_{c\ ini}$)

For $t_w > t_1$, $K_{c\ ini}$ is calculated using the equation in Table A12 (Appendix 1). The $K_{c\ ini}$ calculated from this equation is limited to $K_{c\ ini} \leq 1.15$. When $t_w < t_1$ (i.e. the entire process resides within stage 1),

$$K_{c\,ini} = \frac{E_{so}}{ET_o} = 1.15$$

Where only a portion of the soil surface is wetted, the value for $K_{c\ ini}$ in the above two equations is reduced in proportion to the average fraction of the surface wetted:

$$K_{c\ ini} = f_w K_{c\ ini}$$

9. Maximum value of the crop coefficient following rain ($K_{c\ max}$)

An upper limit to $K_{c\ max}$ is imposed on evaporation and transpiration to reflect the natural constraints placed on available energy represented by the energy balance difference, $R_n - G - \lambda ET - H = 0$; where R_n is the net radiation, H the sensible heat, G the soil heat flux and λET the latent heat flux. This maximum value ranges from about 1.05 to 1.30 when using the grass reference ET_o (Allen *et al.* 1998).

This equation ensures that $K_{c\ max}$ is always greater or equal to the sum K_{cb} + 0.05. This requirement indicates that wet soil will always increase the value for K_{cb} by 0.05 following complete wetting of the soil surface, even during periods of full ground cover. A value of 1.2 instead of 1.0 is used for $K_{c\ max}$ in the equation because of the effect of increased aerodynamic roughness of surrounding vegetation during development, mid-season and late-season growth stages, which can increase the turbulent transfer of vapour from the exposed soil surface. The '1.2' coefficient also reflects the impact of the reduced albedo of wet soil and the contribution of heat stored in dry soil prior to the wetting event. All of these factors can contribute to increased evaporation relative to the reference (Allen *et al.* 1998).

It also represents the effects of wetting intervals that are greater than three or four days. If precipitation events are frequent, e.g. daily or every two days, then the soil has less opportunity to absorb heat between wettings and the '1.2' coefficient can be reduced to about 1.1 (Allen *et al.* 1998).

10. Basal crop coefficient during the mid-season growth stage when plant density and/or leaf area are lower than for full cover conditions ($K_{cb\ mid\ adj}$)

In the equation (Table A12), the value for $K_{c\ min}$ is the minimum K_c for bare soil. In the presence of vegetation $K_{c\ min} \approx 0.15\text{-}0.20$ and for burnt areas, it is set to 0. For vegetation having full ground cover or LAI >3, $K_{cb\ full}$ is the estimated basal K_{cb} during the mid-season (at peak plant size or height).

This equation adjusts the K_{cb} in climates where RH_{min} differs from 45% or where the wind speed is < or > 2 m s^{-1}. $K_{cb\ mid}$ and $K_{cb\ end}$ values larger than 0.45 are adjusted using the same equation.

11. Surface runoff (RO)

Surface runoff was estimated in inches using the modified Runoff Curve Number Model equation (Allen *et al.* 1996) and then converted to mm.

12. Soil evaporation reduction coefficient (K_r)

Evaporation from exposed soil can be assumed to occur in two stages: an energy limiting stage (stage 1), and a falling rate stage (stage 2). When the soil surface is wet, K_r is 1. When the water content in the upper soil becomes limiting, K_r decreases; becoming zero when the total amount of water that can be evaporated from the soil is depleted (Allen *et al.*1998).

Shortly after a major wetting event, it is assumed that the water content of the evaporating layer of the soil is at field capacity, θ_{FC}, the amount of water depleted by evaporation, D_e, is zero, and that the soil can dry to a water content level which is midway between oven dry (i.e. completely dry) and wilting point, θ_{WP}. The amount of water that can be depleted by evaporation during a complete drying cycle is thus be estimated by the equation in Table A12.

The second stage, the 'falling rate' stage, starts when D_e exceeds REW, at which point the soil is visibly dry; evaporation from the exposed soil decreases in proportion to the amount of water remaining in the surface soil layer (Allen *et al.* 1998).

13. Soil evaporation coefficient (K_e)

The soil evaporation coefficient, K_e, describes the evaporation component of the crop evapotranspiration, ET_c under standard conditions. It is maximal when the soil is wet following rain (or irrigation); and small or zero when no water remains near the soil surface for evaporation (Allen *et al.* 1998).

When the soil is wet, evaporation from the soil occurs at the maximum rate, but the crop coefficient ($K_c = K_{cb} + K_e$) can never exceed a maximum value, $K_{c\ max}$, this being determined by the energy available for evapotranspiration at the soil surface.

When the topsoil dries out, less water is available for evaporation and a reduction in evaporation begins to occur in proportion to the amount of water remaining in the surface soil layer.

For dormant periods, i.e. long periods without rainfall when the topsoil layer may have a very low water content, K_{cb} is set to zero. This provides for the opportunity to predict $ET_c = 0$

during such periods and is necessary to preserve the water balance of the evaporation layer and of the root zone in total. The daily water balance calculation with $K_{cb} = 0$ provides the most accurate estimates of ET_c during non-growing periods (Allen *et al.* 1998).

The estimation of K_e in the calculation procedure requires a daily water balance computation for the surface soil layer for the calculation of the cumulative evaporation or depletion from the wet condition. The daily soil water balance calculation for the exposed and wetted soil fraction (f_{ew}) is a complicated process and requires the solution of a number of equations:

$D_{e,i-1}$	cumulative depth of evaporation following complete wetting from the exposed and wetted fraction of the topsoil at the end of day i-1
$D_{e,i}$	cumulative depth of evaporation (depletion) following complete wetting at the end of day i
RO_i	precipitation runoff from the soil surface on day i
E_i	evaporation on day i
$DP_{e,i}$	deep percolation loss from the topsoil layer on day i if soil water content exceeds field capacity
f_w	fraction of soil surface wetted by irrigation
f_{ew}	exposed and wetted soil fraction

Rules and limitations: Allen *et al.* (1998) give guidelines in applying the parameters in the $D_{e,i}$ equation.

By assuming that the topsoil is at field capacity following heavy rain (or irrigation), the minimum value for the depletion $D_{e,i}$ is zero. As the soil surface dries, $D_{e,i}$ increases and in the absence of any wetting event, will steadily reach its maximum value TEW. At that point, no water remains for evaporation in the upper soil layer, K_r becomes zero, and the value for $D_{e,i}$ remains at TEW until the topsoil is wetted once again. The limits imposed on $D_{e,i}$ consequently are:

$$0 \leq D_{e,i} \leq TEW$$

To initiate the water balance for the evaporating layer, it is assumed that the topsoil is near field capacity following heavy rain (or irrigation), i.e. $D_{e,i-1} = 0$. Where a long period of time has elapsed since the last wetting, it is assumed that all evaporable water has been depleted from the evaporation layer at the beginning of calculations, i.e. $D_{e,i-1}$ = TEW. This was the case in this study as calculations commenced during the dry season.

Daily precipitation amounts of less than about $0.2ET_o$ were ignored in the K_e and water balance calculations as this amount is normally entirely evaporated (Allen *et al.* 1998).

For general situations, the amount of rainfall lost by runoff (RO_i) can be assumed to be zero or can be accounted for by considering only a certain percentage of P_i. The procedures of (Allen *et al.* 1996) were used to determine runoff, with light precipitation events producing no runoff. As this study deals exclusively with natural vegetation, the effects of irrigation were ignored. Evaporation beneath the vegetation canopy is assumed to be included in K_{cb} and is therefore not explicitly quantified.

Following heavy rain (≥40 mm during a relatively short period such as a single rainfall event or in 24 hours), the soil water content of the topsoil layer (Z_e layer) may exceed field capacity, though in this simple procedure, it was assumed that the soil water content is at θ_{FC} almost immediately following a complete wetting event so that deep percolation $DP_{e,i}$, was assumed to be zero for rainfall amounts <40 mm. As long as the soil water content in the evaporation layer is below field capacity (i.e. $D_{e,i} > 0$), the soil will not drain and $DP_{e,i} = 0$ (Allen *et al.* 1998). For amounts >40 mm, deep percolation out of the root zone was calculated using the equation of Allen *et al.* (1998), the I_i/f_w factor being ignored as irrigation was not applied.

14. Evaporation depletion factor (p)

The evaporation depletion factor (Table A24) is the average fraction of total available soil water (TAW) that can be depleted from the root zone before moisture stress (reduction in ET) occurs).

Wet soil has a high potential energy. The water is relatively free to move and is easily taken up by plant roots. When the potential energy of the soil water drops below a threshold value, the plant is said to be 'water-stressed' (Allen *et al.* 1998).

Under water stress conditions (the normal, dry-season situation in the KNP), the water in dry soils has a low potential energy and is bound by capillary and absorptive forces to the soil matrix, and is less easily extracted by the plant than is the case under stress-free conditions (Allen *et al.* 1998). The effects of soil water stress are described by multiplying the basal crop coefficient by the water stress coefficient, K_s, giving the crop evapotranspiration under non-standard conditions.

15. Total Available Water (TAW)

Allen *et al.* (1998) state that soil water availability refers to the capacity of a soil to retain water available to plants. After heavy rainfall (or irrigation), the soil will drain until field capacity is reached. *Field capacity* is the amount of water which a well-drained soil should hold against gravity; or the amount of water remaining when downward drainage has markedly decreased.

In the absence of a water supply, the water content in the root zone decreases as a result of water uptake by the plant. As this process continues, the remaining water is held to the soil particles with greater force, lowering its potential energy and making it more difficult for the plant to extract it. A point is eventually reached where the plant can no longer extract the remaining water and the water uptake consequently becomes zero when the wilting point is reached. Wilting point is the water content at which plants will permanently wilt (Allen *et al.* 1998).

As the water content above field capacity cannot be held against gravity and will drain; and as the water content below wilting point cannot be extracted by plant roots, the total available water in the root zone is therefore the difference between the water content at field capacity and wilting point (Allen *et al.* 1998).

TAW is thus the amount of water that a plant can extract from its root zone, its magnitude depending on the type of soil and the rooting depth. Typical ranges for θ_{FC} and θ_{WP} are given in Table A21 for various soil texture classes, and estimated Z_r values in Table A22.

16. Readily Available Water (RAW)

Theoretically, water is available until wilting point, though in reality, water uptake is reduced well before wilting point is reached. Where the soil is sufficiently wet, it supplies water fast enough to meet the atmospheric demand of the plant. Water uptake thus equals ET_c. As the soil water content decreases however, water becomes more strongly bound to the soil matrix and is more difficult to extract. When the soil water content drops below a certain threshold value, soil water can no longer be transported quickly enough towards the roots to respond to the transpiration demand and the plant begins to experience stress. The fraction of TAW which a plant can extract from the root zone without suffering stress is the readily available water (Allen *et al.* 1998).

17. Water stress coefficient (K_s) [-]

The effects of soil water stress on plant ET are described by reducing the value for the crop coefficient by multiplying it with the water stress coefficient.

Water content in the root zone can also be expressed by root zone depletion (i.e. water shortage relative to field capacity), D_r. At field capacity, root zone depletion is zero ($D_r=0$). When soil water is extracted by evapotranspiration, the depletion increases and stress will be induced when D_r becomes equal to RAW. After the root zone depletion exceeds RAW (the water content drops below the threshold θ_t), the root zone depletion is high enough to limit evapotranspiration to less than potential values, plant evapotranspiration beginning to decrease in proportion to the amount of water remaining in the root zone (Allen *et al.* 1998).

The estimation of K_S thus requires the daily computation of the water balance of the root zone ($D_{r,i}$). Rainfall, irrigation and capillary rise of groundwater towards the root zone add water to the root zone, thus decreasing the root zone depletion. Soil evaporation plant transpiration and percolation losses remove water from the root zone and increase the depletion (Allen *et al.* 1998).

In the KNP, except for seasonal 'seeplines', the water table is well below 1 m from the bottom of the grass root zone, in which case capillary rise can be assumed to be zero (Allen *et al.* 1998).

The concept of soil water stress (also referred to as 'root stress' and was used as one of the independent variables in this study) is perhaps best explained with the aid of the following figure. In the graph, the 'spikes' in the coefficient reflect days when soil moisture increases as a result of rainfall (or irrigation).

Rules and limitations:

The limit imposed on $D_{r,i}$ is:

$$0 \leq D_{r,i} \leq TAW$$

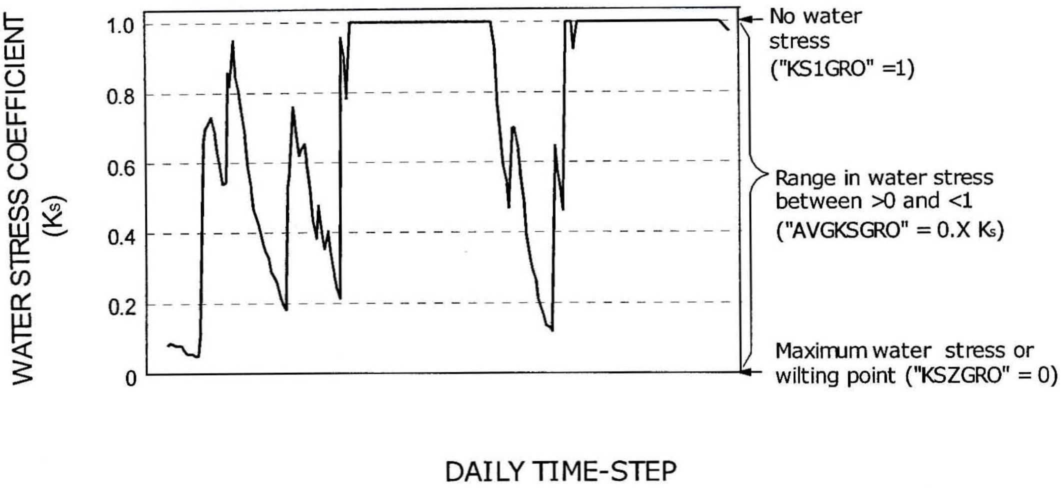


Figure 3.9. The concept of the water stress (or 'root stress') coefficient, K_S.

According to Allen *et al.* (1998), it is assumed that water can be stored in the root zone until field capacity is reached. Although following heavy rain or irrigation the water content may temporarily exceed field capacity, the total amount of water above field capacity is assumed to be lost on the same day by deep percolation, following any ET for that day. By assuming that the root zone is at field capacity following heavy rain or irrigation, the minimum value for the depletion $D_{r,i}$ is zero.

As a result of percolation and evapotranspiration, the water content in the root zone will gradually decrease and the root zone depletion will increase. In the absence of any wetting event, the water content will steadily reach its minimum value θ_{WP}. At that moment, no water is left for evapotranspiration in the root zone, K_s becomes zero, and the root zone depletion reaches its maximum value TAW (Allen *et al.* (1998).

To initiate the water balance for the root zone, the initial depletion $D_{r,i-1}$ should be estimated. The initial depletion can be derived from measured soil water content by solving for $D_{r,i-1}$.

Following heavy rain (or irrigation), it is assumed that the root zone is near field capacity, i.e. $D_{r,i-1} \approx 0$. In this study, θ_{i-1} was assumed to be the wilting point as grasses have wilted completely by the start of the climatic year and was estimated as 0.35TAW [mm]. Estimates for various soil texture classes are given in Table A25.

As for K_e, precipitation amounts of less than $0.2ET_o$ were ignored. No irrigation is applied and was therefore also ignored.

Where the soil water depletion is smaller than RAW, evapotranspiration $ET_c = K_cET_o$. As soon as $D_{r,i}$ exceeds RAW, evapotranspiration is reduced and can be computed by the equation for $ET_{c\ adj}$ (Allen *et al.* 1998). Following heavy rain (or irrigation), the soil water content in the root zone might exceed field capacity. In the simple procedure of Allen *et al.* (1998), it is assumed to be at θ_{FC} within the same day of the wetting event, so that the depletion $D_{r,i}$ becomes zero. As long as the soil water content in the root zone is below field capacity (i.e.$D_{r,i} > 0$), the soil will not drain and $DP_i = 0$ (Allen *et al.* 1998).

18. Crop evapotranspiration under non-standard conditions ($ET_{c\ adj}$)

When the potential energy of the soil water drops below a threshold value, the crop is said to be stressed; the effects of soil water stress being described by multiplying the basal crop coefficient by the water stress coefficient, K_s (Allen *et al.* 1998). Stress may also be due to hard or impenetrable soil, poor soil fertility, waterlogging, pressure by herbivores (vertebrate and invertebrate) and diseases. Some of these environmental conditions are thus described by stress coefficients, which are added to the final equation for determining ET_c and include K_s, K_{cb}, K_e in the dual crop coefficient equation:

$$ET_{c\ adj} = \left(K_s K_{cb} + K_e\right) ET_o$$

3.6. STATISTICAL ANALYSES

3.6.1. GRASS SWARD NETT PRIMARY PRODUCTION (NPP) AND NETT STANDING CROP (NSC)

A primary objective of this study was to identify which variables are important determinants of NPP and NSC, these two concepts being differentiated in Chapter 2, section 2.2.).

The determination of standing crop in the KNP and in many other parts of the country is undertaken routinely using the disc pasture meter, which has been calibrated for particular areas. The basis of the calibration is the mathematical relation between the settling height of the disc pasture meter and the mass of the material underneath it. In time, this may be revised, in which case other relations established between the standing crop value determined by the redundant mathematical equation and other parameters may also automatically become redundant.

The revised calibration of the DPM for the KNP (Chapter 5) has not been subjected to peer review or examination and may, in some way or other, be flawed. It was consequently decided to use the mean DPM height as the dependent variable, instead of using grass NSC values (either the original values of Trollope & Potgieter (1986) or values resulting from the revised DPM calibration equations of this study). The mean DPM measurement can be regarded as being 'generic' or basic and, provided measurements taken using this instrument are used in any future re-evaluation of the relations between DPM height and NSC, the results of this study should still be applicable.

A further advantage is that the results of this study are more directly comparable with similar studies in other areas, provided that the DPM is also used in these studies to determine NPP or NSC. Furthermore, a future revision of the DPM calibration, either in the KNP or elsewhere, should have no effect on such a comparison.

Monthly disc pasture meter adjustment factors

Approximately 85% of the sites are surveyed during March and April. Although no data are available, it is suspected that growth of the standing crop peaks in February or March, the former particularly in the drier, northern parts of the KNP which have a shorter growth period. In order to standardize annual peak DPM values to a common month, monthly adjustment factors were determined and are based on the work undertaken by Grunow *et al.* (1980) at Nylsvley.

Monthly standing crop values were determined from Figure 2 of Grunow *et al.* (1980). Peak standing crop at Nylsvley is reached in February. The proportion of the peak standing crop which a particular month's standing crop comprises was then calculated to produce a factor for each month (Factor = peak standing crop/month's standing crop). Factors for peaks occurring in January to April were determined by drawing (adding) estimated decline curves to Figure 2 of Grunow *et al.* (1980) and are listed in Appendix 1, Table A16. Mean DPM values for the KNP were then adjusted according to the above factors.

The adjustment of DPM heights by these factors however resulted in values being greater than 60 cm in certain cases; the maximum possible for the DPM. This was consequently not pursued further (though there is merit in testing and refining it at a later stage) and use was made of the measured (mean) DPM height instead.

3.6.2. COMPOSITION

A second objective of this study was to determine which factors play a significant role in determining composition, in terms of the major perennial/annual, and Decreaser/Increaser classification categories, and the importance of herbivore utilisation. It was decided however, that in order to limit the scope of this study to practically feasible level, a separate analysis at the grass species level should be left to a separate study, the emphasis in the current study being at the broader, category level.

As with NPP and NSC, stepwise regression was used, with the data being sub-set as shown below. Differences in the coefficient of determination resulting from the inclusion or exclusion of herbivore biomass data, together with the strength of the probability statistic (P) of the herbivore categories, should be an indication of the importance of herbivores in determining composition - the assumption being that the greater the difference, the greater the role which herbivores play in determining composition.

Variables used in these analyses were similar to those used in the NPP and NSC analyses, except that the compositional categories 'Other grasses', 'Forbs' and 'Bare ground' were omitted, on the assumption that they are not determinants of the target groups.

Data sub-sets were similar to the NPP and NSC sub-sets, with perennials and Decreasers being the dependent variables.

A test regression analysis using arc-sine transformed an untransformed grass composition percentages showed little difference between the two. Untransformed percentages were consequently used in all analyses.

3.6.3. INDEPENDENT VARIABLES

A total of 72 independent variables were used in the stepwise and tree regressions. These are listed in Table 3.3, together with their abbreviations and units.

Table 3.3. Independent variables, their abbreviations and units as used in the analyses

VARIABLE	**ABBREVIATION**	**UNIT**
Burn interval (period since previous burn)	BURN.INTER	[years]
Burn frequency during 1980-1999	BURN.FREQ	[years]
Total rainfall during the dormant stage (current year)	RFDOR	[mm]
Total rainfall during the growth stage (current year)	RFGRO	[mm]
Total rainfall during the growth stage (previous year)	RFGRO.1	[mm]
Total rainfall during the growth stage (two years ago)	RFGRO.2	[mm]
Total rainfall during the growth stage (three years ago)	RFGRO.3	[mm]
Total rainfall (current year)	RFYR	[mm]
Total rainfall (previous year)	RFYR.1	[mm]
Total rainfall (two years ago)	RFYR.2	[mm]
Total rainfall (three years ago)	RFYR.3	[mm]
Total raindays during the dormant stage (current year)	DAYDOR	[days]
Total raindays during the growth stage (current year)	DAYGRO	[days]
Total raindays during the growth stage (previous year)	DAYGRO.1	[days]
Total raindays during the growth stage (two years ago)	DAYGRO.2	[days]
Total raindays during the growth stage (three years ago)	DAYGRO.3	[days]
Total raindays (current year)	DAYYR	[days]
Total raindays (previous year)	DAYYR.1	[days]
Total raindays (two years ago)	DAYYR.2	[days]
Total raindays (three years ago)	DAYYR.3	[days]

Variance of raindays (current year)	VAR	[days]
Standard deviation of raindays (current year)	SDEV	[days]
Standardised skewness of raindays (current year)	SSKEW	[-]
Standardised kurtosis of raindays (current year)	SKURT	[-]
Coefficient of Variation of raindays (current year)	CFVAR	[-]
Total evapotraspiration during the dormant stage (current year)	ETDOR	[mm]
Total evapotraspiration during the growth stage (current year)	ETGRO	[mm]
Total evapotraspiration during the growth stage (previous year)	ETGRO.1	[mm]
Total evapotraspiration during the growth stage (two years ago)	ETGRO.2	[mm]
Total evapotraspiration during the growth stage (three years ago)	ETGRO.3	[mm]
Total days without root moisture stress during the growth stage (current year)	KS1GRO	[days]
Total days without root moisture stress during the growth stage (previous year)	KS1GRO.1	[days]
Total days without root moisture stress during the growth stage (two years ago)	KS1GRO.2	[days]
Total days without root moisture stress during the growth stage (three years ago)	KS1GRO.3	[days]
Total days of maximum root moisture stress during growth stage (current year)	KSZGRO	[days]
Total days of maximum root moisture stress during growth stage (previous year)	KSZGRO.1	[days]
Total days of maximum root moisture stress during growth stage (two years ago)	KSZGRO.2	[days]
Total days of maximum root moisture stress during growth stage (three years ago)	KSZGRO.3	[days]
Mean root stress coefficient (>0 to <1) during the growth stage (current year)	AVGKSGRO	[-]
Mean root stress coefficient (>0 to <1) during the growth stage (previous year)	AVGKSGRO.1	[-]
Mean root stress coefficient (>0 to <1) during the growth stage (two years ago)	AVGKSGRO.2	[-]
Mean root stress coefficient (>0 to <1) during the growth stage (three years ago)	AVGKSGRO.3	[-]
Typical clay content of the A horizon for the particular texture class	CLAY	[%]
Typical silt content of the A horizon for the particular texture class	SILT	[%]
Typical organic carbon content of the A horizon for the particular texture class	ORG.CARBON	[%]
pH of the A horizon	PH.A	[pH]
Base status fertility index	BSFI	[-]
Clay content fertility index	CCFI	[-]
Soil fertility index	SOILFERT	[-]
Thickness of the A horizon	THICK.A	[m]
Effective depth of the soil profile	EFF.DPTH	[m]
Distance to the nearest permanent water-point	DIST.H2O	[km]
Amount of perennial grasses	PEREN	[%]
Amount of annual grasses	ANN	[%]
Amount of Decreaser grasses	DECR	[%]
Amount of Increaser II grasses	INC2GR	[%]
Amount of 'Other' grasses	OTHERS	[%]
Amount of forbs	FORBS	[%]
Amount of bare ground	BARE	[%]
Total woody canopy cover	WDYCANO	[m^{-2}]
Total mass of concentrate feeders (current year)	CONCMAS	[tonnes]
Total mass of concentrate feeders (previous year)	CONCMAS.1	[tonnes]
Total mass of concentrate feeders (two years ago)	CONCMAS.2	[tonnes]
Total mass of concentrate feeders (three years ago)	CONCMAS.3	[tonnes]
Total mass of bulk feeders (current year)	BULKMAS	[tonnes]
Total mass of bulk feeders (previous year)	BULKMAS.1	[tonnes]
Total mass of bulk feeders (two years ago)	BULKMAS.2	[tonnes]
Total mass of bulk feeders (three years ago)	BULKMAS.3	[tonnes]

Total mass of mixed feeders (current year)	MIXMAS	[tonnes]
Total mass of mixed feeders (previous year)	MIXMAS.1	[tonnes]
Total mass of mixed feeders (two years ago)	MIXMAS.2	[tonnes]
Total mass of mixed feeders (three years ago)	MIXMAS.3	[tonnes]

3.6.4. SUB-SETTING OF DATA

Data were sub-set as follows:

('ET' is used as collective term and includes ET_c and the other associated parameters).

A. DPM of veld burnt during the preceding dry season (i.e. grass sward NPP)

- Basalt and granite, each with the following grass sward composition groups:
  - Perennial-Annual group
    - ET variables included
    - ET variables excluded
  - Decreaser-Increaser group
    - ET variables included
    - ET variables excluded

B. DPM of veld *not* burnt during the preceding dry season (i.e. grass sward NSC)

- Basalt and granite, each with the following grass sward composition groups:
  - Perennial-Annual group
    - ET variables included
    - ET variables excluded
  - Decreaser-Increaser group
    - ET variables included
    - ET variables excluded

The *rationale* for the inclusion and exclusion of the ET variables was based on the fact that a considerable proportion of the parameters used to calculate the ET estimates are based on estimates, which can differ significantly from actual, measured values. This in turn can result in substantially incorrect ET estimates. At the same time, and assuming that these are within acceptable limits, their omission or inclusion should also indicate how important a role they play as a whole.

The second reason concerned practical considerations in the application of the results. More specifically, to determine whether satisfactorily strong relations could be determined between the dependent and independent variables using data from only those parameters which are readily available or are relatively easy and quick to calculate.

In the case of basalt, herbivore biomass was excluded as there are too many missing values (almost 43% of all the records), resulting in an error and the automatic termination of the regression analysis procedure.

3.6.5. MULTIVARIATE ANALYSES

Multivariate analysis was used as an initial attempt at analysing the data. This however proved to be unsuccessful as these techniques are not suited for identifying those factors (determinants) which influence a single response variable. This was consequently abandoned.

3.6.6. STEPWISE LINEAR REGRESSION

As an alternative to multivariate analysis, stepwise linear regression was employed, with the knowledge that this procedure leads to autocorrelation and a number of other statistical problems, as well as difficulty in interpreting results. The S-Plus 2000 statistical software programme (Mathsoft 1999) was used.

Stepping in both directions was undertaken whereby terms are added (by forward selection) to the model until additional terms no longer improve the goodness-of-fit, at each step the term being added which most improves the fit. Backward selection drops terms from the model as long as dropping terms does not significantly decrease the goodness-of-fit. At each step, the term is dropped whose removal least degrades the fit (Mathsoft 1999). Both forward and backward selection was undertaken, the default method used by the programme.

Paired initial equations were produced by this manner, i.e. to include and exclude the ET variables, as described above. Each was then inspected and variables with $P>0.05$ were removed, and the procedure re-run to produce a modified equation. This was repeated until all the variables had a P of ≤ 0.05. The cost of this procedure however was a progressive reduction in the coefficient of determination, r^2.

3.6.6.1. **Validation**

A number of samples from each category were set aside for validation and were not used in the development of the regression equations. These were chosen by means of random numbers. These data, together with the equations produced by each of the steps described above were then used to calculate DPM estimates for burnt veld (i.e. NPP), unburnt veld (NSC), perennials and Decreasers.

Validation was undertaken using the CurveExpert 1.3 software (http://www.ebicom.net/) . This tests each of over 30 data modelling equations (curve fits, including the linear family) against the data, using the Levenberg-Marquardt algorithm for quick, non-linear regression performance, and chooses the best fit. This software however does not provide the coefficient of determination (r^2) or the probability statistic (P). Consequently, using the equation produced by CurveExpert, the data were re-analysed using the Statgraphics Plus software (Manugistics 1996) in order to obtain this parameter and the Standard Error of Estimate (SEE), Mean Absolute Error (MAE) and the Mean Error (ME). These are explained by Manugistics (1996) as:

SEE: The value for the standard deviation of the residuals, and can be used to construct prediction limits for new observations.

MAE: The average of the absolute values of the residuals. If the result is a small value, it can be used to predict performance more precisely; if the value is large, a different model may be used.

ME: The average of the residuals. The closer the ME is to 0, the less biased, or more accurate, the prediction.

Correlation results varied from strong in the case of NPP and NSC, to very poor in the case of composition. This consequently necessitated that an alternative technique be used.

3.6.7. NON-LINEAR REGRESSION

Throughout this dissertation, non-linear curves were the result of the CurveExpert software automatically fitting the best curve to the data. This may have in some cases resulted in 'over-fitting' the curve. In the case of the disc pasture meter calibration however, the equations of these curves are regarded as means to obtain estimates of standing crop, rather than as accurate predictors. Where higher order polynomial fits were produced by CurveExpert, these are regarded as being mathematical descriptors of relations, rather than mathematical predictors, and were not used as such, nor are they intended to be used for predictive purposes. It is felt that the moderate level of over-fitting does not impact their use in this role.

3.6.8. TREE REGRESSION

Tree regression is part of the CART (classification and regression tree) analytical procedures and are thus useful for both classification and regression problems (Mathsoft 1999) and are ideally suited for the analysis of complex ecological data (De' Ath & Fabricius 2000). Tree-based models provide an alternative to linear and additive models for regression problems. They are exploratory in nature and are fitted by successively splitting the data to form homogenous sub-sets, resulting in a hierarchical tree of decision rules useful for prediction or classification and are suited to summarising large multivariate data sets (Mathsoft 1999).

They also provide better understanding of relations between the response and independent variables, as well as the interactions between these variables (Breiman *et al.* 1984) and are thus perhaps better suited to the objectives of this study than the former methods are. Compared to linear and additive models, tree-based models have the following advantages (Mathsoft 1999; De' Ath & Fabricius 2000):

- Easier to interpret when the predictors are a mix of numeric variables and factors.
- Invariant to monotone re-expressions of predictor variables.
- More satisfactorily treat missing values.
- More adept at capturing non-additive behaviour.
- Allow a more general (i.e. other than that of a particular multiplicative form) interactions between predictor variables.

- Can model factor response variables with more than two levels.
- Are not normally influenced unduly by autocorrelations.

Sub-setting of the data was similar to that described above for stepwise regression. Records with missing values are omitted by S-Plus 2000. This can significantly reduce the total number of samples, as was the case with the NPP data-sets for basalt and granite. These were reduced from 98 and 104 to 25 and 28 respectively. In a preliminary analysis, herbivore mass was in any case eliminated by the analysis. It was consequently decided to exclude these variables completely from the NPP analyses. This increased the total number of samples to 72 on basalt and 82 on granite, thereby ensuring that the results are based on a larger sample.

In addition, for the reasons mentioned above, herbivore mass was initially not omitted, in spite of a large proportion of some of the data sets having missing values.

Tree regressions of NPP and NSC were also undertaken specifically for managers in order to provide an additional tool for decision-support purposes. With the revised burning policy for the KNP, section rangers need to have information on the standing crop in their sections at the start of the dry season for planning purposes.

These tree regressions differ from the other regressions by their simplification: for practical purposes, the independent variables were limited to those parameters which are routinely obtainable or which can be determined easily. In the case of NPP, these are limited to rainfall and composition (percent perennials, forbs and bare ground) only, with the addition of the time since last burn in the case of standing crop. Rainday statistics (skewness, kurtosis, coefficient of variation, variance and standard deviation) were included in the rainfall variables as these are easily computed from daily rainfall data.

Clearly, because of their simplification, these regressions do not provide any insight into the relations between the grass sward and its environment, nor was there any intention to do so. For practical, management purposes, this is not essential and is consequently only intended to serve as practical tools for the manager to rapidly and easily determine standing crop for the specific purpose of veld burning.

The S-Plus 2000 software was used for the tree analyses (Mathsoft 1999). Although this allows for pruning and trimming exercises to be carried out, this was not undertaken in order not to loose information, particularly at the lower (finer) levels as this could prove to be essential in any future use of the results.

3.6.8.1. **Validation of the tree regressions**

Using the data set aside for validation purposes as described above, validation of the tree regressions developed for management purposes was undertaken using simple regression and the CurveExpert 1.3 software (http://www.ebicom.net/) and the Statgraphics Plus software (Manugistics 1996) for non-linear regression.

3.7. SUMMARY

In order to include as many of the variables as possible which are known or may possibly play a role in determining grass sward production, standing crop and composition, a very large diversity and quantity of data had to be obtained. This included data on soil, vegetation, herbivores and burning history. Data on a considerable proportion of the input parameters required for the calculation of crop evapotranspiration had to be calculated from other, existing data, or do not exist for the KNP. In the latter cases, estimates based on personal experience and on the experience and opinions of colleagues with many years' experience in, and knowledge of the KNP ecosystem were used. The calculation of evapotranspiration at a daily time-step following the latest procedures known to the author, those of Allen *et al.* (1998), are complex. This was undertaken for a period of 14 years and for 13 weather stations, requiring many hours of computer programming and processing.

CHAPTER 4

INVESTIGATION OF THE RELATIONS BETWEEN STANDING CROP AND COMPOSITION AND THEIR ENVIRONMENT

4.1. RAINFALL

4.1.1. MAP OF MEAN ANNUAL RAINFALL

The modified map of mean annual rainfall (Dent *et al.* 1989) is shown in Figure 4.1. Classes are according to 50 mm rainfall. Most of the KNP (81.9%) receives a mean annual rainfall of between 401 and 600 mm with 15.9% receiving more than this, and 2.2% receiving 400 mm or less (Table 4.1). The greatest proportion of the KNP can thus be described as being arid to semi-arid.

Table 4.1. Mean annual rainfall classes and percent of the KNP in the class

RAINFALL CLASS (mm)	% OF KNP
350 - 400	2.23
401 - 450	10.56
451 - 500	23.74
501 - 550	25.16
551 - 600	22.38
601 - 650	12.86
651 - 700	2.29
701 - 750	0.44
751 - 800	0.20
801 - 850	0.03
851 - 900	0.08
901 - 950	0.01

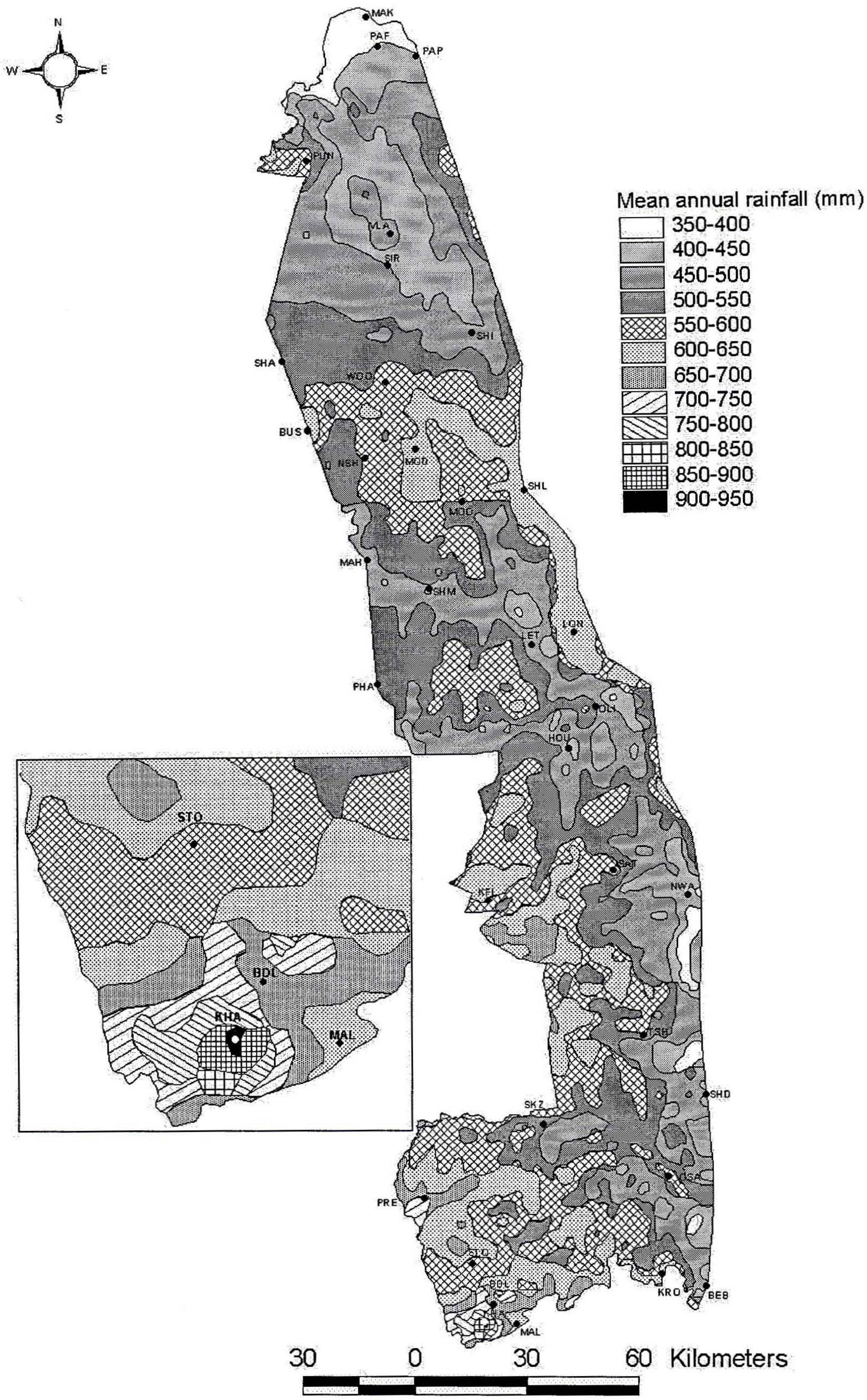


Figure 4.1. Mean annual rainfall map of the KNP. Adapted from Dent *et al.* (1989). Inset shows detail of the south-western corner. See Figure 2.1. for place names.

4.1.2. COEFFICIENT OF VARIATION OF ANNUAL RAINFALL

The relation between CV and mean annual rainfall shows that the greatest range is for those stations situated within the Arid moisture region, followed by stations in the Semi-arid and Mesic regions (Figure 4.2). It is interesting to note that in spite their relatively high mean annual rainfall, the CV of Malelane and Stolznek is higher than that of certain stations with a lower mean annual rainfall. These stations are both situated close to the mountainous region of the south-western corner of the KNP. The relatively high CV thus probably reflects the strong influence of these mountains on the rainfall of this area. The spatial distribution of the coefficient of variation is shown in Figure 4.3.

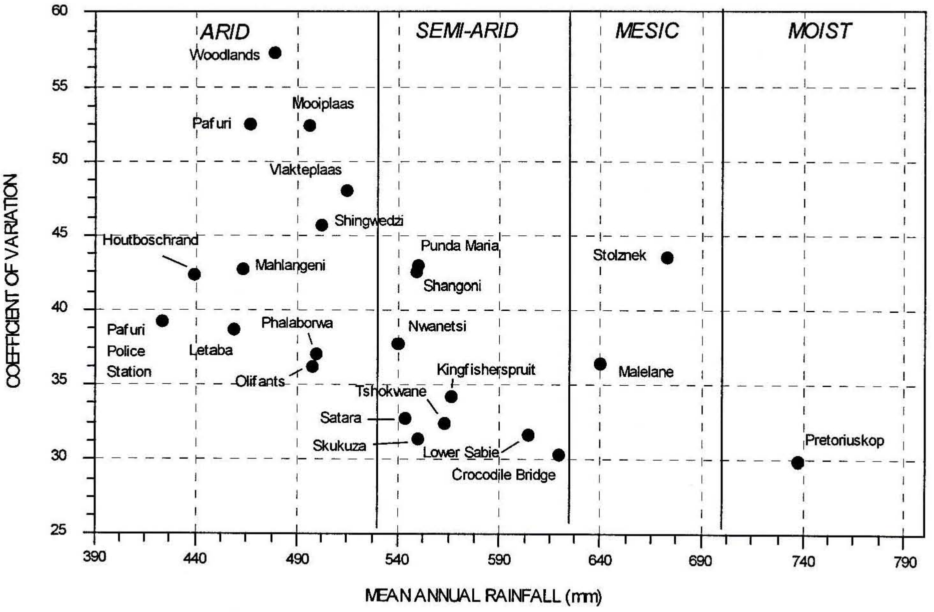


Figure 4.2. Scatter diagram of the coefficient of variation of mean annual rainfall for a range of stations in the KNP.

4.1.3. CONCENTRATION OF ANNUAL RAINFALL

A general gradient in the concentration of annual rainfall is evident in Table 4.2. The greatest concentration, and hence the shortest duration of the rain season, is in the extreme far north, decreasing southwards. Exceptions to this trend are the Vlakteplaas, Mooiplaas, Olifants, Nwanetsi and Lower Sabie regions. They all receive a greater proportion of the annual total during December to February than would be expected for their geographic location, as well as in relation to neighbouring regions.

Table 4.2. Seasonal concentration of rainfall in the KNP. Monitoring stations arranged in geographic sequence north to south (Pafuri to Malelane)

MONITORING STATION	PERCENT OF MEAN ANNUAL RAINFALL OCCURRING DURING DECEMBER TO FEBRUARY
PAFURI	62.9
PAFURI POLICE STATION	58.7
PUNDA MARIA	57.3
SHANGONI	56.6
VLAKTEPLAAS	57.4
SHINGWEDZI	56.0
WOODLANDS	55.4
MOOIPLAAS	57.4
MAHLANGENI	55.3
LETABA	54.6
PHALABORWA	52.7
OLIFANTS	54.9
HOUTBOSCHRAND	53.5
SATARA	52.5
NWANETSI	54.5
KINGFISHERSPRUIT	52.8
TSHOKWANE	52.4
SKUKUZA	50.3
LOWER SABIE	54.0
PRETORIUSKOP	48.7
STOLZNEK	50.3
CROCODILE BRIDGE	50.6
MALELANE	48.6

A common feature of these regions, and which possibly explains this anomaly, is that they are situated approximately along the 'centre line' of the KNP, i.e. they are broadly equidistant from the eastern and western boundaries, with the exception of Nwanetsi, which is situated in the western foothills of the Lebombo mountains. The latter has a strong rain-shadow effect, resulting in a relatively high degree of aridity in this area.

In general, the topography of the KNP gradually increases in elevation in a westerly direction from the western side of the Lebombo mountains on the west, towards the western boundary.

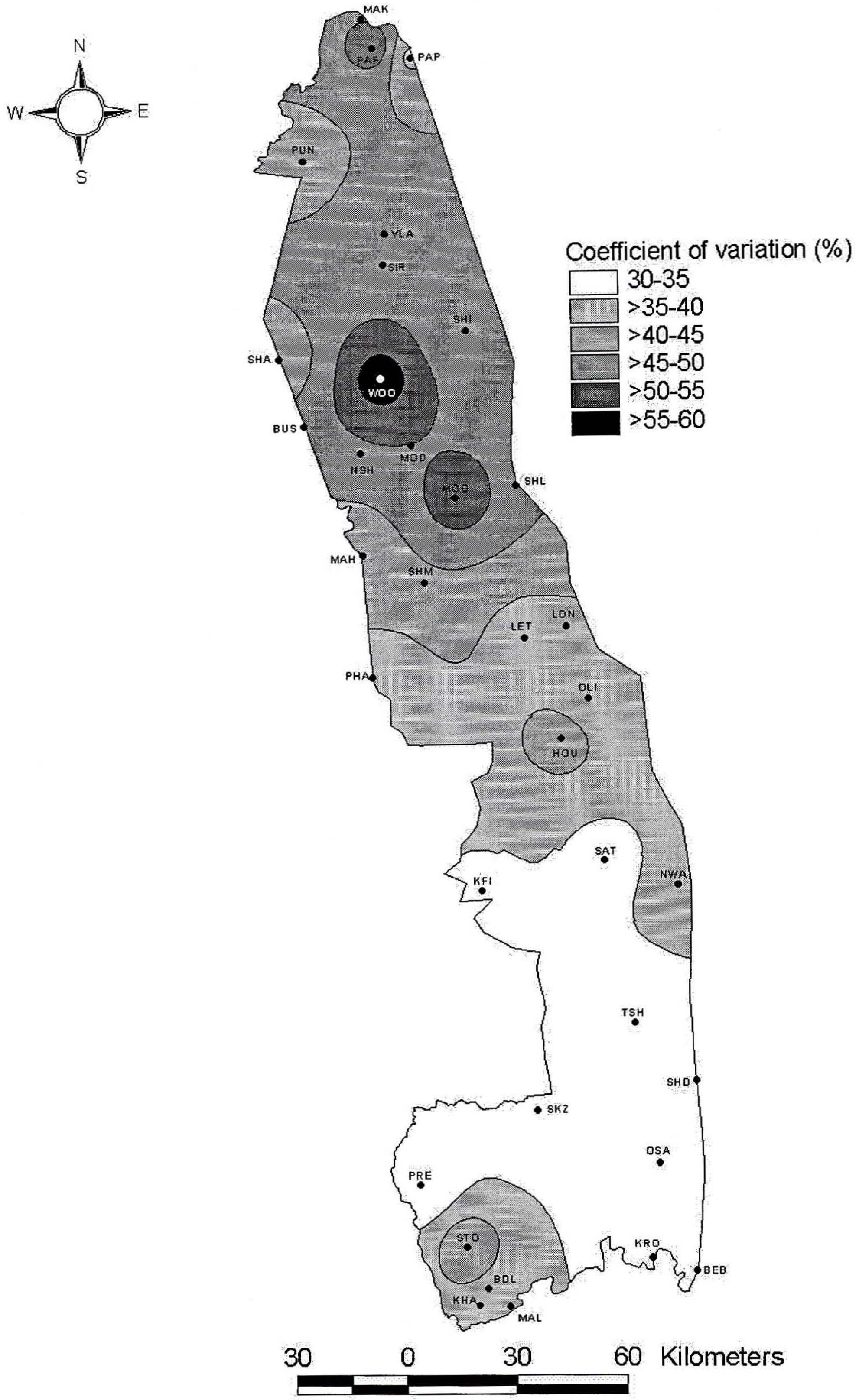


Figure 4.3. Distribution of the coefficient of variation in rainfall across the surface of the KNP. See Figure 2.1. for place names.

During their passage over the KNP, rain-bearing fronts entering the KNP from the east and south-east possibly do not receive sufficient upward lift until they have passed this central region, after which they rise sufficiently to deposit a greater amount of rain on the higher ground to the west. Consequently, the overall effect in these regions is a shortened rainfall season and reduced rainfall total.

Being relatively far from high ground of any significance, it is speculated that convective thunderstorm activity in these areas may possibly occur less frequently, or if it does, may not be as well-developed as that near to the higher areas. Consequently, the overall effect in these regions is a shortened rainfall season as well as a reduced rainfall total.

A simple linear regression analysis with the percent of total rainfall occurring during December to February as the dependent variable and latitude as the independent variable (Figure 4.4) showed that a strong relation exists between these two parameters ($r = -0.91$; $r^2 = 0.830$; SEE = 1.446; $P = 0.0000$; D.f. = 22) with the equation:

$$\% = 130.408 - 3.17097 * \text{Latitude}$$

It is therefore possible to predict the mean percent of annual rainfall occurring during December to February in the KNP, and hence rainfall concentration.

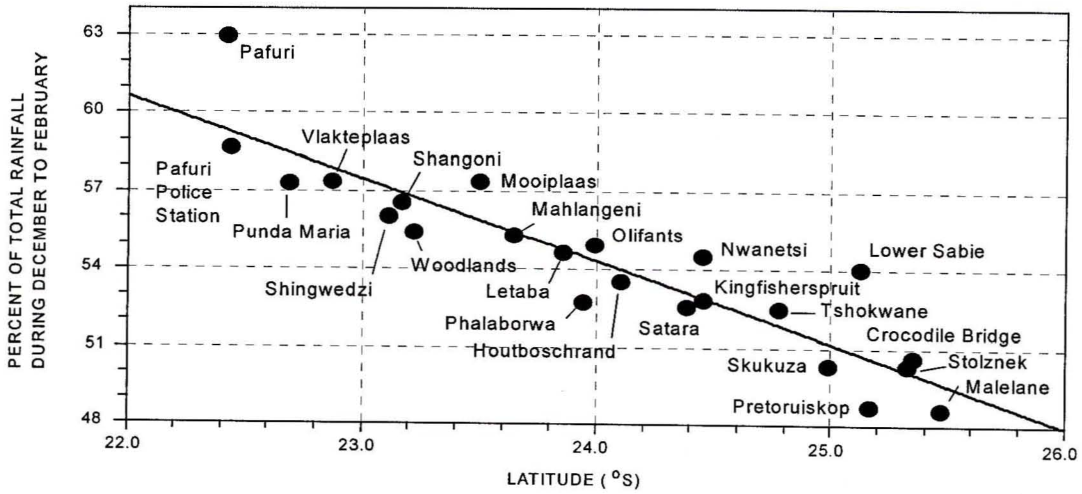


Figure 4.4. The relation between the percent of annual rainfall occurring during December to February, and latitude in the KNP.

4.2. CLASSIFICATION OF THE KNP ACCORDING TO THE MOISTURE MATRIX OF RUTHERFORD AND WESTFALL

Although not one of the main objectives of this study, the classification of the KNP according to the moisture matrix procedure of Rutherford & Westfall (1986) gives a different (and useful) perspective of soil moisture availability or the lack of it, in interpreting the results, as well as forming a background for a better understanding of plant-soil-climate relations generally.

Comparing Figures 4.1 and 4.5 it is becomes apparent that those stations (and by implication, the areas around them) with the lowest MAR in most cases have the highest CV in MAR. It is also the same stations that have the highest summer aridity indices, all occurring within the 'Arid' region. At the lower ends of the scales of both these figures (i.e. the 'Mesic' and 'Moist' regions), the reverse is true, namely that areas with the highest MAR also have the lowest summer aridity index.

Figure 4.5 is however somewhat misleading in that it only reflects the classification of the rainfall stations themselves, and not the greater, surrounding area. The higher, mountainous area in the south-western corner of the KNP receives a higher annual rainfall than the Pretoriuskop area, and therefore also falls within the Moist Savanna region; in all probability, receiving a higher proportion of the half-year rainfall in winter than Pretoriuskop does. Similarly, the area north and east of Pafuri ranger post (the Limpopo river valley) is markedly more arid, with an estimated mean annual rainfall of approximately 350 mm.

At a broader, regional (biome) scale, the KNP has a strong summer rainfall position in the moisture matrix of the southern African biomes (Figure 4.6). This figure is a simplified version of a similar figure produced by Rutherford & Westfall (1986). Other noteworthy aspects of this comparison is the KNP's position relative to the upper SAI limit for forest patches; and the location of Acocks' veld types 9, 10, and 15 outside the moisture matrix boundaries of the KNP.

The forest patch limit possibly implies that even in the total absence of fire, the south-eastern area of the KNP is unlikely to develop successionally towards a forest due to a relatively high SAI. From personal observation, it appears that where fire has been excluded in areas immediately to the west of the KNP, a dense, almost-closed canopy 'bushveld' interspersed with trees seems to be the general tendency.

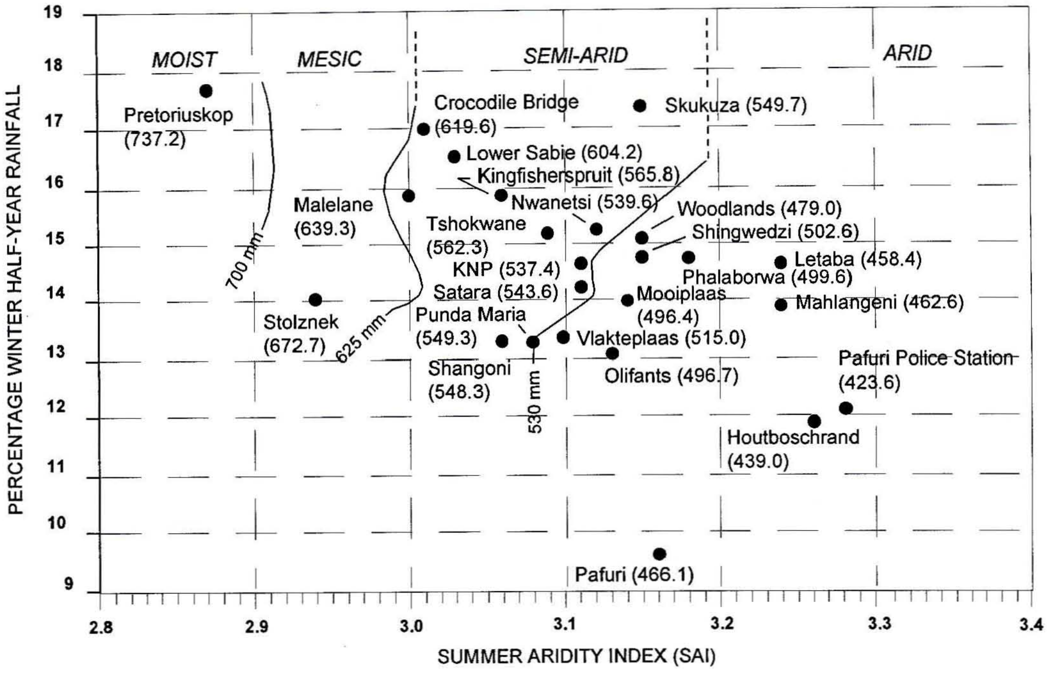


Figure 4.5. Moisture matrix of the KNP (after Rutherford & Westfall 1986). Figure in parentheses is the mean annual rainfall.

The position of the grassland biome within the boundary of the savanna biome is due to the fact that its moisture matrix falls entirely within the moisture matrix domain of the savanna biome (Rutherford & Westfall 1986).

The rainfall stations used by Rutherford & Westfall (1986) in determining the matrix positions of the Acocks veld types are unknown. In the case of veld type 9, no rainfall stations exist within the KNP in this veld type, which is situated in the higher-lying area to the north-west of Punda Maria. It is assumed that because of this elevated locality, the rainfall regime is relatively more mesic than that of Punda Maria. The lower limit of the moisture matrix range of the KNP may therefore possibly approximate 2.6 on the SAI scale.

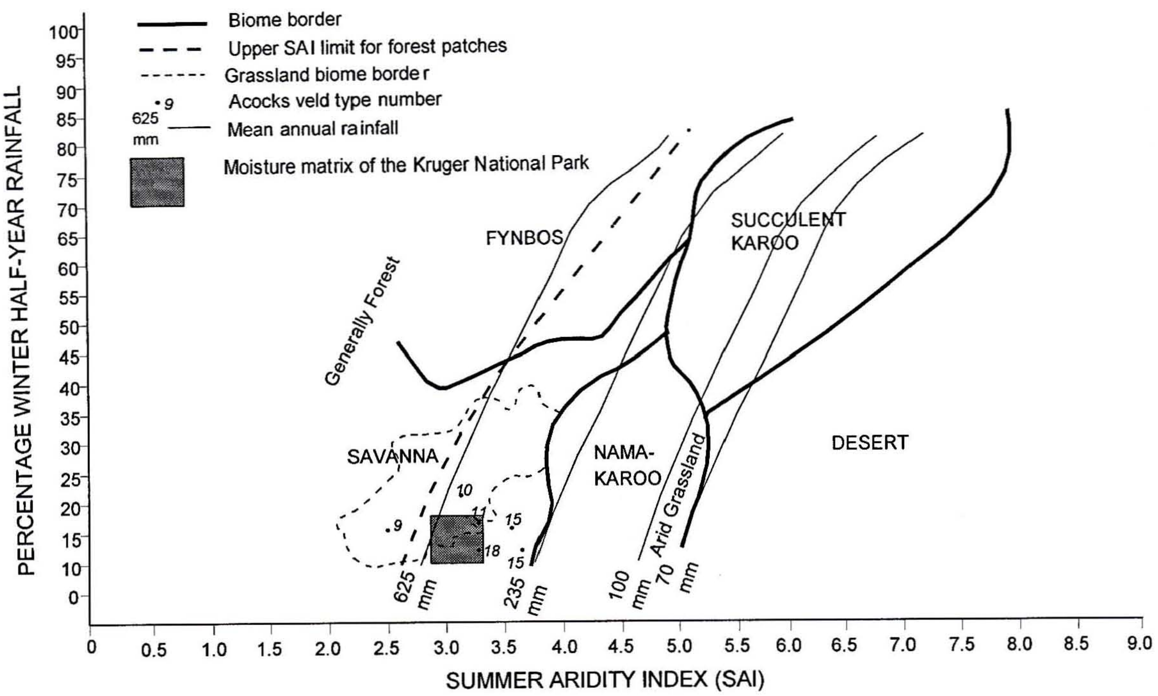


Figure 4.6. The position of the KNP (shaded block) in the moisture matrix of the biomes of southern Africa (after Rutherford & Westfall 1986).

Similarly, rainfall stations used by Rutherford & Westfall (1986) to determine the positions of veld types 10 and 15 probably did not include those within the KNP. It appears that in the case of veld type 10, a more mesic station was used, whereas in the case of veld type 15, a more arid station, possibly Messina, was used.

Rutherford & Westfall (1986) state that the MAR of the savanna biome ranges from 235 to 1 000 mm and sub-divide it into Arid savanna (with a MAR of 530 to 650 mm) and Moist savanna (>530 mm). An overlap consequently exists. They state however that areas where subdivisions overlap in terms of MAR indicate the domain where additional factors can be significant in delimiting sub-divisions, and that "Any classification of natural systems that ignores vegetation (the primary producer component) is likely to be irrelevant to the functioning of the ecosystem".

In their discussion of the Grassland biome, Rutherford & Westfall (1986) state that in areas with a MAR >625 mm sour grasses tend to predominate, whereas in areas below 625 mm, sweet grasses are more common but are seldom dominant. The 625 mm isohyet is also reported by Tainton (1988) as being the lower limit for increased plant yields with the application of nitrogen and phosphorus.

In the KNP, sour grass species become apparent from approximately the 650 mm isohyet upwards, increasing in abundance as the rainfall increases. Landscapes 1, 3, 5, and 19 (Gertenbach 1983) largely fall within the 600 mm isohytet, as does Venter's (1990) Skukuza Land System.

At the lower end of the rainfall gradient, the Limpopo river valley, parts of the Olifants and Bangu Gorges, and the Lindanda Flats area south of Nwanetsi are distinctly arid in their nature, as is evidenced by the structure and composition of the vegetation. The herbaceous stratum in these areas generally is sparser than in other areas of the KNP. Consequently, taking these factors into account and in terms of MAR and the moisture matrix classification, the KNP can be divided into a number of rainfall regions:

Very arid savanna	>300 - 400 mm	(2.18% of KNP)
Arid savanna	>400 - 500 mm	(34.32%)
Semi-arid savanna	>500 - 625 mm	(55.05%)
Mesic savanna	>625 - 700 mm	(7.49%)
Moist savanna	>700 mm	(0.96%)

At a broader scale, a sixth category, Extremely Arid savanna (<300 mm) could be included, though as far as is known, this does not occur within the KNP.

Using the above rainfall classes, a map of the Rainfall Regions of the KNP was produced and is based on the adjusted MAR values of Dent *et al.* (1989). These are shown in Figure 4.7.

Besides the Limpopo-Levuvhu area in the extreme far north, pockets of 'Very Arid' savanna are evident in the Letaba, Olifants, Nwanetsi, south of Tshandlhana and Godleni (south of Lower Sabie) regions and are a reflection of the 'rain-shadow' effect of the Lebombo mountains (Figures 4.1. and 4.7.). As is to be expected, this is also reflected in the vegetation of these areas, particularly in the herbaceous component in the northern areas. Annual grasses are dominant, with a low to very low annual production.

Local drought is a common feature of these areas. In the Letaba area this occurs once in every 2.8 years on average (compared to the overall KNP average of 3.6 years) and once in every 2.5 years at Nwanetsi. The Limpopo-Levuvhu area is an inherently low-rainfall area, experiencing drought only once in every 4.3 years.

The drought frequency at Olifants (rest camp) is once in every 4.7 years. Being situated on relatively high ground, Olifants in all likelihood annually receives considerably more rainfall than the river valley and the area to the east of it, and is therefore not representative of these lower-lying areas. A rainfall monitoring station was established at the Olifants trails camp in 1995. This is approximately 10 km east of the rest camp and in the rain-shadow of the Lebombo mountains. It has unfortunately not been in existence for a long enough period to enable the calculation of a reliable mean annual figure for this area. Nevertheless, a comparison of the annual rainfall totals of these two points for the past seven years shows that on average, rainfall at the trails camp was 9.5% lower than that of the rest camp.

It is a well-known fact that the Olifants river catchment area, and in particular the valley itself, is arid. The dryness is accentuated by steep slopes and shallow soils, with the herbaceous stratum seldom developing beyond the pioneer stage (Gertenbach 1983). Forbs are an important component. Annual production here is also low to very low, and is reflected by a low fire frequency record.

In the Houtboschrand area further west, the situation is very similar, with droughts being experienced once in every 2.7 years. Soil here generally is also shallow with steep slopes, and a herbaceous cover comprising mainly annual grasses and forbs, resulting in a low annual production.

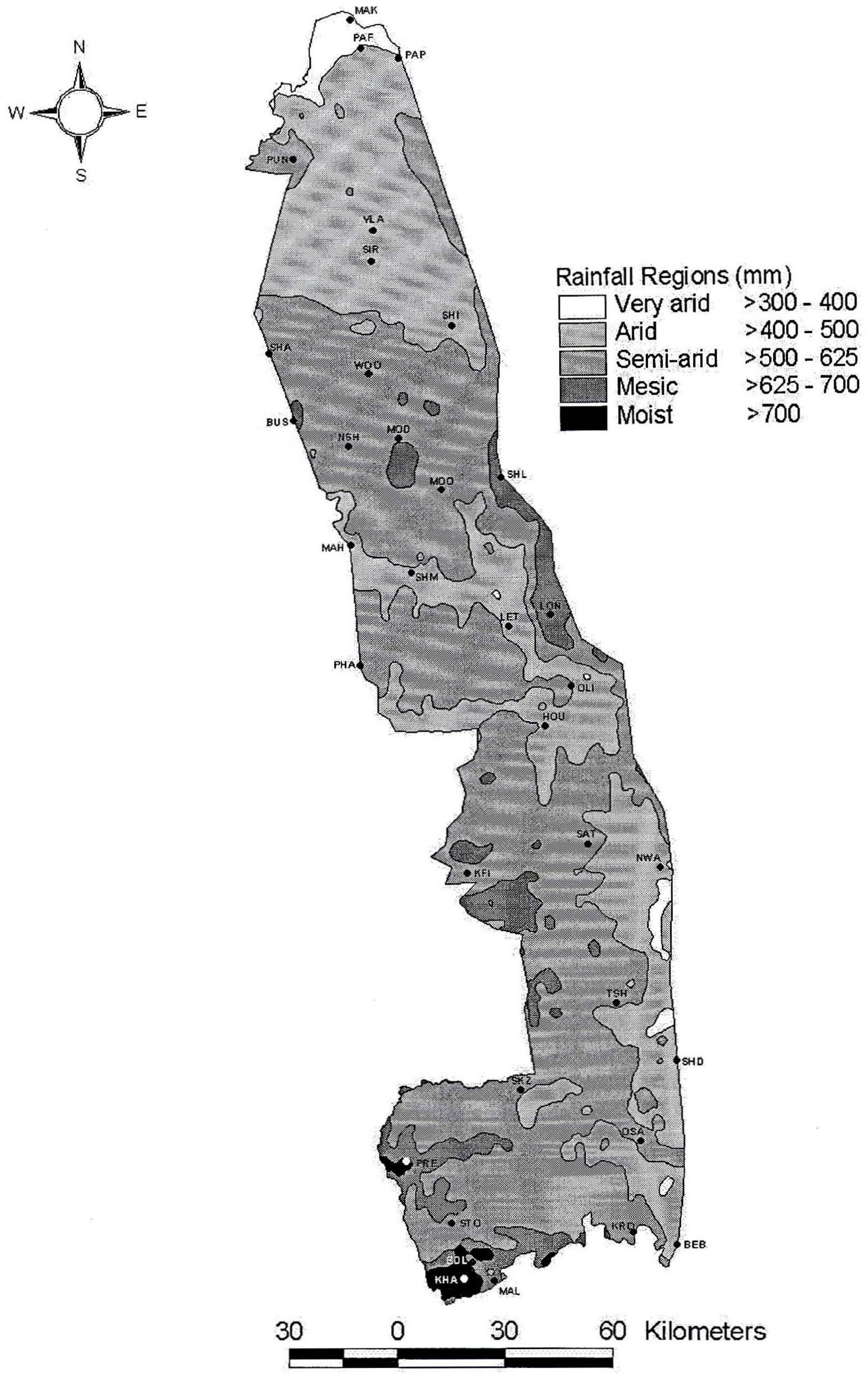


Figure 4.7. Rainfall regions of the KNP. See Figure 2.1. for place names.

4.3. MEAN DISC PASTURE METER HEIGHT AND DISTANCE FROM DRINKING WATER

A simple regression analysis between composition (percentage perennials) and distance from permanent drinking water showed that a very poor relation exists between these two criteria:

Perennials on basalt: $r = 0.1938$
Perennials on granite: $r = 0.2869$
Decreasers on basalt: $r = 0.2061$
Decreasers on granite: $r = 0.2479$

The relation between mean DPM height and distance to water is somewhat stronger though still relatively weak: for basalt $r = 0.8031$; r^2 (adj.) = 0.422 and for granite $r = 0.8787$; r^2 (adj.) =0.569. Both these relations are of a non-linear nature (4th Degree Polynomial Fit, Figure 4.8).

It is difficult to interpret and explain the polynomial relations between mean DPM height and distance from water. On both geological formations, this may be indicative of complex, non-linear relations between these parameters as distance increases; the details of which may possibly become apparent with detailed investigation.

It is also difficult to explain the differences between basalt and granite. In the latter case, it may possibly be indicative of a greater concentration of nutrients resulting from dung and urine deposition nearer to drinking water, in turn positively influencing grass growth. It is unlikely though, that such a relation will persist for a distance greater than perhaps one kilometer from a water-point. At the same time, increased utilization and trampling nearer to water will counter a higher DPM height.

Thrash (1993) and Thrash *et al.* (1993) found a weak but widely variable relation between dung deposition and distance from drinking water in the KNP. Using nitrogen and phosphorus concentration in faeces, Grant *et al.* (2000) report that phosphorus is significantly higher on basalt, and nitrogen significantly higher on granitic areas. Besides the availability of soil moisture, the availability of these nutrients primarily controls grass production in savannas (Frost *et al.* 1985; Scholes 1990; O'Connor & Bredenkamp 1997).

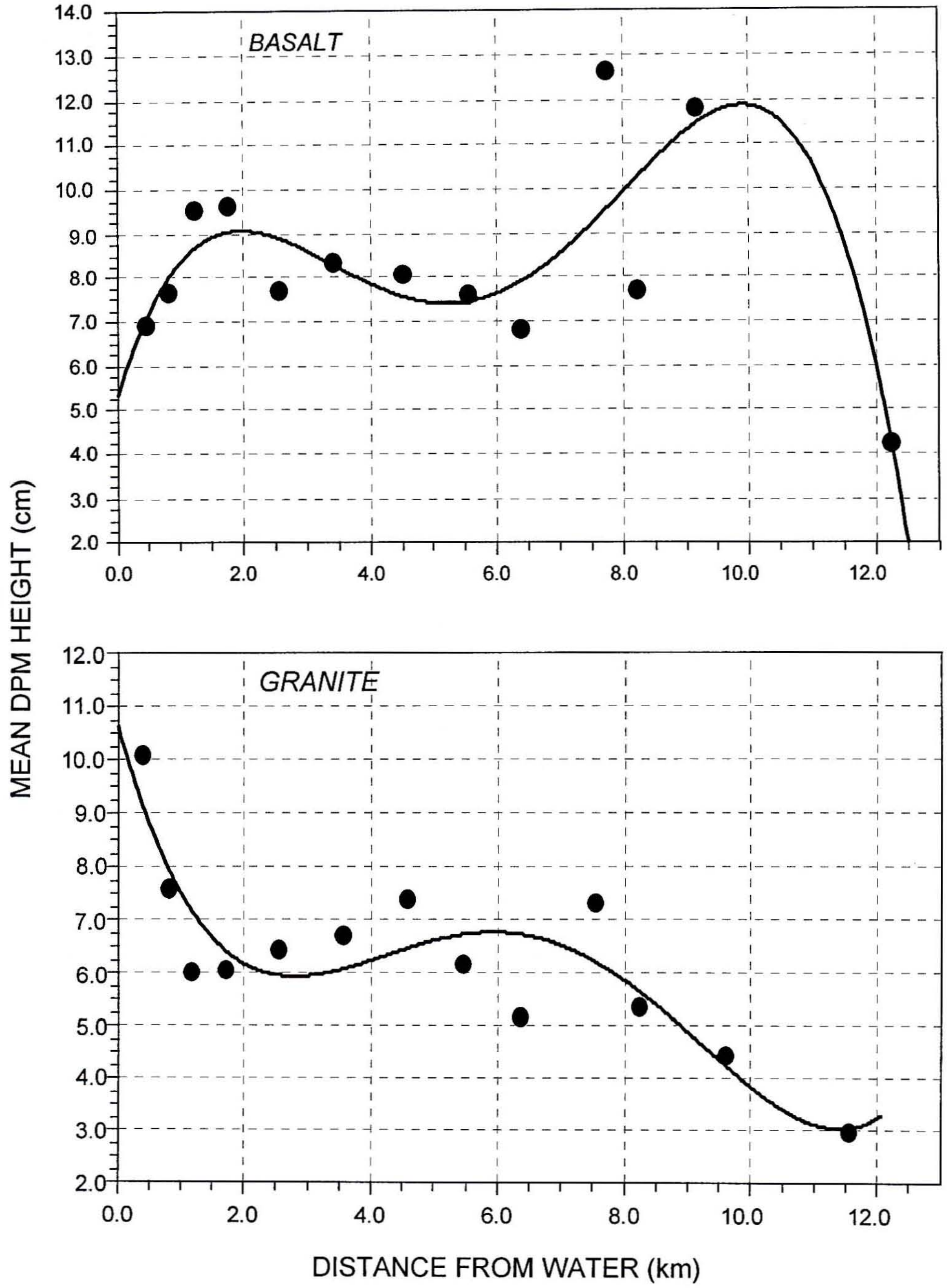


Figure 4.8. Relations between mean DPM height and distance from drinking water on basalt (top) and granite (bottom).

Annual grass production was significantly higher ($P<0.0001$) on basalt than on granite (Grant *et al.* 2000). This could however be as a result of an apparently higher density of grass tufts on basalt than on granite, resulting in a higher standing crop per unit area. Grass structural characteristics (explained in greater detail in Chapter 5), may also be responsible for a higher DPM height on basalt, leading to an inflated estimate of standing crop.

4.4. STEPWISE LINEAR REGRESSION

In terms of coefficients of determination and correlation coefficients, the success of stepwise linear regression varied. The best results are for nett primary production and nett standing crop but were poor to very poor for composition. Results for composition are consequently not discussed further. All the variables in the equations below are significant ($P = <0.05$). Validation results for the best stepwise regression fits are also presented and shown graphically in Figures 4.9 and 4.10. Validation statistics are given in Tables 4.3. and 4.4. The most important variables are summarised in Table 4.5.

In order to eliminate lengthy wording and descriptions, the time-lagged variables are referred to as, for example, 'Y_{-2} year, i.e. 'the current year minus two', etc. 'The total number of days with maximum root moisture stress during the growth stage of three years ago' (KSZGRO_3) would thus be referred to simply as "maximum root moisture stress days of year Y_{-3}" etc.

Any reference to 'stress-free days' refers exclusively to the root stress coefficient; expressed as maximum root stress, or the mean root stress coefficient when this is between zero and maximum (but excluding these extremes).

Abbreviations of independent variables are given in Tables 3.3. and 4.6.

4.4.1. NETT PRIMARY PRODUCTION (NPP) & NETT STANDING CROP (NSC)

4.4.1.1. **Nett primary production**

BASALT (ET VARIABLES INCLUDED)

In the case of basalt, the inclusion of the ET variables strengthened both the coefficient of determination and the correlation coefficients (Table 4.3) indicating that these factors better explain variation in grass sward NPP. Besides the rainfall and rainday parameters, ET_c during the growth stage as well as in year Y_{-2} is important. Total annual rainfall during the preceding three years appears to have a greater effect on NPP that the current year's total rainfall. This indicates that soil water content at deeper depths is important, as is the mean soil moisture stress during the growth period and in years Y_{-1} and Y_{-3}. The base status of the A horizon also plays a significant role.

Stepwise regression equation:

DPM HEIGHT =

Coefficients:	Value	Std.Error	t value	Pr(>|t|)
(Intercept)	-14.1309	8.2783	-1.7070	0.0935
RFGRO	0.0263	0.0066	3.9972	0.0002
RFYR.1	-0.0378	0.0097	-3.8992	0.0003
RFYR.2	0.0265	0.0103	2.5616	0.0132
RFYR.3	0.0199	0.0054	3.6610	0.0006
DAYYR.1	0.2679	0.1208	2.2183	0.0307
DAYYR.2	-0.2484	0.1018	-2.4408	0.0179
VAR	3.9606	1.1586	3.4185	0.0012
SSKEW	-3.4849	1.0842	-3.2143	0.0022
SKURT	5.3661	1.3848	3.8749	0.0003
CFVAR	-0.5771	0.2856	-2.0206	0.0482
ETGRO	-0.0604	0.0169	-3.5823	0.0007
ETGRO.2	0.0620	0.0129	4.7965	0.0000

AVGKSGRO	34.5961	8.3086	4.1639	0.0001
AVGKSGRO.2	-22.7937	7.6120	-2.9945	0.0041
AVGKSGRO.3	-10.4442	4.2315	-2.4682	0.0167
BSFI	2.5249	1.1703	2.1575	0.0354

Residuals:

Min	IQ	Median	3Q	Max
-7.254	-1.218	-0.1248	1.082	10.09

Residual standard error: 3.002 on 55 degrees of freedom

Multiple R-Squared: 0.8128

F-statistic: 14.92 on 16 and 55 degrees of freedom. P = 1.465e-014

Validation equation (Exponential Association):

$$y = a\left(1 - e^{-bx}\right)$$

a	32.362769
b	0.043450762
x	DPM height

$r = 0.8603$; $SE = 3.362$

GRANITE (ET VARIABLES EXCLUDED)

In the case of granite, the exclusion of the ET variables strengthened the relations considerably. In essence, rainday parameters were identified as the most important determinants of NPP on granite. The terrain on granitic areas in the KNP is generally more undulating than on basalt, which in turn would be expected to influence soil water dynamics, both as surface water (runoff) and subterranean water.

Coarse-textured soils allow for a greater infiltration and deeper percolation of rain-water than heavier-textured soils, and consequently, an increased moisture storage capacity in the sub-soil (Dye & Spear 1982). Although such soils have a lower opportunity for evaporative loss because of lower capillary movement and consequently buffer soil moisture against the effects of erratic rainfall (Dye & Spear 1982), their coarser texture also allows for a faster through-flow of water. The frequency and spread of rainfall on granitic soils consequently seems to be more important than the total amount.

None of the soil nutrient or herbivore density variables were identified as being important. Surprisingly, the percentage of annuals and not perennials, was identified as one of the important determinants of production as measured by disc height.

Stepwise regression equation:

DPM HEIGHT =

Coefficients:	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	75.9989	28.2521	2.6900	0.0088
DAYYR	0.1165	0.0261	4.4718	0.0000
DAYYR.1	-0.1997	0.0486	-4.1073	0.0001
VAR	11.3330	4.7638	2.3790	0.0199
SDEV	-53.6304	23.0295	-2.3288	0.0226
SSKEW	-3.2105	0.8944	-3.5894	0.0006
ANN	-0.1544	0.0387	-3.9856	0.0002

Residuals:

Min	1Q	Median	3Q	Max
-5.313	-1.6	-0.2972	1.079	11.25

Residual standard error: 2.77 on 75 degrees of freedom

Multiple R-Squared: 0.5988

F-statistic: 18.65 on 6 and 75 degrees of freedom. P = 3.789e-013

Validation equation (3^{rd} Degree Polynomial Fit):

$$y = a + bx + cx^2 + dx^3 + \ldots$$

a	-3.2195609
b	3.5298769
c	-0.40786151
d	0.016202301
x	DPM height

r = 0.7042; SE = 1.589

6.4.1.2. Nett standing crop

BASALT (ET VARIABLES EXCLUDED)

Fire appears to have a strong effect on NSC on basalt, with both the time since the last burn and the overall burning frequency being highly significant (P = 0.0000 for both). Important parameters are the total annual rainfall of the growth period and of year Y_{-2}, the number of raindays in the growth period, the percentage silt content of the A horizon, effective soil depth, percentage perennials and the amount of concentrate feeders. Webber (1979) found that on duplex soils of granitic origin, an increased frequency of burning dramatically decreased soil moisture. Burning frequency may therefore have a similar effect on basaltic soils, which are also high in clay content.

The importance of annual carry-over of soil moisture is indicated by the results of the Towoomba fertilizer trial in which the control treatment showed a significant correlation between annual rainfall and production ($r^2 = 0.532$; P = 0.01). This became more significant when the preceding year's rainfall was included in the analysis (Donaldson *et al.* 1984). In the KNP, the relation between NSC and annual rainfall on basalt is rather poor: r = 0.60; $r^2 = 0.360$ (n = 695).

Stepwise regression equation:

DPM HEIGHT =

Coefficients:	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	-7.6796	1.2741	-6.0273	0.0000

BURN.INTER	0.3691	0.0548	6.7315	0.0000
BURN.FREQ	-0.3648	0.1063	-3.4322	0.0007
RFGRO.2	0.0043	0.0016	2.7782	0.0057
RFYR	0.0148	0.0020	7.5360	0.0000
RFYR.3	0.0023	0.0010	2.2456	0.0252
DAYGRO	0.0691	0.0259	2.6671	0.0079
SKURT	0.9671	0.3464	2.7919	0.0055
SILT	0.0477	0.0124	3.8519	0.0001
EFF.DPTH	2.4453	1.0347	2.3632	0.0186
PEREN	0.0628	0.0083	7.5696	0.0000
CONCMAS	-0.0339	0.0083	-4.0808	0.0001

Residuals:

Min	1Q	Median	3Q	Max
-10.49	-2.071	-0.0768	1.536	14.25

Residual standard error: 3.54 on 427 degrees of freedom

Multiple R-Squared: 0.5598

F-statistic: 49.36 on 11 and 427 degrees of freedom. P = 0

Validation equation (4^{th} Degree Polynomial Fit):

$$y = a + bx + cx^2 + dx^3 + \ldots$$

a	1.8297902
b	0.53564825
c	0.14401722
d	-0.012347411
e	0.00026710642
x	DPM height

r = 0.8265; SE = 2.763

GRANITE (ET VARIABLES EXCLUDED)

In contrast to production, the inclusion of the ET variables strengthened the correlations, though on granite, only marginally so (Table 4.3). This again possibly indicates a dominant influence of the soil water balance. The number of raindays during the growth period, as well as those of the previous year's growth period and the skewness of raindays (i.e. temporal distribution) are important factors in NSC on granite. The correlation between NSC and annual rainfall only is poor: $r = 0.56$; $r^2 = 0.317$ ($n = 720$).

Comparing the correlation strengths of production between basalt and granite, it is difficult to explain why production on basalt shows a stronger relation when ET variables are included than granite does. The selected variables are broadly similar, except that on basalt, the kurtosis in raindays is important whereas on granite, their standard deviation and skewness are important. Concentrate feeders are important on basalt whereas on granite, none of the herbivore categories were shown to be important.

Stepwise regression equation:

DPM HEIGHT =

Coefficients:	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	1.7730	1.8633	0.9516	0.3417
BURN.INTER	0.1348	0.0321	4.1943	0.0000
BURN.FREQ	-0.2650	0.0570	-4.6488	0.0000
RFGRO.2	0.0038	0.0010	3.9744	0.0001
RFGRO.3	0.0029	0.0009	3.2265	0.0013
RFYR	0.0144	0.0013	11.4626	0.0000
RFYR.1	0.0124	0.0017	7.3151	0.0000
DAYGRO	-0.0568	0.0168	-3.3711	0.0008
DAYYR.1	-0.0504	0.0190	-2.6463	0.0083
SDEV	-3.6737	0.8467	-4.3387	0.0000
SSKEW	-0.7206	0.2858	-2.5210	0.0119
PEREN	0.0667	0.0067	10.0065	0.0000

Residuals:

Min	1Q	Median	3Q	Max
-10.93	-2.115	-0.2598	1.572	13.22

Residual standard error: 3.131 on 707 degrees of freedom

Multiple R-Squared: 0.5246

F-statistic: 70.93 on 11 and 707 degrees of freedom. P = 0

Validation equation (Saturation Growth Rate):

$$y = \frac{ax}{b + x}$$

a	18.214751
b	9.1025509
x	DPM height

r = 0.7234; SE = 2.092

Table 4.3. Validation statistics of stepwise linear regression for nett primary production and nett standing crop. Best fits are shown in bold

PARAMETER	STATISTIC	BASALT		GRANITE	
		INCL. ET	EXCL. ET	INCL. ET	EXCL. ET
NETT PRIMARY PRODUCTION	r	**0.8603**	0.8147	0.5247	**0.7042**
	r^2 (adj.)	**0.7358**	0.6441	0.1775	**0.4052**
	SEE	3.371	3.773	2.144	1.610
	MAE	2.301	2.844	1.685	1.094
	ME	-0.192	-0.121	-7.133e-8	-5.665e-8
	Durb.-Wat.	1.517	1.629	1.920	1.602
	n	30	30	30	30
NETT STANDING CROP	r	0.8166	**0.8265**	0.7131	**0.7234**
	r^2 (adj.)	0.6582	**0.6730**	0.5026	**0.5181**
	SEE	2.761	2.773	2.086	2.099
	MAE	2.199	2.138	1.588	1.555
	ME	-0.000052	-0.000083	0.0082	0.0036
	Durb.-Wat.	1.582	1.566	1.416	1.343
	n	134	134	134	134

4.4.2. COMPOSITION

Stepwise regression results for composition range from poor to very poor (Table 4.4) and are consequently not discussed further. In all cases, errors are also too large to be of any practical value. Moreover, in three cases, the Durbin-Watson statistic is less than 1.4, indicating serious autocorrelation (Manugistics 1996). These results therefore imply that the regression equations on which they are based are of no value for practical purposes and perhaps only marginal value in better understanding which variables are important determinants of composition, be they perennials or Decreasers.

For both NPP and NSC, the errors are small enough to allow for a reasonably accurate prediction of these parameters. These regression results are however regarded as preliminary and warrant further investigation with the aim of possibly improving them, if this is indeed possible with linear regression.

Table 4.4. Validation statistics of stepwise regression for composition. Correlation values for best fits are shown in bold

PARAMETER	STATISTIC	BASALT		GRANITE	
		INCL. ET	EXCL. ET	INCL. ET	EXCL. ET
PERENNIALS	r	0.5038	**0.5390**	**0.4696**	0.2193
	r^2 (adj.)	0.2049	**0.2244**	**0.2262**	0.0394
	SEE	23.301	24.109	17.035	23.054
	MAE	18.079	19.510	13.562	18.051
	ME	-0.0043	-0.122	-0.000091	0.046
	Durb.-Wat.	1.374	1.471	1.827	1.432
	n	134	134	134	134
DECREASERS	r	**0.5993**	0.5794	**0.2140**	0.2089
	r^2 (adj.)	**0.3525**	0.3293	**0.0315**	0.0276
	SEE	16.815	15.395	14.908	15.213
	MAE	13.418	12.136	11.751	12.767
	ME	0.0000028	0.000417	0.033	0.000064
	Durb.-Wat.	1.552	1.567	1.857	1.673
	n	134	134	134	134

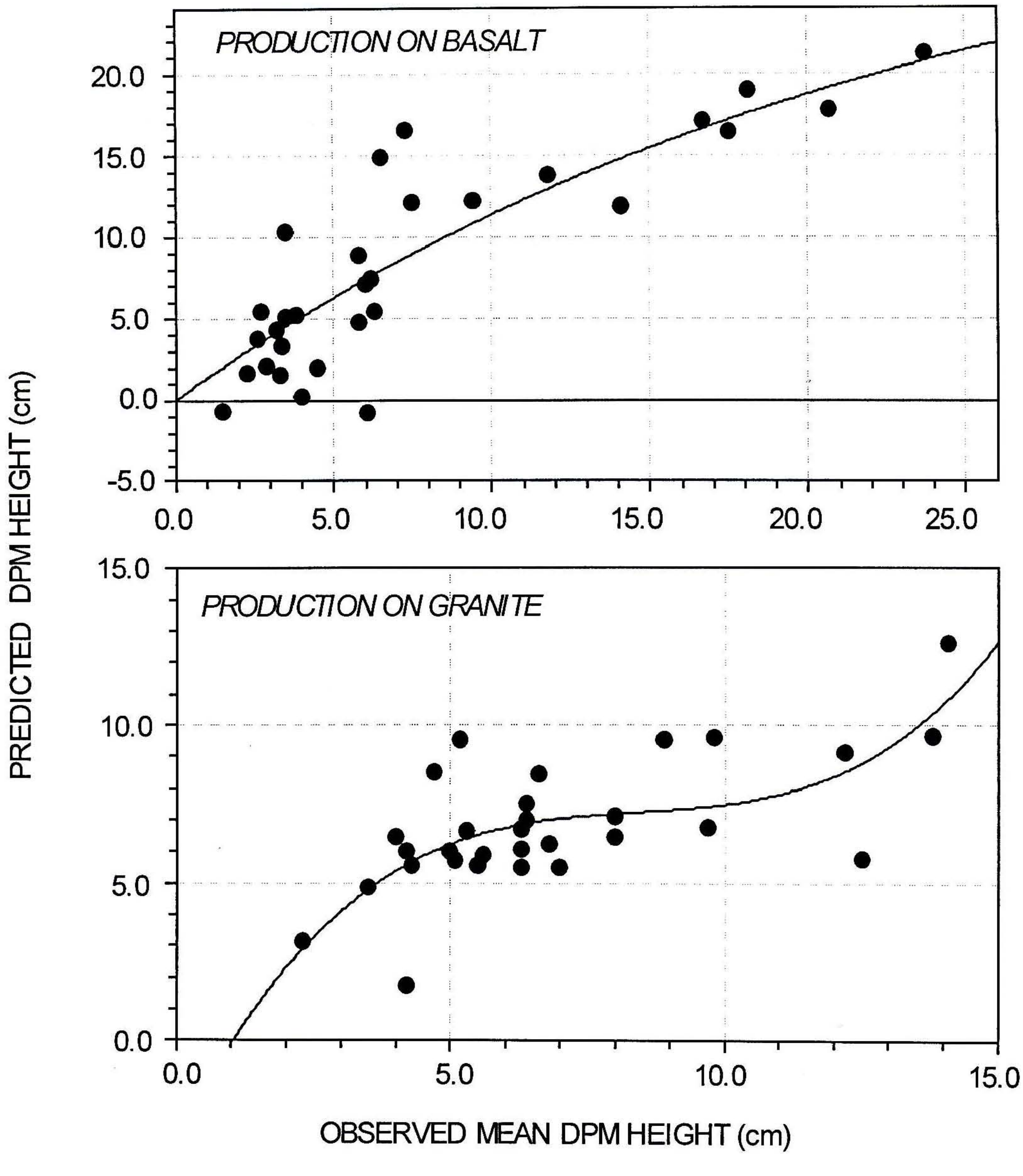


Figure 4.9. Validation relations between observed and predicted mean DPM height for NPP on basalt (top) and granite (bottom).

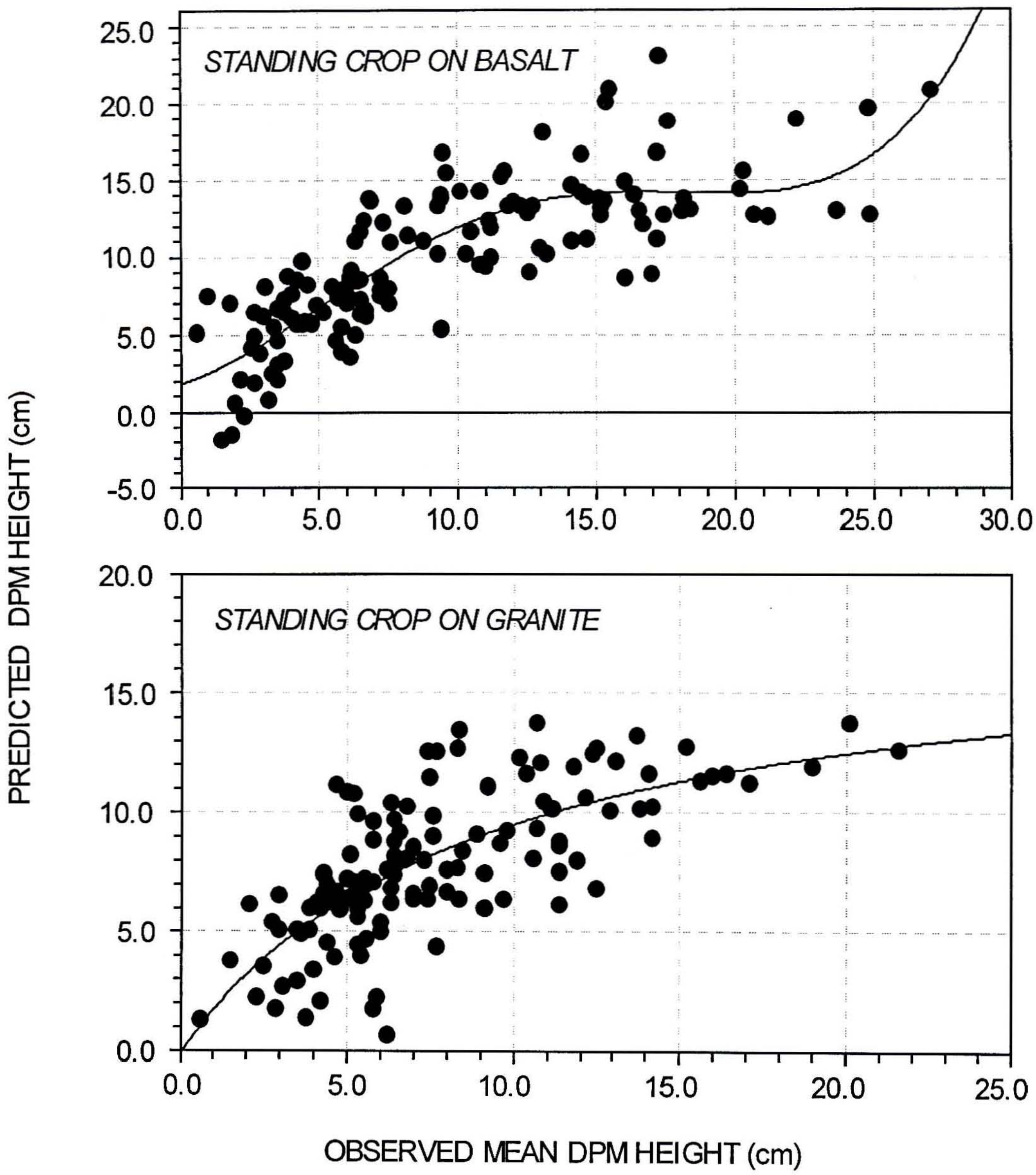


Figure 4.10. Validation relations between observed and predicted mean DPM height for NSC on basalt (top) and granite (bottom).

Table 4.5. Variables identified by the stepwise regression procedures as being important determinants of grass production and standing crop. Variable abbreviations are explained in Tables 3.3 and 4.6.

MAJOR GROUP	VARIABLE	NET PRIMARY PRODUCTION		NET STANDING CROP	
		BASALT (INCL. ET)	GRANITE (EXCL. ET)	BASALT (EXCL. ET)	GRANITE (EXCL. ET)
FIRE	BURN.INTER			●	●
	BURN.FREQ			●	●
RAINFALL PARAMETERS	RFGRO	●			
	RFGRO.2			●	●
	RFGRO.3				●
	RFYR			●	●
	RFYR.1	●			●
	RFYR.2	●			
	RFYR.3	●		●	
	DAYGRO			●	●
	DAYYR		●		
	DAYYR.1	●	●		●
	DAYYR.2	●			
	VAR	●	●		
	SDEV		●		●
	SSKEW	●	●		●
	SKURT	●		●	
	CFVAR	●			
	ETGRO	●			
	ETGRO.2	●			
	AVGKSGRO	●			
	AVGKSGRO.2	●			
	AVGKSGRO.3	●			
SOIL PARAMETERS	SILT			●	
	BSFI	●			
	EFF.DPTH			●	
COMPOSITION	PEREN			●	●
	ANN		●		
HERBIVORES	CONCMAS			●	
TOTALS:		16	6	11	11

It is evident from Table 4.5. that in a general sense, rainfall variables are the most important, with 70.8% of the variables initially included in the regression procedures being selected, followed by the ET variables (47.1%), soil (44.1%), composition (37.5%), and herbivores

(8.3%). To a large degree, this is in agreement with Snyman & Fouché (1993) who state that seasonal rainfall and evapotranspiration on veld in semi-arid areas are equally useful for the estimation of phytomass production values.

O'Connor (1985) states that the relative significance of grazing on trends in production increases as aridity increases, though stocking rate, rather than the system of grazing, has the greatest influence. In the higher-rainfall savannas, he adds that grazing has little effect on production, a relatively weak effect on sandveld of the more mesic savannas, and a more significant effect on the heavier-textured soils. This corresponds with the results of this analysis.

In terms of the number of variables and the complexity, the determination of grass production on basalt has the most complex combination of variables, necessitating the inclusion of ET variables - 16 in total. This makes it difficult to apply the regression equation in practice.

4.5. TREE REGRESSION

A great deal of detailed information was produced by the tree regression procedure, as is evident from the figures and accompanying reports (Appendix 2). Furthermore, unlike stepwise regression, the two-dimensional nature of the diagrams clearly shows the relative importance of each variable: The length of the vertical lines (splits) reflects the magnitude of the variance accounted for by the particular parameter. The length of the horizontal lines is indicative of the range in the values of the variables below it, as well as that of the terminal nodes.

Relations and interactions can be followed much like a decision-support diagram or a taxonomic key, whereby the user is repeatedly faced with a choice between two alternatives. The branch to the left of the split is the 'lesser than' option, whereas that to the right, the 'greater than' choice. Inter-actions between variables are also clearly evident, unlike the case with stepwise linear regression.

In the tree regression analyses undertaken in this study, the full spectrum of variables listed in Table 3.3 were used, with the exception that Decreasers were not included, perennials being used as composition variables instead.

In the tree regression diagrams, for the sake of clarity and to reduce clutter to the minimum, terminal values in the case of NPP and NSC were rounded off to the nearest 0.1 cm (DPM height), and to 0.1% in the case of perennials and Decreasers. Original values are however given in the detailed reports presented in Appendix 2. Total canopy cover of woody (m^{-2}) was used in the analyses and is thus also the values given in the tree regression models. The equation to convert this to percentage cover is: $-0.001322+0.0666635^{*}\ m^{-2}$.

To facilitate the understanding of the tree regression figures, the abbreviations of the variables given these figures are listed and explained after the last tree regression figure (Figure 4.28) in Table 4.6. This table thus serves as a legend for Figures 4.11. to 4.28.

In the following discussions dealing with production, standing crop and composition, reference is made to herbivore density and is expressed as kg ha^{-1}. This was determined by converting the mass values (i.e. tonnes per grazing zone of 4 347 ha) of the various feeder groups shown in the tree regression diagrams to kg ha^{-1} as follows:

$$\text{kg ha}^{-1} = (\text{tonnes x 1 000 kg})/\ 4\ 347$$

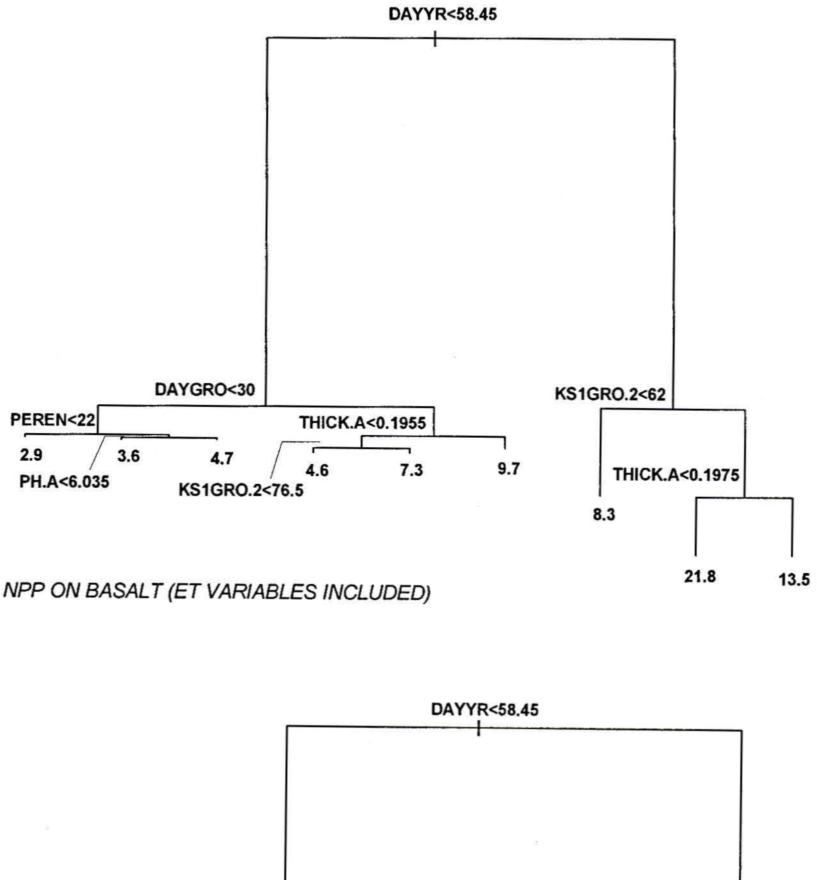
4.5.1. NETT PRIMARY PRODUCTION

4.5.1.1. Basalt

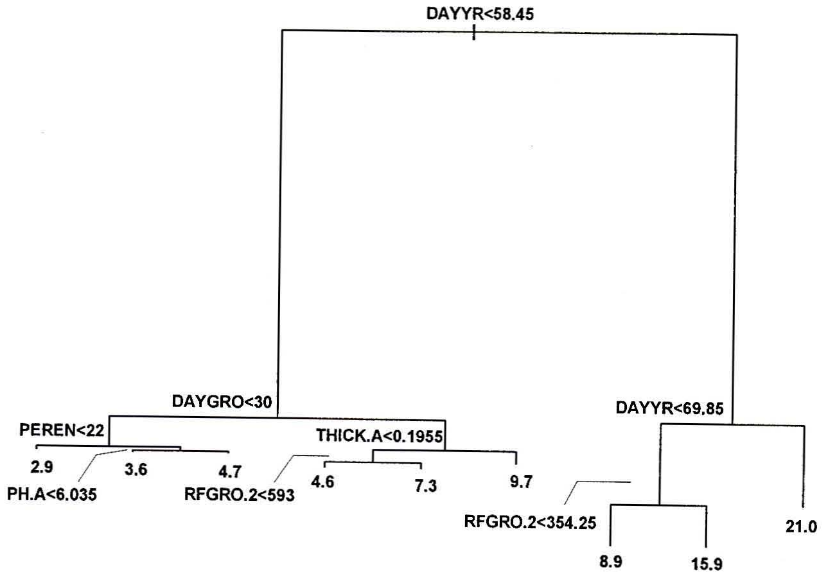
Production on basalt is primarily dependent on the total number of raindays during the year, with approximately 58.5 days being the minimum for maximum production (Figure 4.11). When these are higher and preceded by >62 days without soil moisture stress during the Y_{-2} year, production is at its highest. The number of raindays during the growth stage, the thickness of the A horizon and percentage perennial grasses are also important. Perennials in turn could be influencing soil water dynamics. Infiltration capacity is linearly related to basal cover of perennials (van den Berg *et al.* 1976; O'Connor & Bredenkamp 1997). More than 80% of the root mass of perennial grasses occurs within the top 150-200 mm of the soil (Tainton 1988; Snyman 1993)

It is significant to note that an increase in the thickness of the A horizon to more than 0.195 m plays an increasingly important role in production. The pH of the A horizon on the other hand makes a very small contribution and can be disregarded, at the same time bearing in mind that the partition of the data into the basalt and granite sub-groups reduced the range in pH. For basalt, this ranged from 5.18 to 7.60 and for granite, 4.45 to 7.24. The pH for granite is therefore entirely subsumed in the basalt range.

Very similar results were obtained when the ET variables were excluded from the analysis. This indicates that production on basalt can be predicted without the use of the ET variables, the total number of raindays during the year being used as a surrogate instead.



NPP ON BASALT (ET VARIABLES INCLUDED)

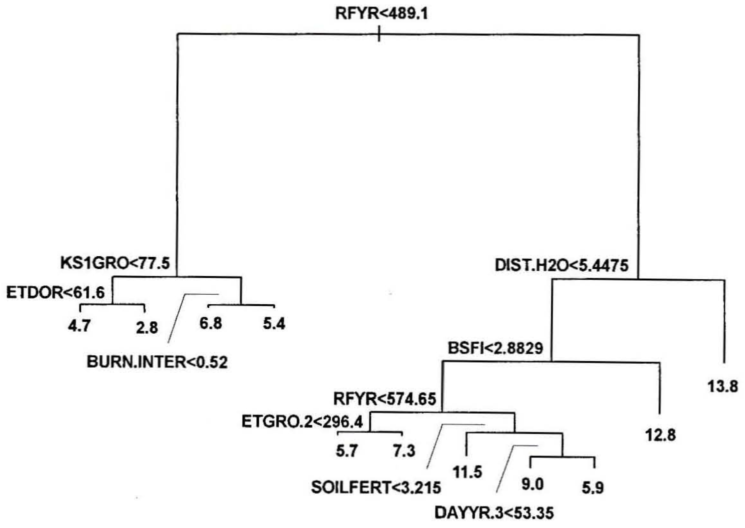


NPP ON BASALT (ET VARIABLES EXCLUDED)

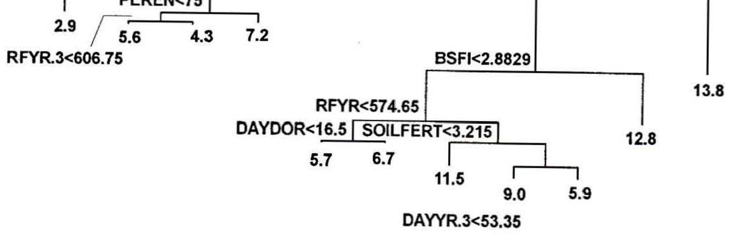
Figure 4.11. Tree regressions of NPP on basalt.

4.5.1.2. Granite

Rainfall has a major influence on NPP on granite and can be regarded as the primary determinant, influencing all levels (Figure 4.12). The proximity of permanent drinking water is also important. Soil fertility properties becomes evident at lower but more specific levels. The exclusion of the ET parameters makes very little difference to the results, indicating that production on granite can be predicted without these variables. Under stress-free conditions, herbivores do not appear to have any direct influence on production.



NPP ON GRANITE (ET VARIABLES INCLUDED)



NPP ON GRANITE (ET VARIABLES EXCLUDED)

Figure 4.12. Tree regressions of NPP on granite.

4.5.2. NETT STANDING CROP

Whether on basalt or granite, variables determining NSC are substantially more numerous, and with more complex interactions, than are those of NPP.

4.5.2.1. Basalt

Evapotranspiration during the growth stage is the primary determinant of DPM height on basalt. When this is <203.5 mm and the raindays are <36.9, DPM height can be expected to range from 2.9 to 15.2 cm (Figures 4.13 and 4.14). Under these circumstances, percentage perennials, woody plant competition (>3.8% cover), the number of days with maximum soil moisture stress during the preceding year, time since last burn, and the thickness of the A horizon have an influence, though of a relatively minor nature.

There is considerable evidence that trees have a marked competitive effect on grasses and other trees, but little evidence that grasses have much effect on trees once they are taller than the grass layer (Knoop & Walker 1984). According to Scholes (1997), the main separation of water use between trees and grass is not depth but season of use. Because woody plants are able to store water and carbohydrates from the previous season, aided by a few deeper roots, they are able to expand their leaves immediately before or after the first rains. This ability allows them preferential resource access before grasses are able to grow enough leaf area to be serious competitors. On heavier-textured soils, O'Connor (1985) states that the woody component can exert a more profound effect on production than grazing.

When evapotranspiration exceeds 203.9 mm, the total rainfall for the year is an important determinant: when it is <587.4 mm, the percentage perennials, time since last burn and percentage organic carbon content of the A horizon play important roles. With an annual rainfall of more than 587.4 mm, evapotranspiration during the growth stage of year Y_{-2} replaces percentage perennials in importance, followed by the mean mass of bulk grazers during year Y_{-1}, time since last burn, and percentage organic carbon content of the A horizon. For the KNP as a whole, which is intermediate in soil fertility, grass consumption is estimated at approximately 6.5% of production (Owen-Smith & Danckwerts 1997).

When the ET variables are excluded from the analysis, the number of raindays during the growth stage have the greatest influence on DPM height. When raindays are <28.5, the time since the last burn, percentage perennials and the number of raindays during the growth stage play substantial roles in determining DPM height.

When the raindays during the growth stage exceed 28.5, the total rainfall during the year plays a very significant role, followed by composition (percentage bare ground and perennials), organic carbon content of the A horizon, the variance in the raindays, and woody plant competition. It is interesting to note that when the percentage bare ground is >0.5%, a substantial decline in DPM height occurs, compared to the situation when it is <0.5%.

This is in agreement with O'Connor & Bredenkamp (1997) who state that in a semi-arid region, production shows a pronounced linear relation between rainfall and perennial grasses with a high basal cover, whereas degraded grassland comprising mainly short-lived perennial and annual species and a poor basal cover show a far weaker relation. Snyman & Fouché (1993) found that 78% of the variation in above-ground phytomass production may be attributed to the interaction between the effects of rainfall and veld condition.

Herbivores generally seem to have a minor influence in determining DPM height on the basalt sites, whether the ET variables are included or not. The absence or presence of these variables also makes practically no difference to the range of mean DPM heights included in the tree model. In semi-arid grassland, production is affected more by sward composition than by defoliation (Danckwerts & Barnard 1981). It is significant to note however, than when herbivores do exert an influence on standing crop, concentrate feeders do so at very low densities of 1.5 kg ha^{-1} on average.

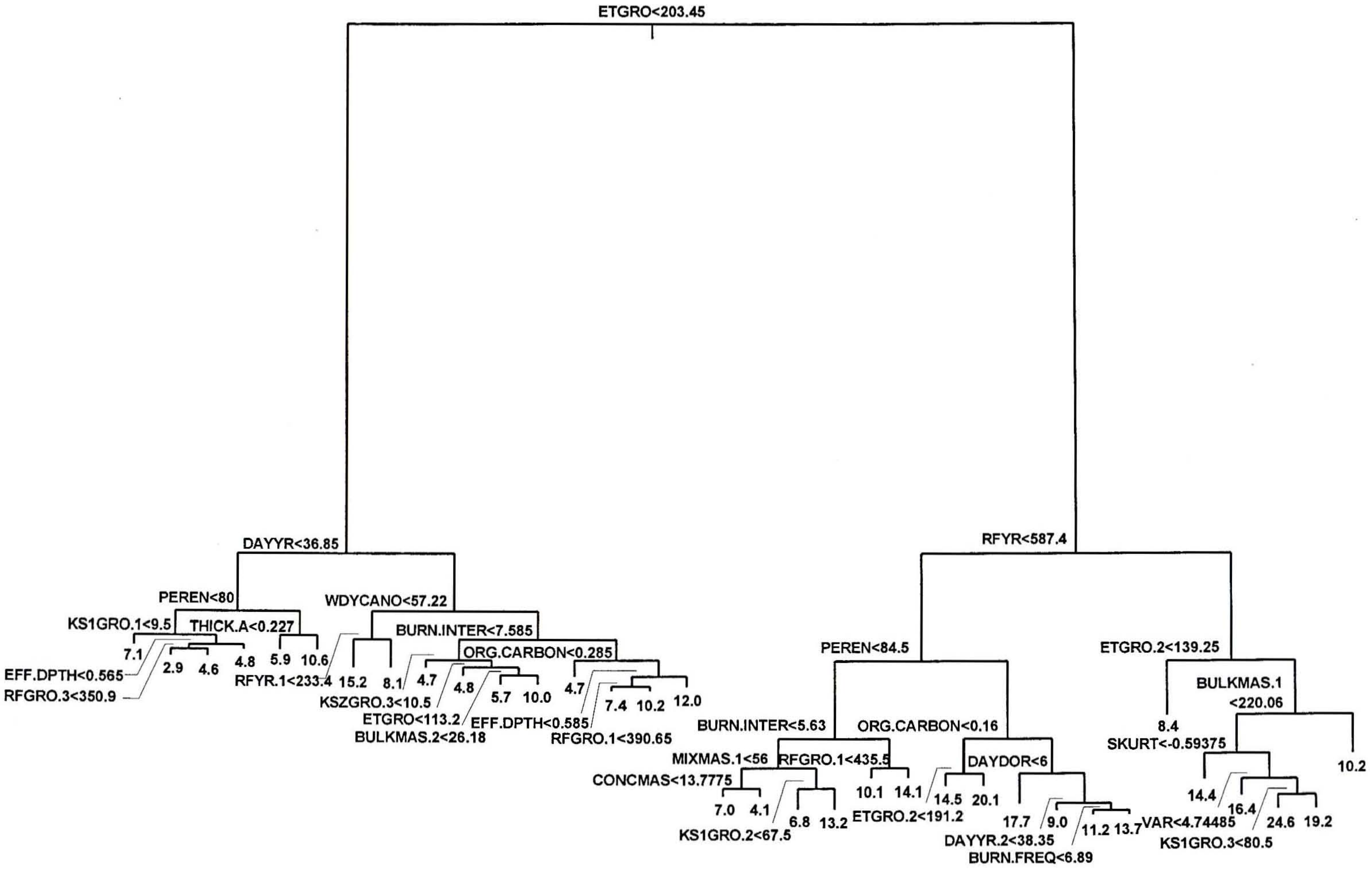


Figure 4.13. Tree regression of NSC on basalt (ET variables included).

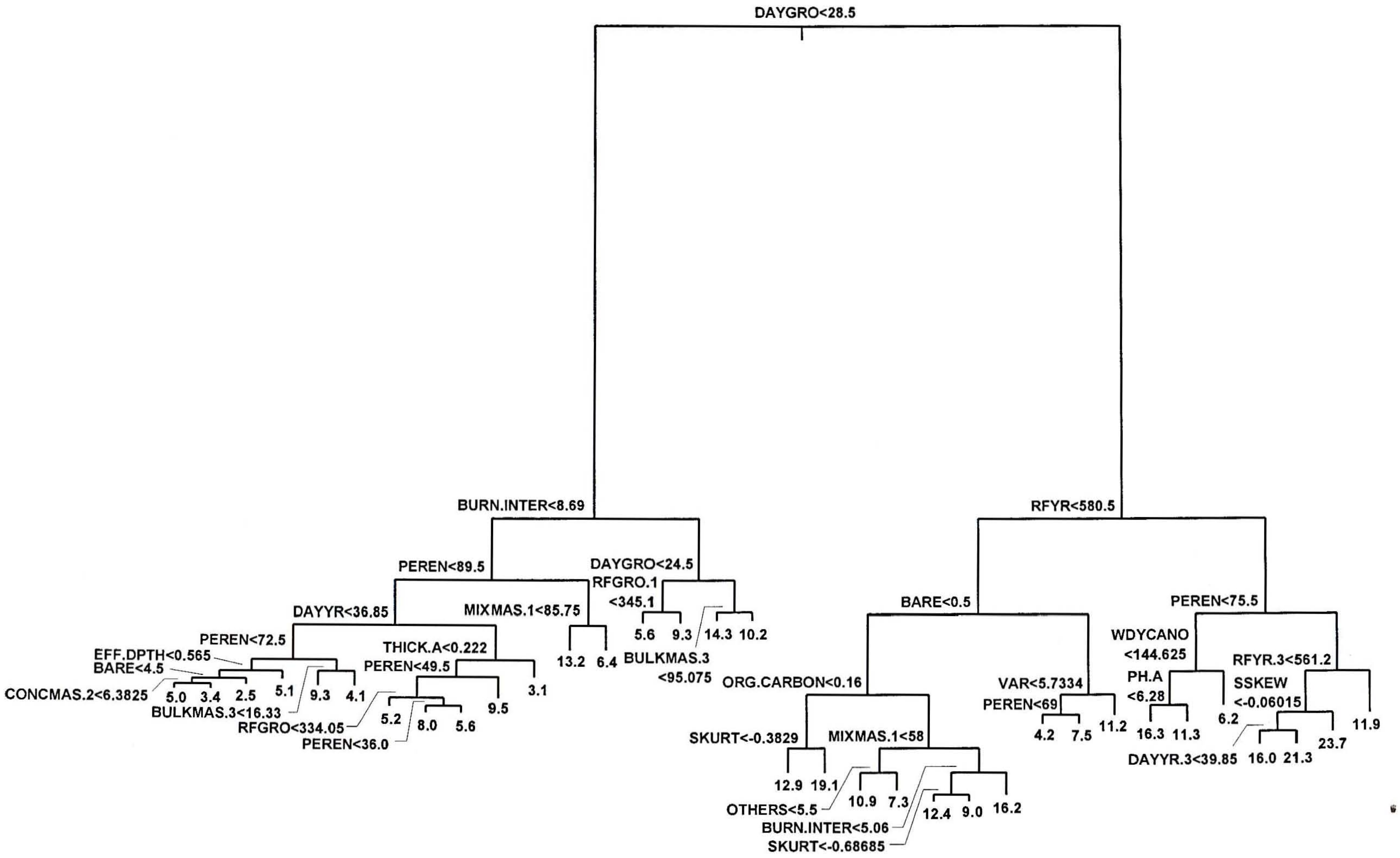


Figure 4.14. Tree regression of NSC on basalt (ET variables excluded).

4.5.2.2. Granite

Unlike basalt, the total rainfall for the year is a primary determinant of NSC, with the evapotranspiration parameters generally playing minor roles (Figures 4.15 and 4.16). Composition, and more specifically, the abundance of perennials and annuals, as well as the time since the previous burn, are important determinants. When annual rainfall exceeds 556 mm and the number of stress-free days exceeds 80.5, then the pH of the topsoil becomes an important factor. A pH<6 may possibly be a reflection of the situation in the higher rainfall regions of the KNP, that, as is also indicted by the model, also produce some of the highest DPM values. Ungulate herbivores generally have a minor influence on standing crop on granite. Nevertheless, concentrate feeders do so at very low densities.

Excluding the ET variables from the tree regression made practically no difference to the model, particularly at the higher levels. In this combination, composition in the form of perennials plays an equally important role as it does when ET variables are included.

When raindays during the growth period exceed 28.5 with an annual rainfall of more than 580.5 mm, competition by woody plants becomes important, even though perennials can be up to 75.5%. This corresponds with the results of other studies dealing with the effects of woody plant removal on grass production on different soil types. Although results vary, removal or thinning of woody plants generally has a positive effect on grass production (O'Connor 1985). In Mixed Bushveld with a mean annual rainfall of 415 mm, Smit & Swart (1994) found that potential tree competitiveness was the most important determinant of grass production on plots on sandy soil thinned out to different tree densities.

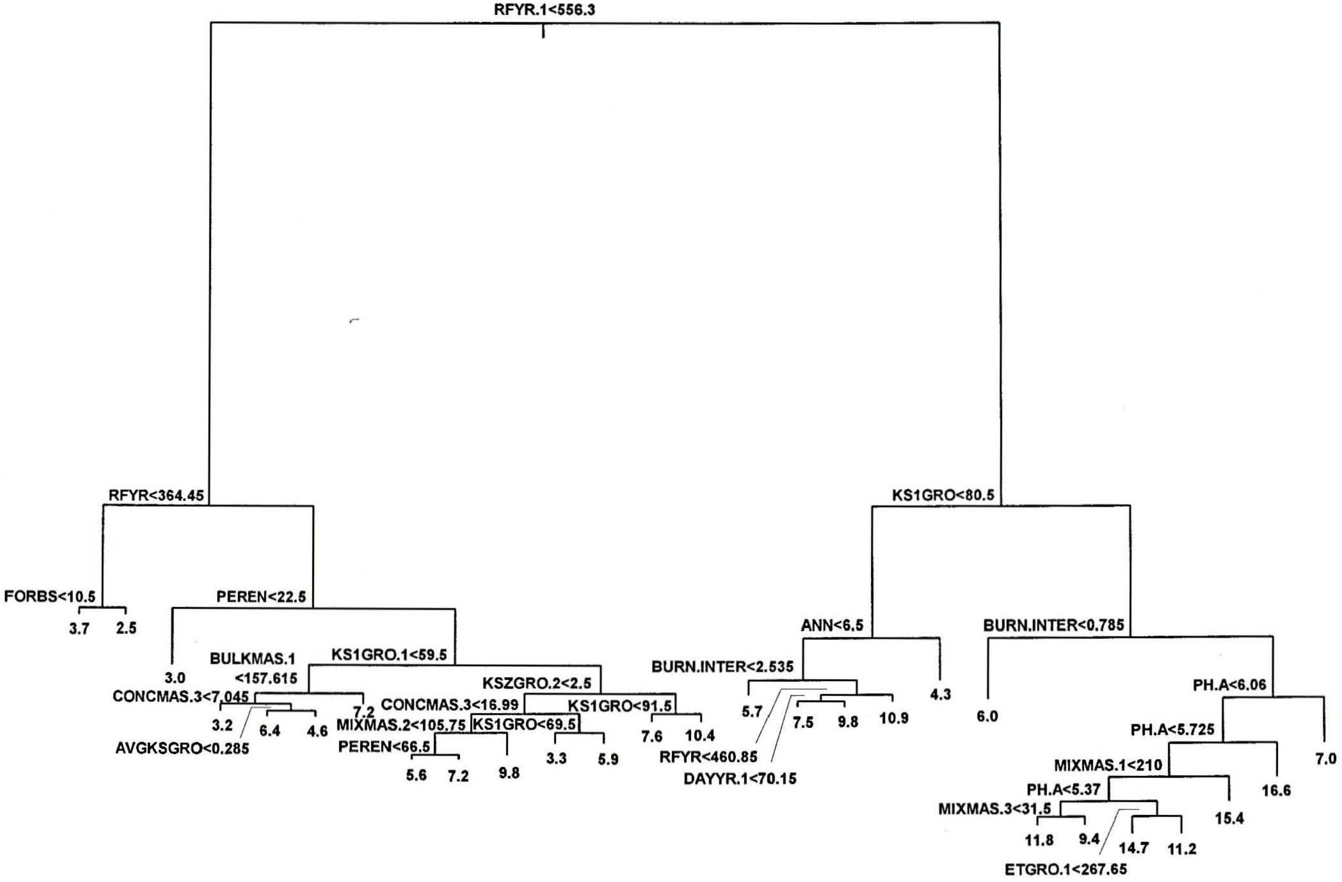


Figure 4.15. Tree regression of NSC on granite (ET variables included).

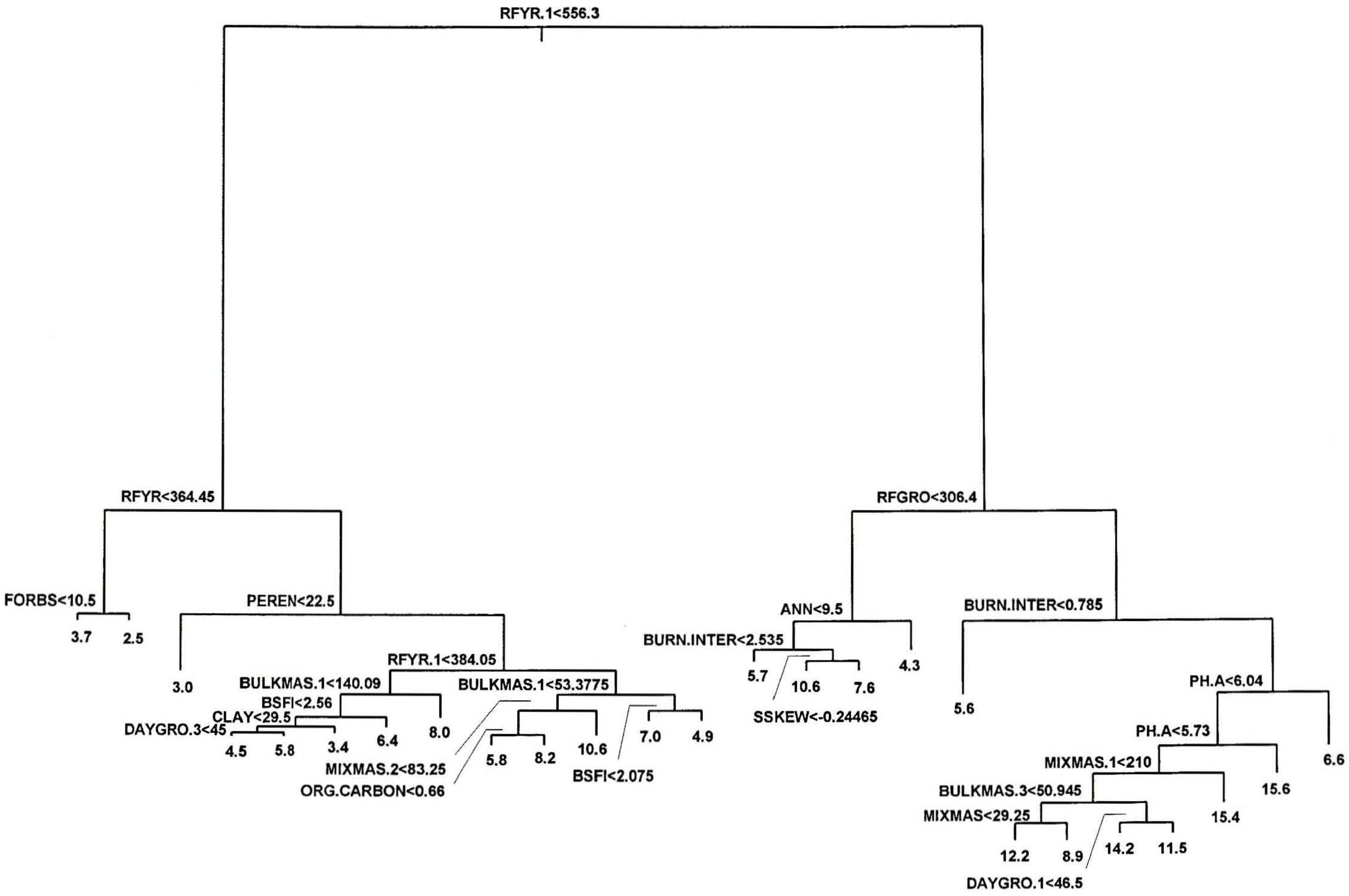


Figure 4.16. Tree regression of NSC on granite (ET variables excluded).

4.5.3. COMPOSITION

4.5.3.1. Perennials

Basalt

The availability of soil moisture during the growth period is a primary determinant of perennial grass survival on basalt, as is indicated by the dominance of the model by evapotranspiration during the growth period (Figures 4.17 and 4.18). When soil moisture content decreases to the point where total ET_c during the growth period is less than 180 mm, root stress sets in and when this exceeds a relatively low amount of 9.5 days, perennial grass abundance declines substantially. When stress-free days are less than 9.5, concentrate feeders show a strong influence on the abundance of perennials but only on veld in good condition (64-88% perennials).

The importance of soil moisture is indicated when the ET variables are excluded (Figure 4.18) The number of raindays in the *dormant* stage play a major role, followed by the number of raindays in the growth stage. This indicates that the availability of soil moisture in the preceding dormant period is a key factor in the survival of perennial grasses on basalt. Other factors, including the abundance of herbivores, play minor or even insignificant roles as soil moisture increases. Herbivore influence however, and particularly that of concentrate feeders, occurs at very low densities, ranging from a mean of 0.9 to 30.5 kg ha^{-1}. Perennials on basalt furthermore appear to be more tolerant of mixed feeders than those on granite.

Granite

As is the case on basalt, but even more so on granite, the availability of soil moisture (and hence the ability to transpire) during the growth stage is the major determinant of perennial abundance on granite (Figures 4.19 and 4.20). Veld in moderate or poor condition ($\leq$60% perennials) appears to be very sensitive to maximum soil moisture stress in the root zone when evapotranspiration is <193 mm. On average, only 0.5 days of severe root stress during the growth stage are necessary to interact in a negative manner with the rainfall during the growth stage of year Y_{-1} and concentrate and mixed feeders of years Y_{-2} and Y_{-1} respectively, to keep the abundance of perennials relatively low.

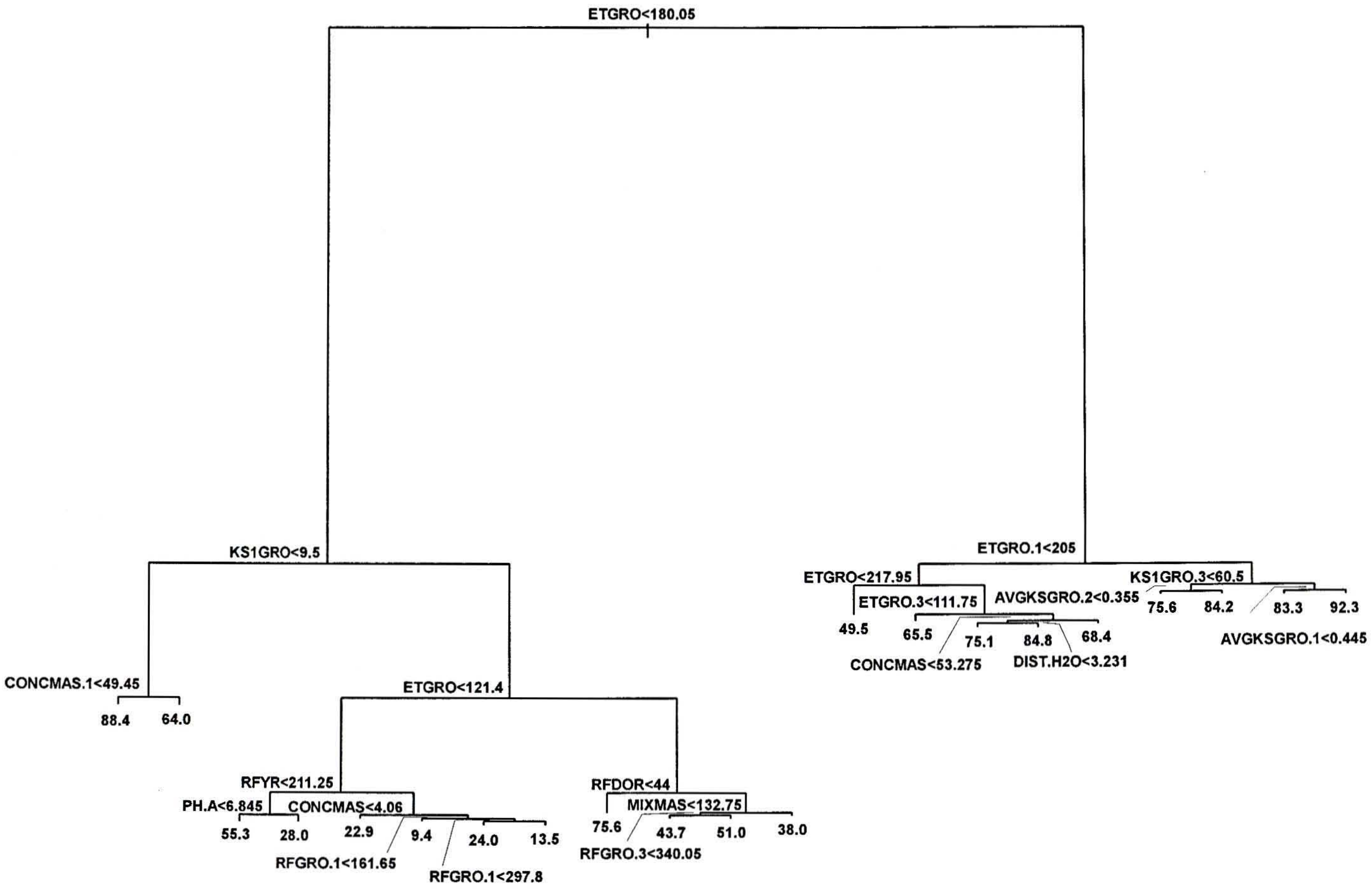


Figure 4.17. Tree regression of perennials on basalt (ET variables included).

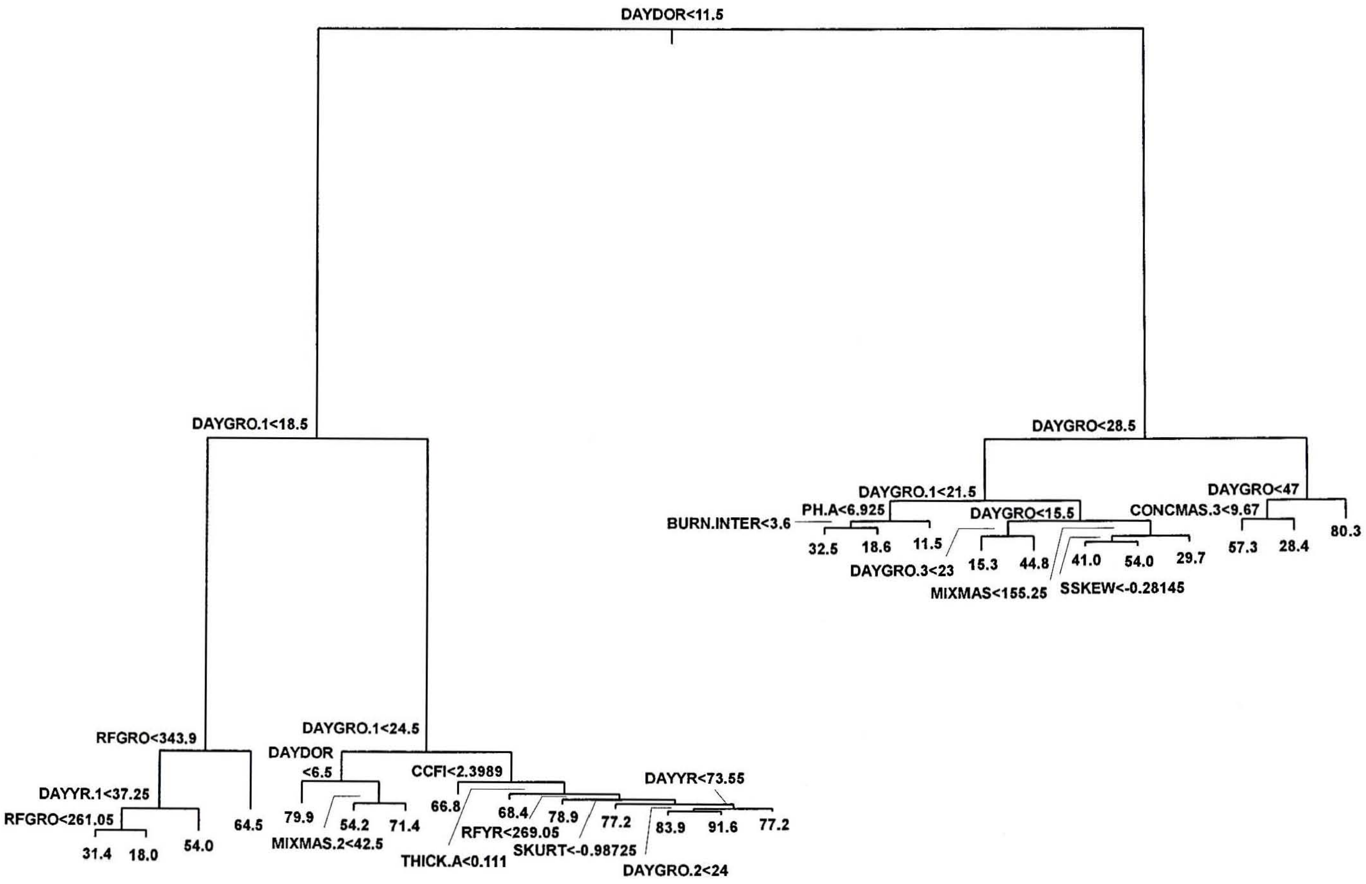


Figure 4.18. Tree regression of perennials on basalt (ET variables excluded).

At higher levels of evapotranspiration (>193 to <267 mm), the number of stress-free days in the growth season, the concentration of the rainfall, and the number of raindays in year Y_{-2} play important roles. At these higher levels, herbivores have little or no influence.

When the ET variables are excluded (Figure 4.20), the number of raindays during the dormant stage becomes the most important determinant of perennial grass abundance, as is the case on basalt. Moreover, there is only one day's difference in the threshold value between granite and basalt - 10.5 and 11.5 respectively. On granite, if these are less than 10.5, then the total rainfall of the previous year's growth stage plays an equally important role. When this is <190 mm, coupled with <14 raindays during the growth stage, the result is veld in poor to very poor condition, with perennials ranging from 32% to 14%.

If the rainfall of the preceding year's growth stage exceeds 190 mm, together with the total rainfall of the preceding year exceeding 476 mm, then the abundance of perennials is of its highest, resulting in veld which is primarily in good to very good condition (up to 84% perennials). Time since last burn, coupled with insufficient rainfall in terms of raindays during years Y_{-2} and Y_{-3}, together with concentrations of bulk feeders, appear to have a suppressive effect on the abundance of perennial grass plants.

When the number of raindays in the dormant stage exceed 10.5, the number during the growth stage is the critical factor. When these are <38.5, a negative skewness in the temporal distribution of rainfall interacts via some complex relations which include the abundance of mixed feeders during year Y_{-2}, the thickness of the A horizon, effective depth and base status to suppress perennial grass abundance.

When raindays during the growth stage exceed 38.5, perennials are relatively high in abundance, though this is again mitigated against by bulk feeders during the current year, or by concentrate feeders of year Y_{-3}. Even though the rainfall during the dormant stage may exceed 168 mm, and that of the growth stage may exceed 336 mm, a relatively low density, of bulk feeders (8.2 kg ha^{-1}) has an over-riding effect in suppressing perennial grass abundance.

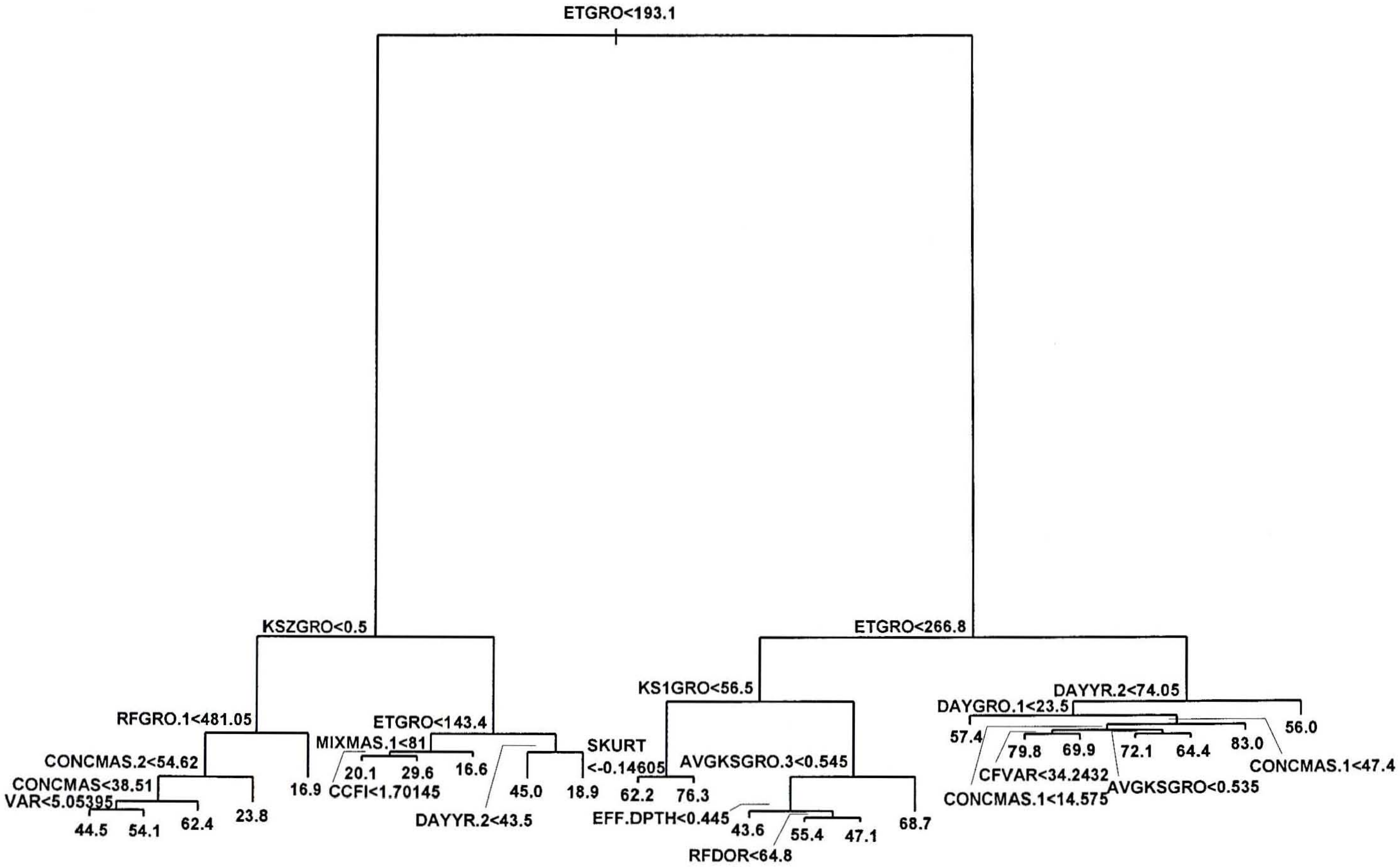


Figure 4.19. Tree regression of perennials on granite (ET variables included).

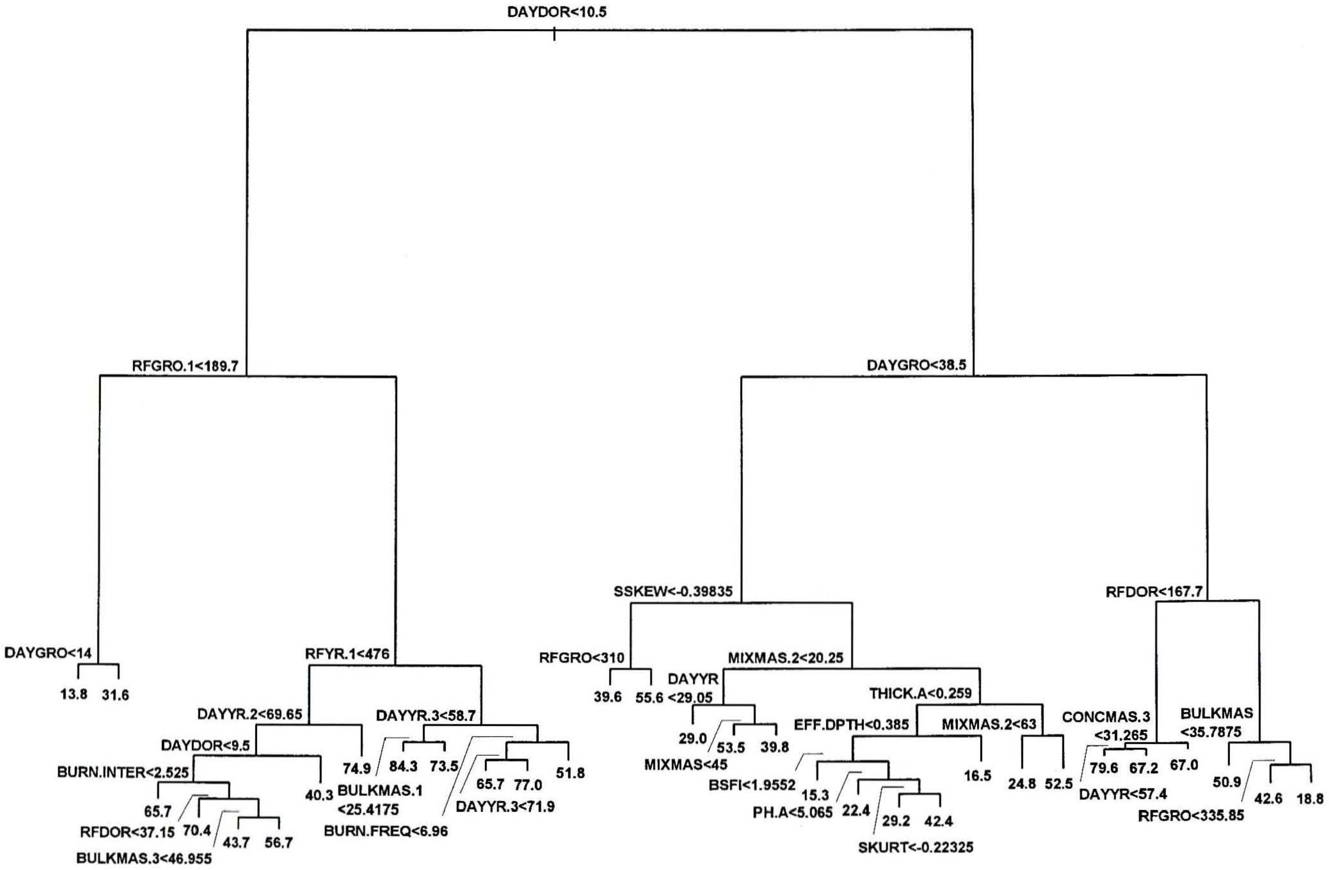


Figure 4.20. Tree regression of perennials on granite (ET variables excluded).

4.5.3.2. Decreasers

Basalt

The number of raindays during year Y_{-2} together with evapotranspiration during the growth stage, clay content of the A horizon (texture), and the base status of the soil have major influences on composition in terms of percentage Decreasers (Figures 4.21 and 4.22). At a finer level, interactions are complex, with a variety of parameters influencing Decreaser abundance. These include woody plant competition, effective depth of the soil, the mean burning frequency, some rainfall and evapotranspiration parameters, and herbivore abundance, though the latter group generally accounts for a very small proportion of the variance in Decreaser abundance. When the previous year's abundance of mixed feeders exceeds 191 tonnes (44.0 kg ha^{-1}) on soils with a clay content >29.5% clay (i.e. clay loam, silty clay loam, sandy clay, silty clay and clay), Decreasers decline from a mean of 56% to a mean of 36%.

When the mean number of raindays during year Y_{-2} is less than 61.3, it is apparent that grazers have an influence on Decreaser abundance at much lower concentrations than in the above case, though this in combination with a variety of other factors. Under such conditions, very low densities of concentrate and mixed feeders appear to influence Decreaser abundance negatively to a substantial degree. It thus appears that grazers in general are not primarily responsible for a decline in Decreasers but, together with a variety of other factors, have a synergistic effect on Decreaser abundance.

When the ET variables were excluded from the analysis, the total number of raindays during year Y_{-2} and percentage clay content not only still proved to be the most important factors in determining Decreaser abundance, but at exactly the same thresholds as well, with the number of raindays during the growing season replacing evapotranspiration. On an overall basis, these three parameters account for the greatest proportion in the variance of Decreaser abundance. At a finer level of detail, when the number of raindays during the growth stage are less than 28.5 on average, effective soil depth plays a substantial role. Below this level, herbivore abundance has a negative influence, but generally of a relatively minor nature. Nevetheless, under such stressful conditions, a generally very low herbivore density apparently is sufficient to cause a decline in Decreasers.

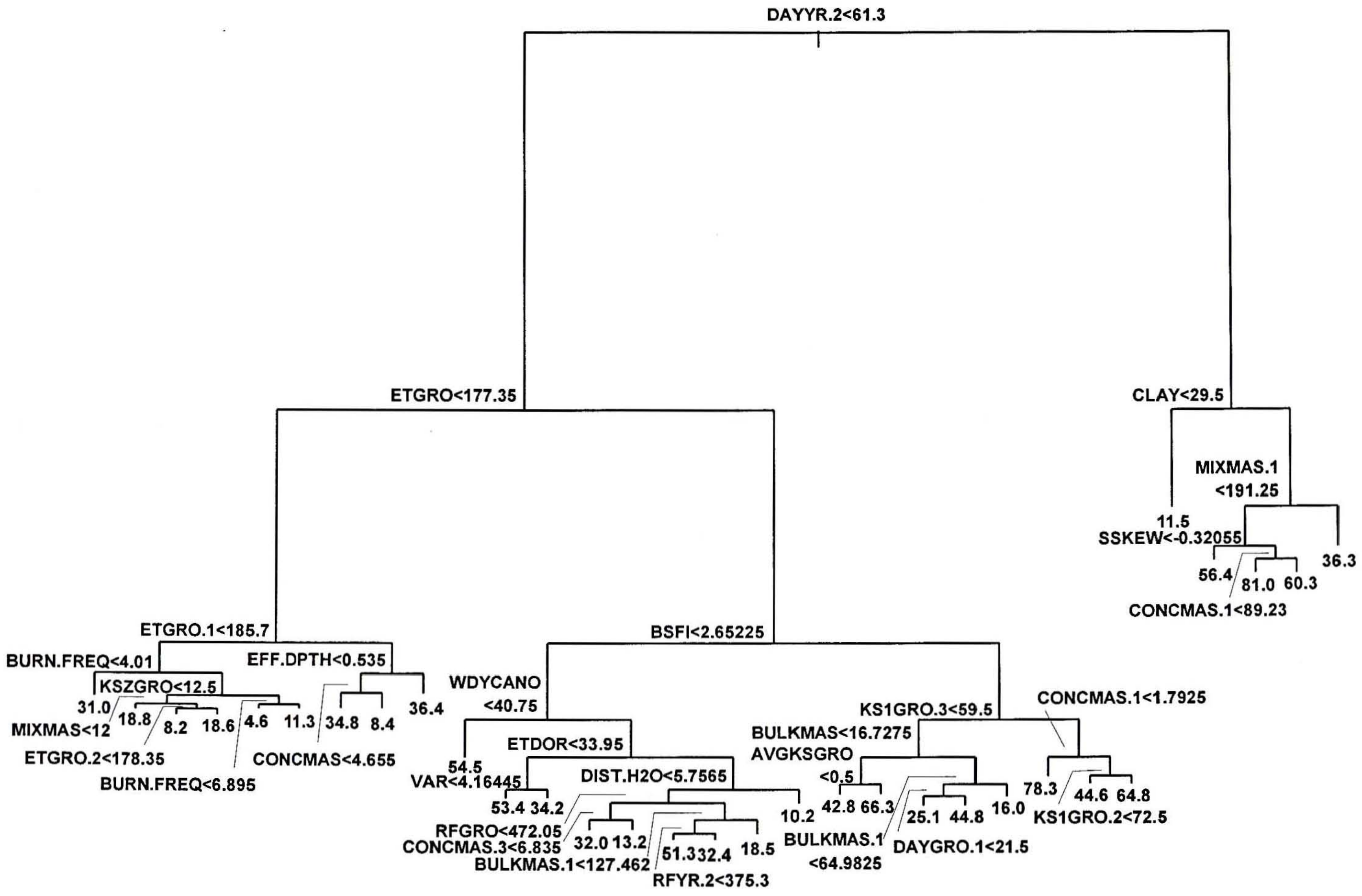


Figure 4.21. Tree regression of Decreasers on basalt (ET variables included).

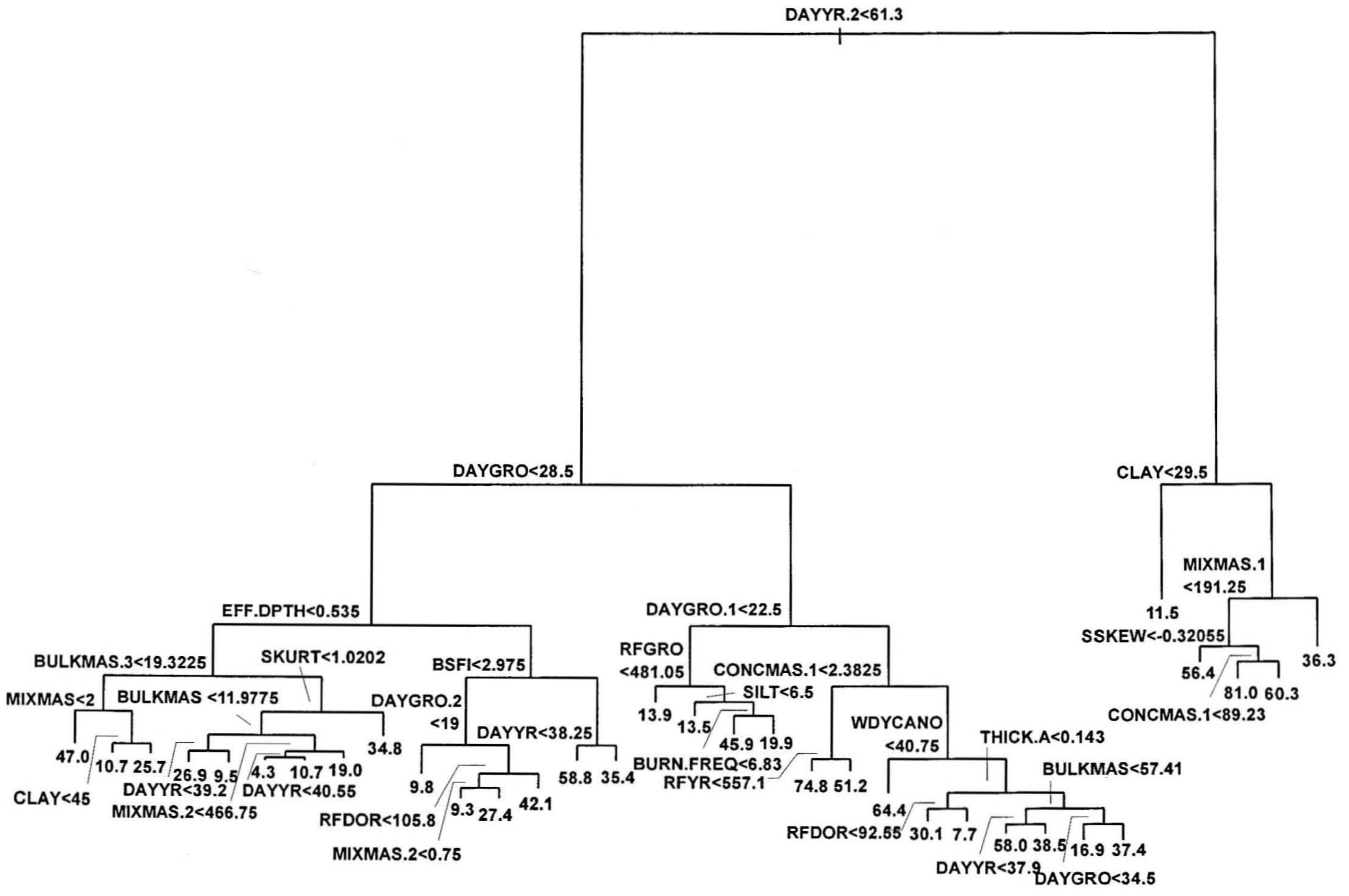


Figure 4.22. Tree regression of Decreasers on basalt (ET variables excluded).

Granite

Soil moisture content during the growth stage, and more specifically, at the 200 mm evapotranspiration threshold, is the key factor in Decreaser abundance on granite (Figures 4.23 and 4.24). It is significant to note that when ET_c exceeds 200 mm, as is the case on basalt, soil texture class plays an important role. Moreover, the threshold of this parameter is at exactly the same clay content percentage as is the case on basalt (i.e. the same texture classes prove to be important). At finer levels, soil moisture stress, coupled with herbivore abundance, has an influence.

Herbivore thresholds on granite are however more than twice as high (117.7 tonnes or 27.1 kg ha^{-1}) on average, than on basalt (57.2 tonnes or 13.2 kg ha^{-1}). This may indicate that Decreasers on granite have a higher resilience to herbivore pressure than they do on basalt. This is alluded to by the parameters describing soil moisture stress in the root zone ('KS' parameters). On basalt, the threshold in the number of days with maximum root stress is 12.5 days, whereas on granite, this drops to an average of 0.5 days before the other factors start to have an influence.

When ET variables were excluded, the number of raindays during the growth stage are the single most important criterion, accounting for approximately 30% in the variance of Decreaser abundance. Collectively however, when these exceed 30.5, a variety of other parameters influence the abundance of Decreasers to a substantial degree. The number of raindays in the dormant stage, texture class of the A horizon, total rainfall during the year, number of raindays during the growth stage of years Y_{-2} and Y_{-3}, as well as distance from permanent drinking water, all play major roles. In the KNP, Thrash *et al.* (1993) found that permanent drinking water has an impact on the herbaceous community composition, though only up to a small distance from the water-point. Sacrificial areas where the herbaceous community consists mainly of annual plants, extends from 20-300 m from water.

As has been shown with the other tree regressions dealing with Decreasers, grazer pressure on its own plays a relatively minor role in the abundance of Decreasers on granite, though it appears to act in combination with other parameters in complex ways, to exert a synergistic influence on them when soil moisture stress is acute.

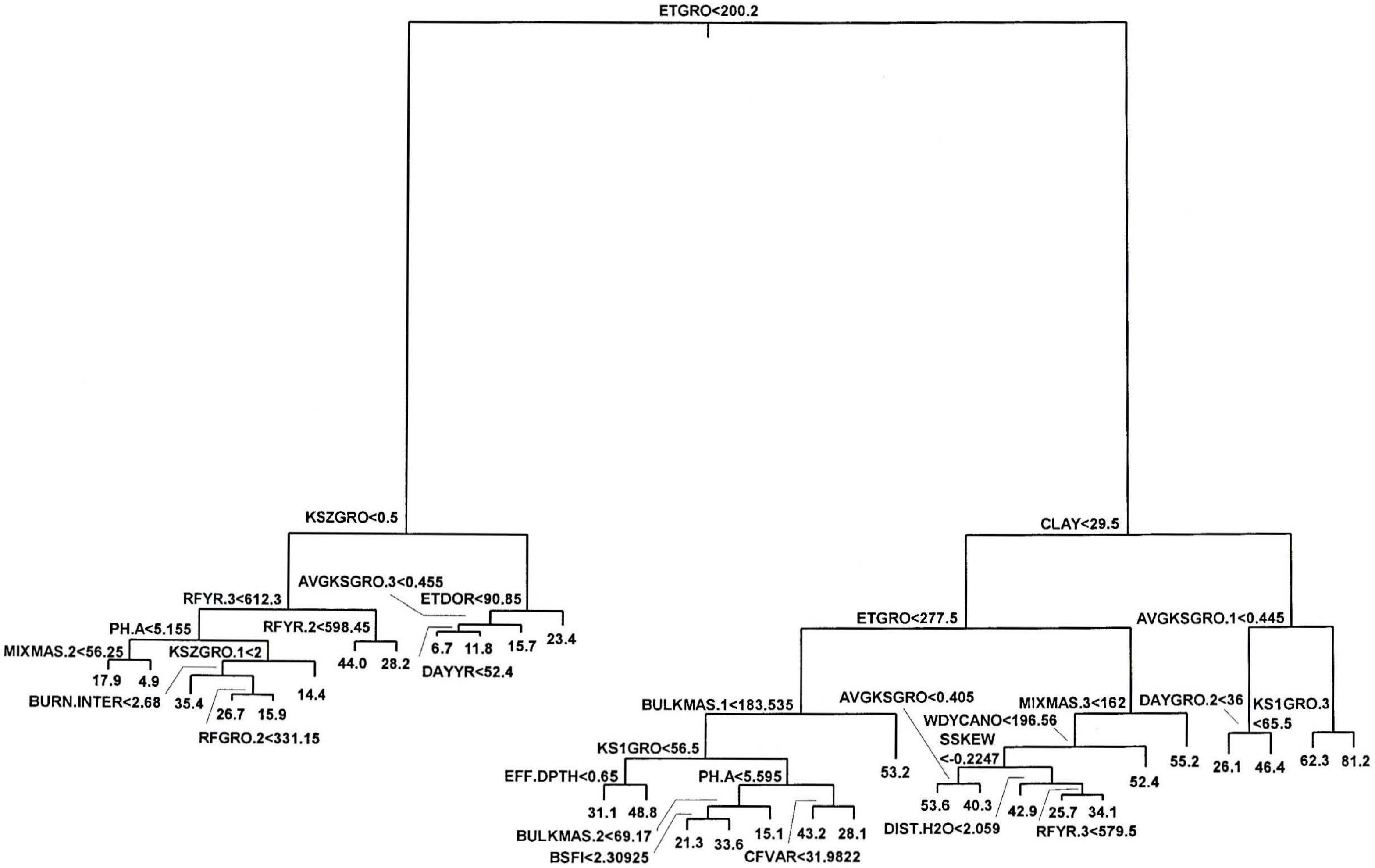


Figure 4.23. Tree regression of Decreasers on granite (ET variables included).

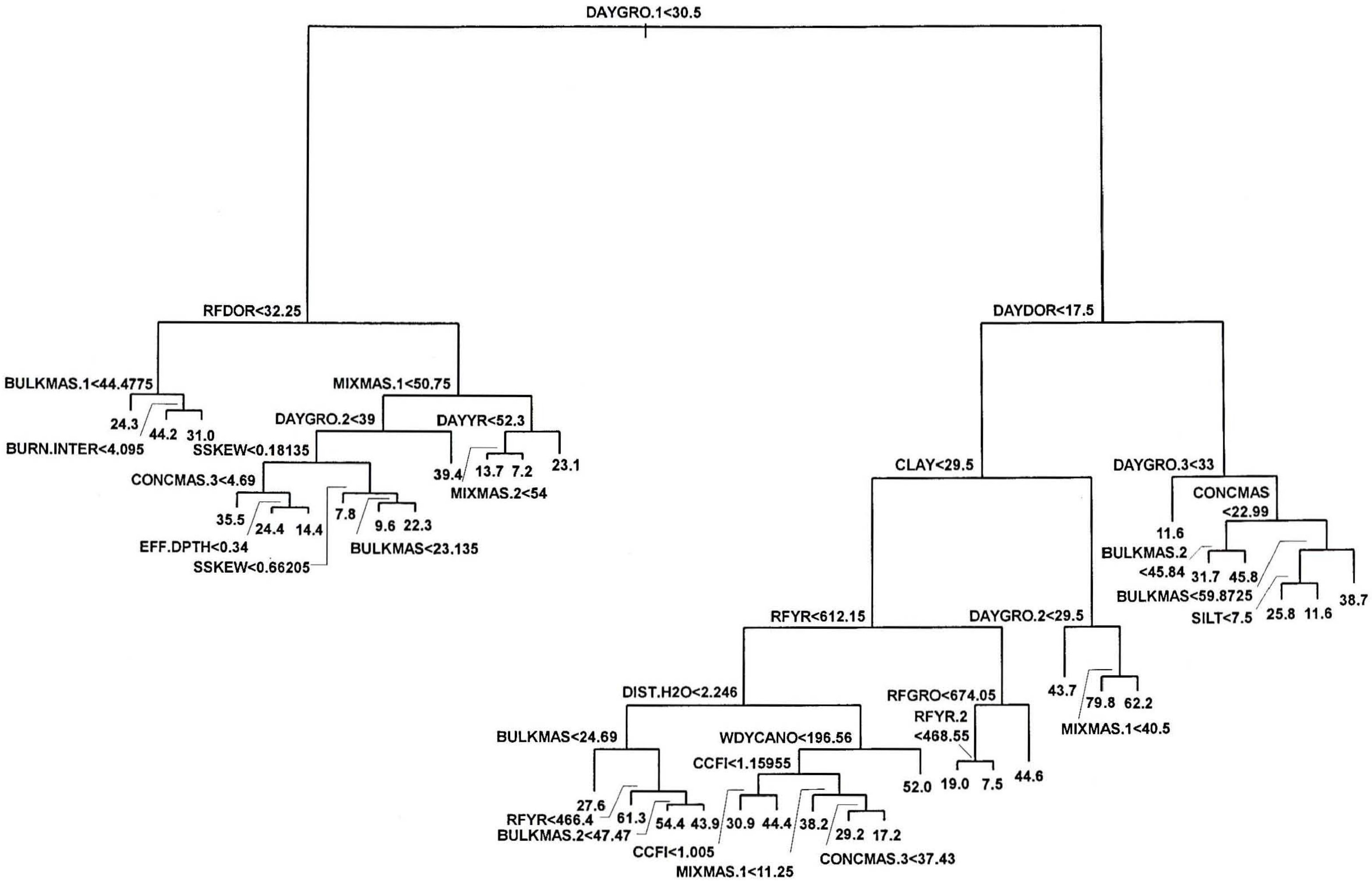


Figure 4.24. Tree regression of Decreasers on granite (ET variables excluded).

4.5.4. TREE REGRESSIONS FOR MANAGEMENT PURPOSES

The foregoing analyses in which a large variety of independent variables were used are complex and in most cases produced equally complex relations and insights into the determinants of grass production and composition. Data on many of the parameters identified by these analyses as being important are however not universally available or require a great deal of computation to derive. Clearly, for applied (i.e. management) purposes, this is impractical, particularly when the application must be undertaken by section rangers.

Tree regression analyses were consequently undertaken using easily obtainable information, or information which can be calculated easily, specifically for applied purposes (Figures 4.25 and 4.26). For NPP, only rainfall parameters and composition (in terms of perennials) were included. The same parameters were used for NSC, with the addition of time since the last fire as this emerged as an important parameter in the more detailed analyses of NSC. The models extend over a wide range of mean DPM heights and hence standing crop values. These include the ranges pertinent to veld burning and fire safety.

Values for all the required parameters can either be obtained or calculated directly from routine daily rainfall observations or from VCA survey results. Information on the burn interval, i.e. time since last burn, is available from burning records at each ranger's office.

Table 4.7 lists the parameters for which information is required in order to use the appropriate tree regression model successfully

4.5.5. VALIDATION

Using the data files set aside for validation purposes and the tree regressions developed for management purposes (Figures 4.25 to 4.28), mean DPM heights were calculated as the actual values and the means given in these figures were used as the predicted values. The validation files however each comprise only 134 records, resulting in the mean DPM values being based on a relatively small number of records, and hence small degrees of freedom. For this reason, only six mean values could be determined for NPP on basalt and eight for granite and they were consequently combined as a single, overall test for this parameter. This is too low.

On average, in the case of NPP, each value required 17.5 records (range 7-33) to produce a mean; 3.6 (range 1-14) for NSC on basalt, and 3.9 (range 1-12) for NSC on granite. Although not determined, the standard deviation in the latter two cases in all probability is high.

NPP (basalt and granite combined) $r = 0.915$; $r^2 = 0.834$; SEE = 1.60; $P = 0.0000$; D.f. = 13
NSC (basalt): $r = 0.892$; $r^2 = 0.796$; SEE = 2.53; $P = 0.0000$; D.f. = 32
NSC (granite): $r = 0.793$; $r^2 = 0.629$; SEE = 1.87; $P = 0.0000$; D.f. = 31

In spite of the limitations in validating the simplified tree regressions, results are encouraging and warrant further investigation and development of this procedure.

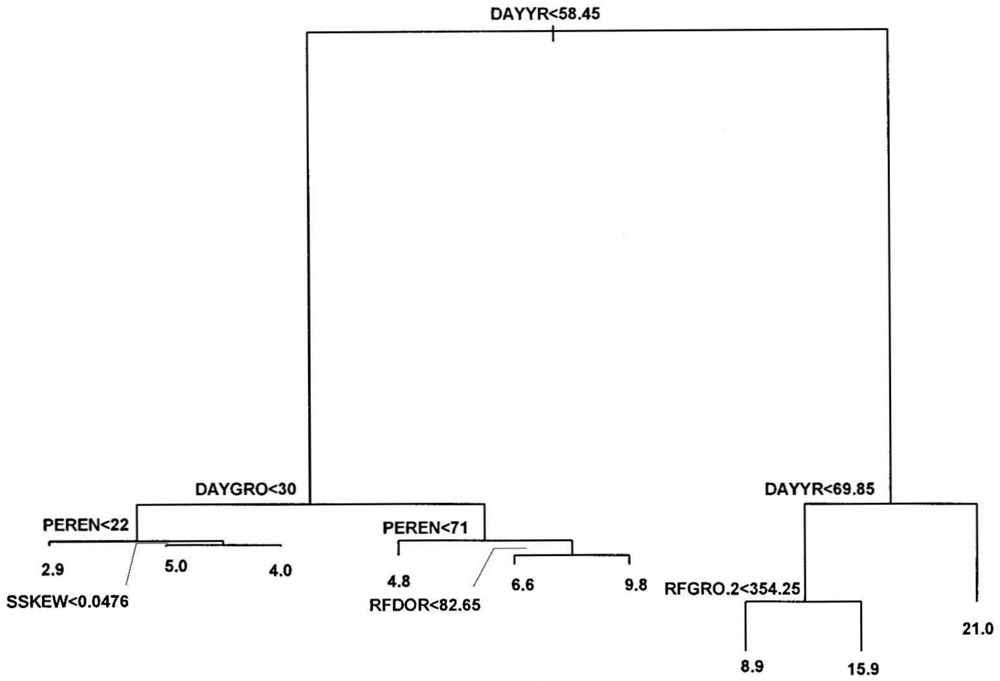


Figure 4.25. Tree regression of NPP on basalt for management purposes.

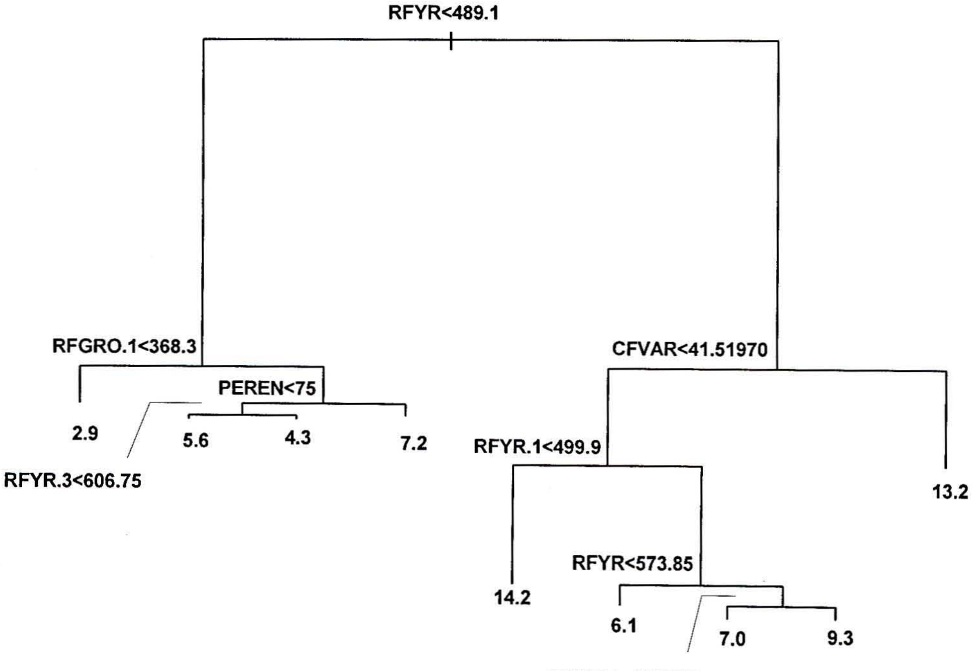


Figure 4.26. Tree regression of NPP on granite for management purposes.

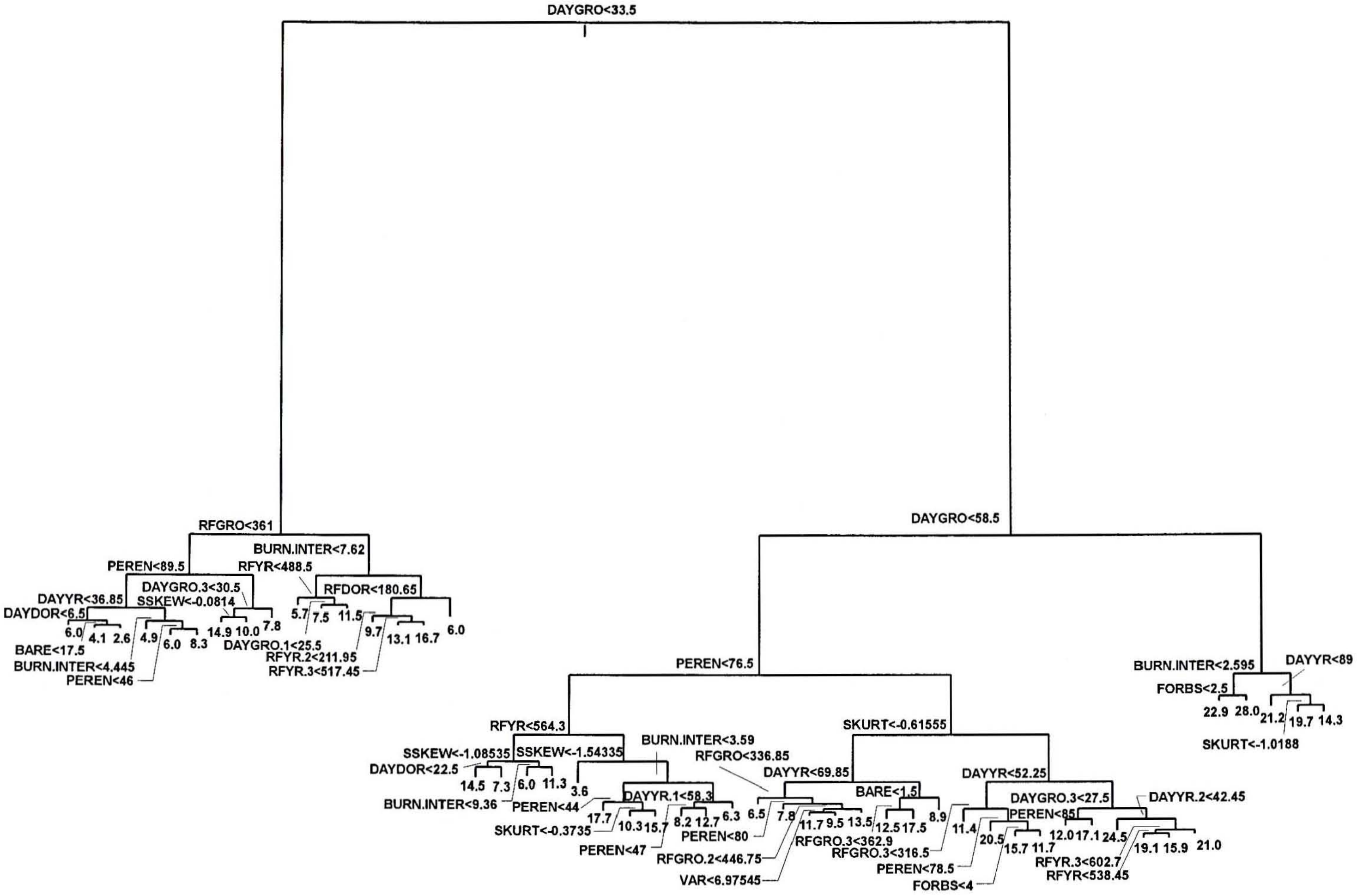


Figure 4.27. Tree regression of NSC on basalt for management purposes.

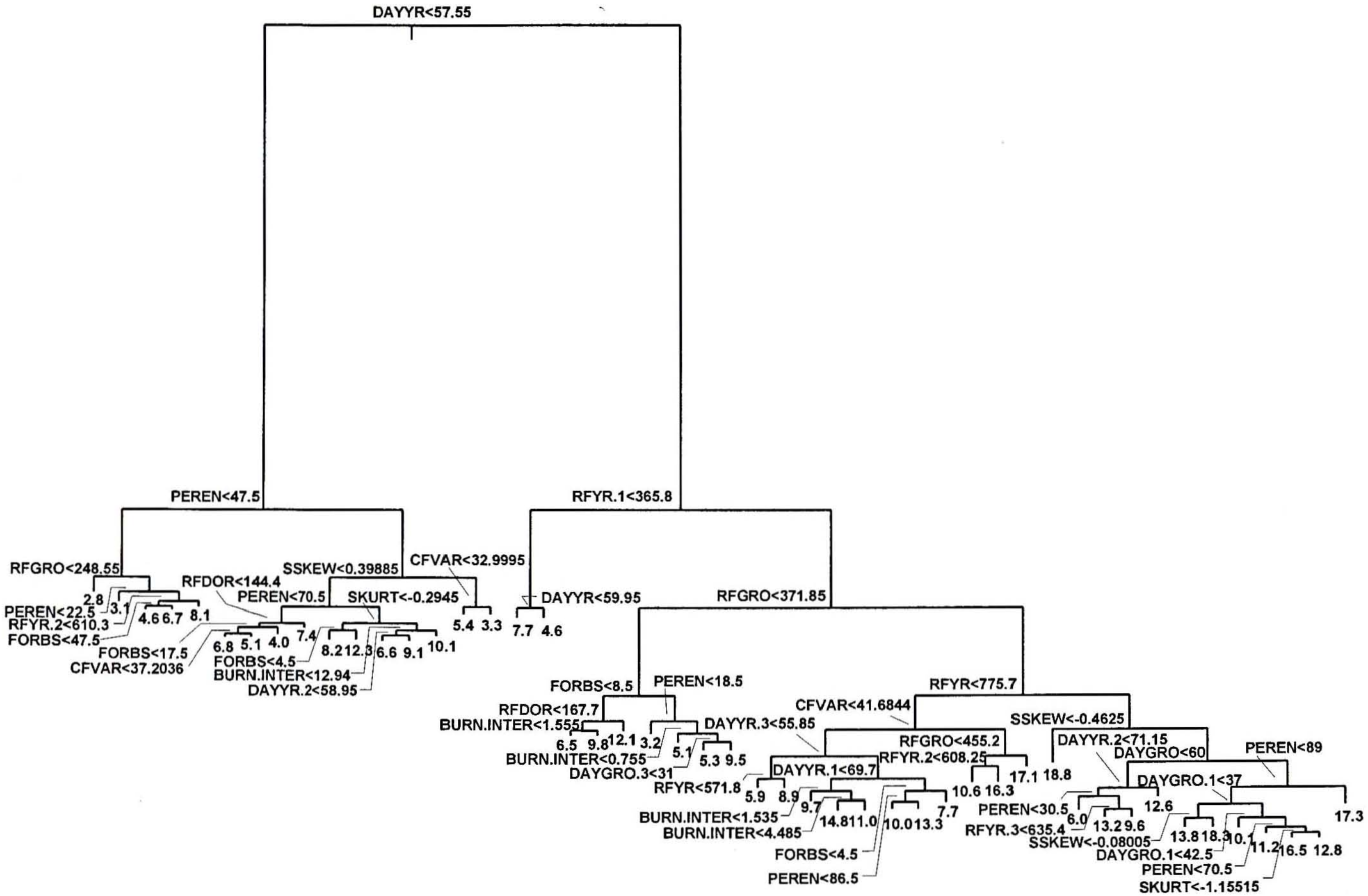


Figure 4.28. Tree regression of NSC on granite for management purposes.

Table 4.6. Legend for Figures 4.11 to 4.28

ANN	Amount of annual grasses	[%]
[1]AVGKSGRO	Mean root stress coefficient (>0 to <1) during the growth stage (current year)	[-]
BARE	Amount of bare ground	[%]
BSFI	Base status fertility index	[-]
[1]BULKMAS	Total mass of bulk feeders (current year)	[tonnes]
BURN.FREQ	Burn frequency during 1980-1999	[years]
BURN.INTER	Burn interval (period since previous burn)	[years]
CCFI	Clay content fertility index	[-]
CFVAR	Coefficient of Variation of raindays (current year)	[-]
CLAY	Typical clay content of the A horizon for the particular texture class	[%]
[1]CONCMAS	Total mass of concentrate feeders (current year)	[tonnes]
DAYDOR	Total raindays during the dormant stage (current year)	[days]
[1]DAYGRO	Total raindays during the growth stage (current year)	[days]
[1]DAYYR	Total raindays (current year)	[days]
DECR	Amount of Decreaser grasses	[%]
DIST.H2O	Distance to the nearest permanent water-point	[km]
EFF.DPTH	Effective depth of the soil profile	[m]
ETDOR	Total evapotraspiration during the dormant stage (current year)	[mm]
[1]ETGRO	Total evapotraspiration during the growth stage (current year)	[mm]
FORBS	Amount of forbs	[%]
INC2GR	Amount of Increaser II grasses	[%]
[1]KS1GRO	Total days without root moisture stress during the growth stage (current year)	[days]
[1]KSZGRO	Total days of maximum root moisture stress during growth stage (current year)	[days]
[1]MIXMAS	Total mass of mixed feeders (current year)	[tonnes]
ORG.CARBON	Typical organic carbon content of the A horizon for the particular texture class	[%]
OTHERS	Amount of 'Other' grasses	[%]
PEREN	Amount of perennial grasses	[%]
PH.A	pH of the A horizon	[pH]
RFDOR	Total rainfall during the dormant stage (current year)	[mm]
[1]RFGRO	Total rainfall during the growth stage (current year)	[mm]
[1]RFYR	Total rainfall (current year)	[mm]
SDEV	Standard deviation of raindays (current year)	[days]
SILT	Typical silt content of the A horizon for the particular texture class	[%]
SKURT	Standardised kurtosis of raindays (current year)	[-]
SOILFERT	Soil fertility index	[-]
SSKEW	Standardised skewness of raindays (current year)	[-]
THICK.A	Thickness of the A horizon	[m]
VAR	Variance of raindays (current year)	[days]
WDYCANO	Total woody canopy cover	[m^{-2}]

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[1] Variables which are also lagged by one to three years, indicated in the figures by the suffix '.1' or '.2' or '.3' respectively.

Table 4.7. Variables required for the successful use of tree regressions for management purposes. Variable abbreviations are explained in Tables 3.4 and 4.6.

MAJOR GROUP	**PARAMETER**	**NPP**		**NSC**	
		BASALT	**GRANITE**	**BASALT**	**GRANITE**
FIRE	BURN.INTER			●	●
RAINFALL	RFDOR	●		●	●
	RFGRO			●	●
	RFGRO.1		●		
	RFGRO.2	●		●	
	RFGRO.3			●	
	RFYR		●	●	●
	RFYR.1		●		●
	RFYR.2			●	●
	RFYR.3		●	●	●
	DAYDOR			●	
	DAYGRO	●		●	●
	DAYGRO.1			●	●
	DAYGRO.3			●	●
	DAYYR	●		●	●
	DAYYR.1			●	●
	DAYYR.2			●	●
	DAYYR.3				●
	VAR			●	
	SSKEW	●		●	●
	SKURT		●	●	●
	CFVAR		●		●
COMPOSITION	PEREN	●	●	●	●
	FORBS			●	●
	BARE			●	

4.6. VELD CONDITION ASSESSMENT IN CONSERVATION AREAS

'Veld condition' is defined by Trollope *et al.* (1990) as the "condition of the vegetation in relation to some functional characteristic, normally maximum forage production and resistance to soil erosion". Tainton (1988) defines it as the "state of health" of a particular piece of veld, adding that the criterion commonly used to judge veld condition has an ecological basis: the long-term "stability" of the plant community and its ability to protect the soil from unacceptable rates of soil loss, these criteria being regarded as being of primary importance. In some areas, regardless of the management practices applied, the inherent characteristics of the area (climatic and edaphic) preclude any possibility of an 'improvement' in veld condition. In such cases some fundamental change in the system occurs and so its ability to sustain the original components in a productive state. In many cases this will include the loss of the topsoil mantle and a different species composition of plants and/or animals.

In conservation areas, the use of conventional, agriculturally-based techniques for evaluating veld condition in terms of grazing quality and quantity have played, and will continue to play, a very important role in the successful management of such areas. It is, however, becoming increasingly important that, in *addition* to grazing value, 'veld condition' needs to be defined and evaluated according to broader criteria. According to Stuart-Hill & Hobson (1991), traditional veld condition assessment methods, which score veld either in terms of its 'state of health' or its value for a specific land-use objective is problematic and should simply be a descriptive index, devoid of value judgement.

In a conservation area, *habitat diversity,* must be maintained (in addition to providing grazing of a 'good' quality for ungulate herbivores), in order to cater for the needs of a relatively very wide diversity of organisms, both plant and animal; in other words, *biodiversity.* This requirement immediately complicates the evaluation of the veld in that besides composition, the structure of the vegetation must also be evaluated, be it grassland, savanna or forest.

Veld that would otherwise be described as being 'poor' in a grazing context, be it from a domestic livestock (agricultural) or game production perspective for example, represents ideal habitat for certain organisms which prefer this type of situation; the assessments usually made against a relatively small set of profit driven objectives. Examples where a broader range of objectives would apply are habitat requirements for a variety of ground-living birds, and certain mammals and reptiles which prefer short, open veld, e.g. blue wildebeest, zebra, black-backed jackal, some bustard and francolin species, etc.

The presence of a large number of forbs or herbs with little or no grass is ideal habitat for steenbok, to give another example, yet this would be regarded as veld in a very poor condition. These same forbs or even just one forb species could also be key plants essential for the survival of a particular insect species, to give another example. In terms of preserving these organisms, such veld would be in good or even excellent condition! The same can be said for the woody layer. 'Bush-encroached' veld is not suited to plains-loving animals such as wildebeest and zebra, yet this situation is ideal for a variety of other animals. Scholes (1997) states that at moderate levels and at small scales, the trampling, soil disturbance and uprooting that occurs during grazing by large mammals helps to maintain diversity in the herbaceous layer by creating gaps. Burrowing animals, from dung beetles to warthogs, turn over large amounts of soils and create patches suitable for the maintenance of early-succession species.

By implication then, veld in 'optimal' condition requires that the vegetation be in different states, depending of the user objectives. Patches of 'degraded' veld thus have a place in conservation areas. How large or small they should be, or what percentage of the total area is acceptable is, however, a debatable point. Whatever the size that such areas can be however, the need for soil stability and the prevention of accelerated soil loss cannot be compromised and should be actively combated wherever it occurs, particularly if this is as result of management practices.

Stuart-Hill & Hobson (1991) propose a multivariate, descriptive approach devoid of value judgement for reducing the dimensionality of complex vegetation data so that the index so derived, describes the main attributes of the veld. Central to their approach is that different land-users will all use the same descriptive index but interpret it differently (i.e. attach different values to it), depending on their objectives.

Where the emphasis is neither on agricultural or wildlife production but on the conservation of the natural fauna and flora, as is the case in most national parks and nature reserves, 'veld condition assessment' thus has (or can have) a far wider scope or meaning than the evaluation of the state of the vegetation in terms of grazing quality and quantity. The latter objective can thus be part of a wider, *habitat* evaluation programme whereby the state of the vegetation could be evaluated according to widely differing criteria.

Consequently, in order to cater for these wide-ranging needs, the veld condition assessment programme of the KNP has been modified to include an evaluation of composition and structure of the woody layer as well as the more common component based on species composition. The original objectives of evaluating veld condition in terms of the quality and quantity of grazing remain a very important element of the programme and have not been diluted in any way. On the contrary, modifying the procedure to obtain data on absolute abundance, in addition to relative abundance, has strengthened this.

4.7. RELATIVE vs ABSOLUTE ABUNDANCE MEASUREMENTS FOR LONG-TERM MONITORING PURPOSES

A standard feature of many (if not most) veld condition evaluation techniques in semi-arid regions is to record the nearest plant to a point using the Decreaser-Increaser species classification (e.g.Vorster 1982; Danckwerts & Stuart-Hill 1988; Friedel 1988; Tainton 1988). Composition is then calculated on the basis of the abundance of the different species or categories of species, each being expressed as a percentage of the total. Forage, fuel and overall site 'scores' or ratings are also determined and are generally based on these percentages.

The shortcomings of this classification system apart, these procedures cannot be faulted if the intention is simply to determine veld condition in terms of grazing potential or the potential to produce fuel for veld burning, or to determine the *relative* abundance of the species or the groups concerned, especially in 'one-off' surveys. In other words, veld condition assessment in terms of grazing and fuel production for burning.

Relative abundance (percentage frequency) however has the serious disadvantage of masking true changes in composition that may have occurred between one survey and another (generally, the time interval being a year). Changes in relative abundance are not necessarily a reflection of changes in the density of individual species or species groups. This makes it very difficult or perhaps even impossible to understand the reasons for inter-annual fluctuations in composition (Zambatis 1996), leading to a great deal of confusion and uncertainty regarding the true situation. Fourie *et al.* (1984) came to the conclusion that basal cover is a better indicator of trends in veld condition than botanical composition, the former probably being a more sensitive criterion, while retrogression in botanical composition probably indicates a more permanent and advanced stage of veld degradation.

In a study undertaken in Mixed Bushveld to determine the influence of habitat, rainfall and grazing on herbaceous species composition and production, van den Berg *et al.* (1996) found that the nearest plant method was not suitable to monitor changes in absolute species density and basal cover. They also state that in a wet year, the 'explosion' of annuals can cause severe discrimination against perennial species if relative frequencies are used and recommend the use of a circular plot to overcome these problems. Working in the Karoo, Vorster (1982) came to a similar conclusion, namely that nearest plant data favour annual grasses (and karoo bushes) on account of their smaller size and higher density. Regarding basal cover, he states that this is inclined to favour perennial grasses above the karoo bush component because perennial grasses have a narrow base to canopy spread ratio, whereas karoo bushes have a much wider ratio.

In long-term monitoring of veld condition, the confounding effects of relative abundance have a debilitating effect on the usefulness of the data obtained from year to year in terms of determining trends in abundance of individual species and in attempting to determine the causes of these trends, or to relate them to other phenomena; for example, concentrations and shifts in herbivore abundance. Absolute abundance is of greater value in long-term monitoring of composition than is relative abundance as it allows the trends of species (or groups of species) to be tracked accurately and reliably from year to year.

CHAPTER 5

RE-EVALUATION OF THE DISC PASTURE METER CALIBRATION FOR THE KRUGER NATIONAL PARK

5.1. INTRODUCTION

Since its initial development in New Zealand (Phillips & Clarke 1971), the disc pasture meter (DPM) is widely used in South Africa as a simple and rapid means of measuring compressed grass height, from which grass standing crop is calculated by means of a calibration equation. It is generally used in applied veld management practices such as determining the standing crop prior to burning the grass sward (Trollope & Potgieter 1986; Trollope *et al.* 1989; 1990) and to determine stocking rates (e.g. Bransby & Tainton 1979).

Depending on the objective of the burn, information on the standing crop quality, together with weather conditions, enables the manager to determine the likely effectiveness of the fire in for example, burning back woody shrubs or removing moribund grass material. It is also used to determine available standing crop when calculating and adjusting herbivore stocking rates. The instrument is also used in rangeland research, though its calibration precision at times is inappropriate where it is essential to detect relatively small temporal or spatial differences in standing crop.

The principle of the instrument is a constant mass falling from a constant height. The greater the standing crop, the greater the height above ground level at which the disc will settle, i.e. the 'compression height'.

The instrument is made of aluminium and consists of four parts (Figure 5.1): a 970 mm-long tube of 27 mm external diameter attached to a 175 mm diameter and 6 mm thick base-plate. A disc 458 mm in diameter and 1.5 mm thick is attached to the base-plate by means of four 6 mm diameter brass bolts. In earlier models, the tube was welded onto the base-plate but with prolonged use, metal fatigue developed in the welding seam, frequently resulting in a breakage at this point. This problem was solved by attaching the sleeve to the base-plate by means of a thread, which also has the advantage that it can be dismantled to reduce bulk for transport and storage. These three components together have a mass of 1.5 kg.

The fourth component is an aluminium rod, T-shaped in cross-section and 1 800 mm long by 22 mm wide. The rod is marked off at 1 and 0.5 cm (10 and 5 mm) intervals, to a maximum of 600 mm and passes through the tube and disc. With the latter placed on a perfectly flat surface, the 0-mm mark is in line with the top of the tube.

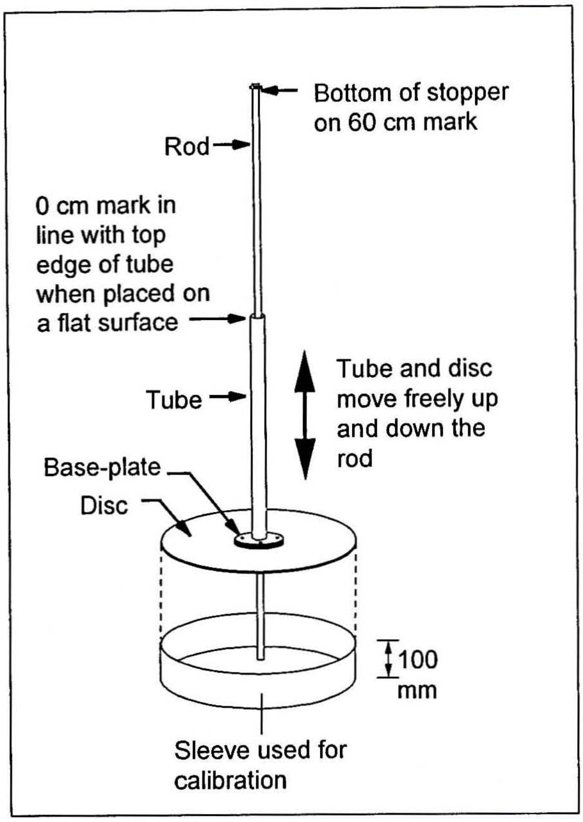


Figure 5.1. The modified disc pasture meter based on the original design of Bransby & Tainton (1977), and the sleeve used for its calibration.

In its field application, the rod is passed through the tube and the two held perpendicular to the ground surface. The tube and disc assembly is raised to the stopper and then released to fall onto the underlying grass sward. The compressed height of the sward is then read off the rod at the top edge of the tube; either to the nearest 0.5 cm or estimated to 1 mm.

In their evaluation of three quick methods commonly used to assess sward height, Stewart *et al.* (2001) report that each method has strengths and weaknesses. The 'drop disc', apparently similar to the DPM, was found to be the worst method for recording micro-heterogeneity in sward architecture and was completely unsuitable in measuring variation in short turf. In other tests though, it obtained much closer correlations ($r^2 = 0.70$-0.90) between herbage dry weight and sward height measurements than those using a 'sward stick'. They conclude that the drop disc is the most suitable method for measuring productivity and vertebrate herbivory, and for large-scale monitoring of sward height on nature reserves and agri-environment areas.

Calibration of the instrument is described by Bransby and Tainton (1977), who calibrated it for various studies in the Kwazulu-Natal region. Their procedure has since been followed by others in calibrating the instrument for other areas and can be considered to be the standard calibration procedure. Briefly, this involves the use of a sleeve having an internal diameter very slightly larger than the disc and 100 mm high (Figure 5.1).

After the disc has been dropped on the sward and the compressed height read off the rod, the sleeve is carefully passed over the tube and the disc so as not to unduly to disturb the underlying material. With the disc assembly and rod removed, all the material inside the sleeve is then clipped with sheep-shears or a similar instrument to a height no greater than 30 mm above the ground surface, and placed in paper bags (not plastic, to allow the escape of moisture). The material is then oven-dried to constant mass, weighed, and the mass converted to kg ha^{-1} or gm m^{-2}.

Calibration of the instrument involves the regression of the mass as the dependent variable against the DPM reading. In all the calibrations undertaken in South Africa, linear regression has been applied routinely, apparently based on the assumption that the relation between the settled height of the DPM and the mass of the material below it is linear (as recommended by Bransby & Tainton 1977).

In the scatter diagram of Trollope & Potgieter (1986) (Figure 5.2, points A-I) eight points are outliers from an otherwise asymptotic and possibly even an optimum (i.e. quadratic) distribution pattern. In the analysis of Trollope & Potgieter (1986) these outliers were removed and a linear regression fitted. In doing so they set the condition that the calibration equation was only to be used in situations where the sward is not lodged or moribund, the reason being that in all cases of outliers, the grass sward had become moribund due to a lack of grazing or fire.

Although much variation is evident, the scatter diagram of the data used in this study (Figure 5.2.) shows that the general relationship between DPM height and standing crop is not linear but tends to level off beyond a DPM height of approximately 300 mm.

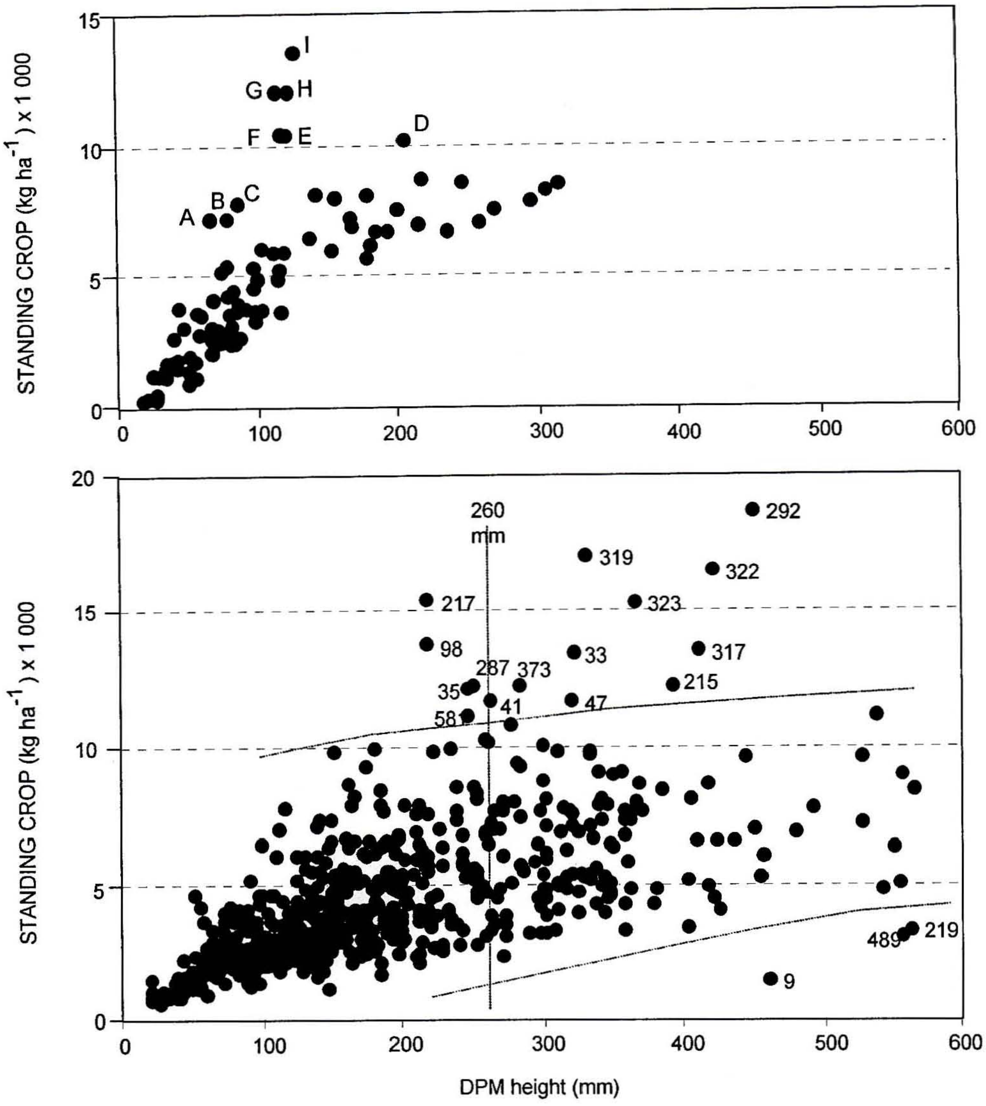


Figure 5.2. Top: Scatter diagram of the Trollope & Potgieter (1986) calibration data, and of this study (bottom). Labelled outliers are discussed in the text.

In a sense, this is a reflection of the relatively large diversity in the grass sward of the KNP, both in terms of composition and structure. Approximately 235 grass taxa have been recorded in the KNP. The herbaceous stratum ranges from short, sparse grasses in the arid areas, to a dense sward of medium height in the more mesic areas (especially on basalt); and a tall, tufted sward structure in the wettest (sourveld) areas of the south-western quarter of the KNP - the

Moist region, with a mean annual rainfall of >700 mm. In addition, in certain areas, forbs are dominant, with grasses being scarce. ('Sourveld' is defined as veld in which the forage plants become unacceptable and less nutritious on reaching maturity; 'sweetveld' as veld in which forage plants retain their acceptability and nutritive value after maturity (Trollope *et al.* 1990).

This area is classified by Acocks (1988) as Lowveld Sour Bushveld, stating that "It is a transition between the Lowveld and the North-eastern Mountain Sourveld ...it is either an open parkland; tall, well formed trees, well spaced in tall grassveld, or else bushveld dotted with big trees".

The structure of the grass sward of this area varies greatly, and includes taxa which are short and with a relatively low volume and a scattered distribution such as *Aristida congesta* subp. *barbicollis*, *Pogonarthria squarossa* and *Schizachyrium sanguineum*, short but dense, high-volume species such as *Setaria sphaecelata, S. flabellata*, and *Urochloa oligotricha*; and tall taxa, the most common being *Hyperthelia dissoluta, Hyparrheinia hirta* and *H. fillipendula* (Gertenbach 1983). *Hyperthelia dissoluta*, often taller than 2 meters, is frequently the dominant species over large areas. This relatively high degree of structural heterogeneity makes it particularly difficult to successfully develop a technique for determining above-ground grass standing crop for this area.

A similar structure is described by Gibb & Ridout (1986, 1988) and Morris *et al.* (1999, 1999a) where the grass sward develops into two components - 'short' (patches) and 'tall' (non-patches) areas in the sward as a result of grazers concentrating on certain areas of the sward, resulting in skewed distribution in the frequencies of height measurements,in turn resulting in a "double normal distribution". This comprises a mixture of two 'short' and 'tall' components, each with overlapping normal distributions, and respective means and variances (Gibb & Ridout 1986, 1988; Morris *et al.* 1999).

The DPM was calibrated by Danckwerts & Trollope (1980) and Trollope (1983) to estimate grass fuel loads in the Easten Cape, the Kruger National Park (Trollope & Potgieter 1986), the east Caprivi region of Namibia (Trollope *et al.* 2000) and by Brockett (1996) for the Zululand coastal grasslands, respectively.

Brockett (1996) reported a correlation coefficient between the compressed DPM and grass biomass of 0.759 ($r^2 = 0.576$; $n = 427$) for the Zululand coastal grasslands. In 13 calibrations undertaken by Danckwerts & Trollope (1980) in the Eastern Cape, the correlation coefficient ranged from 0.55 to 0.85, with a mean of 0.73, improving to a range of 0.67 to 0.93 with a mean of 0.79 after "non representative" samples were excluded from the data. This was done when the DPM fell on herbage which is non-representative of the sward which the operator wishes to sample, particularly on natural veld.

In their calibration of the DPM for the grassy plains of Ol Choro Oiroua in south-western Kenya, van Essen *et al.* (2001) used the same field sampling procedure as did Trollope & Potgieter (1986). The reading for DPM height ranged from 16 to 246 mm. Square root transformation of the mean DPM height produced a significant correlation ($r = 0.950$; $r^2 = 0.903$; Df=68; $P<0.01$).

In the latter calibration, "above-normal growth occurred at ...nutrient rich sites of old cattle bomas. The data from these sites were therefore omitted from the analysis on condition that the resultant regression equation should only be used to estimate ...standing crop in areas where the grass sward has not been subjected to the deposition of unnaturally high levels of plant nutrients".

In a preliminary investigation in *Themeda-Tristachya* grassveld (possibly in the Kokstad area of Kwazulu-Natal), Hardy & Mentis (1985) report correlation coefficients of 0.83 and 0.92. In two subsequent field trials, correlation coefficients ranged from 0.23 to 0.93 (mean 0.79) in *Themeda-Tristachya* veld, and from 0.60 to 0.90 (mean 0.81) in *Hyparrhenia-Eragrostis* veld. The heterogeneity of the species composition of these areas is however not given.

In their calibration of the DPM for the KNP in which a single equation was produced for the entire KNP, Trollope & Potgieter (1986) did not use the standard procedure of Bransby & Tainton (1977) as grasses in the central and southern regions of the KNP are tall, and it was also feared that the "edge effect associated with harvesting a small circular quadrat would jeopardize accuracy of the regression". (The 'edge effect' is taken to be the risk of including material at the edge of the sampling cylinder when it should be excluded, and *vice versa*).

The procedure they consequently followed was to lay out a 2x2 m quadrat and determine the mean settling heights of nine DPM readings taken inside the quadrat. The grass sward of the whole quadrat was then harvested, dried and weighed.

Calibration was undertaken using seventy-five paired values, the DPM height ranging from 19-316 mm. A simple linear regression analysis using square root transformation of the DPM reading to ensure a linear relationship between the dependent and independent variables (Trollope & Potgieter 1986) was fitted. Square-root transformation resulted in the best fit of the linear regression, with a correlation coefficient of 0.95 for their resulting regression ($P<0.01$) between the mean DPM height and standing crop.

Comparing the calibrations of the DPM for rangeland with those of planted pastures, it becomes evident that mono-specific planted pastures generally show a stronger relation between compressed disc height and grass biomass than that of rangelands. Bransby & Tainton (1977) obtained a correlation coefficient of 0.758 for Coastcross II pasture. In other calibrations on planted pastures in the RSA and USA, correlation coefficients for simple linear regression ranged from 0.76 to 0.94, averaging 0.87.

These findings for mono-specific pastures possibly indicate a relatively low variance in DPM height for a given above-ground grass standing crop, in turn possibly implying a high correlation between DPM and standing crop. Bransby & Tainton (1977) and Bransby (1978) state that on a mono- specific pasture, measurements taken with a DPM serve as an effective objective basis on which to adjust animal numbers based on expected forage intake.

For natural vegetation however, the correlation appears to be poorer, in some cases markedly so. Trollope & Potgieter (1986) report that calibrations developed over a wide range of sward conditions in the Eastern Cape resulted in the slopes and intercepts of the different linear regression equations varying significantly from each other. The same data showed that in 43 different calibrations, DPM height accounted for only $\leq 64\%$ of variation in grass standing crop.

5.2. OBJECTIVES

This study arose as a result of two observations:

- During field application of the DPM in the tall-grass veld area of the KNP, it was observed that the instrument frequently settles above the bulk of the grass leaf mass, at times resulting in inflated DPM settling heights. This in turn led to the suspicion that, taking into consideration the relatively heterogeneous nature of the herbaceous stratum as explained above, a single calibration equation for the entire KNP is perhaps inappropriate; possibly necessitating that a distinction be made between at least the tall grassveld and the rest of the KNP.
- The scatter diagram of Trollope & Potgieter (1986) shows a non-linear (i.e. asymptotic or possibly an optimum) distribution pattern.

The objective of this work was therefore twofold, namely to:

- re-examine the relation between the compressed DPM reading and standing crop to determine whether it is in fact linear over the full range of the herbaceous stratum structure or not; and
- develop improved calibration equations for research and management purposes.

5.3. METHODS

Annual grass production is strongly related to annual rainfall. Using this as a starting point, the moisture regions of the KNP were determined and mapped according to the criteria of Rutherford & Westfall (1986) and by GIS (Arcview programme). Four regions were identified. The size of each, as a percentage of the KNP, is given in parentheses:

Very arid savanna (VA)	>300 - 400 mm (2.18%)
Arid savanna (AR)	>400 - 500 mm (34.32%)
Semi-arid savanna (SA)	>500 - 625 mm (55.05 %)
Mesic savanna (ME)	>625 - 700 mm (7.49%)
Moist savanna (MT)	>700 mm (0.96%)

Existing standing crop data (5 100 records) collected over a period of eleven years at approximately 530 permanent veld condition assessment (VCA) sites in the KNP according to the technique of Trollope *et al.* (1989) and Trollope (1990) were then classified according to these moisture regions and a one-way ANOVA was undertaken using a variety of tests, each with 95% confidence levels, in order to determine whether the different tests produced different results. These were Least Significant Differences (LSD), Tukey, Scheffe and Bonferroni. All showed that the square-root transformed mean standing crop differed significantly between the Moist and other regions. The natural log of mean mass also showed significant differences between the Mesic and Arid; and between Arid and Moist regions (Table 5.1). Consequently, on the basis of these results, it was decided to collect grass samples in each of these regions.

Table 5.1. Variance test results of mean mass using four tests (Regions: VA= very arid; AR = arid; ME = mesic; MT = moist)

TEST	SIGNIFICANTLY DIFFERENT POPULATIONS			
	Mass	$\sqrt{}$Mass	Mass^2	log Mass
LSD	None	VA-MT;AR-MT	None	VA-ME; VA-MT; ME-AR; AR-MT
Tukey	None	VA-MT; AR-MT	None	VA-ME; VA-MT; ME-AR; AR-MT
Scheffe	None	VA-MT; AR-MT	None	VA-ME; VA-MT; ME-AR; AR-MT
Bonferroni	None	VA-MT; AR-MT	None	VA-ME; VA-MT; ME-AR; AR-MT

The number of samples to be collected in each region then had to be determined. A sample size determination procedure using the null hypothesis was consequently undertaken with a confidence level of 95% and at a power of 95%. It was decided that for research purposes in particular, a relatively high degree of accuracy was required. Tolerance was thus set at 300 kg ha^{-1}, i.e. a need to be able to detect a difference of some 300 kg ha^{-1} between one site and another within the same landscape and in the same growing season. Results showed that for the Arid region, a minimum of 130 samples are required: 136 for the Semi-arid region, 132 for the Mesic region, and 149 for the Moist region - a mean of 137 sites per region. This was rounded off to 150, primarily to have a few extra samples to replace any which may be 'spoilt' for some reason or other and therefore unusable.

The previous year's (1998) VCA surveys were used as a rapid means of finding localities with differing veld condition, the latter determined simply by the abundance of perennial and annual grasses. ('Poor' ≤30% perennials, 'Moderate' >30-60%, and 'Good' ≥60%). Sampling was distributed in equal numbers in the four rainfall regions, and as far as possible, the 150 samples per region were distributed approximately evenly across the gradient in veld condition. The distribution of sample points is shown in Figure 5.3. It is evident from Figure 5.3. that in certain areas, a relatively high density of sampling was undertaken. This is due to the restricted size of the particular moisture region in this area.

In cases where the number of VCA sites was insufficient to achieve this spread, or where sites were clustered, additional sites were located on the map in order to achieve spatial uniformity. In the latter cases, the distance of each of these additional sites from an identifiable point (e.g. a cross-roads, windmill, etc.) was measured on the map. Where sampling was undertaken at non-VCA localities, a quick, subjective evaluation of veld condition was made and a site chosen accordingly.

In all cases, in order to sample randomly, as well as to avoid any edge effects, 10 paces were stepped off from the edge of the road and a DPM reading of the compressed grass height taken to the nearest 1 mm. Sampling of the herbaceous material was undertaken according to the procedure of Bransby & Tainton (1977). The collected material was then placed in paper bags, oven-dried at 65°C for 24 hours, and weighed to two decimal places of a gram using an electronic balance. Sample mass was then converted to standing crop (kg ha^{-1}). A total of 605 paired DPM height-biomass samples were collected.

The same one-way analysis of variance described above was then undertaken on the DPM readings and dry weights. No significant differences with any of the tests were shown between the mean DPM reading of the various rainfall regions. The data were consequently not subdivided according to these regions.

In habitat studies, it is often a necessary to determine the height of the grass sward as a whole and unless this is estimated, it must be physically measured, obviously increasing total survey time. The level of accuracy required and effort made to achieve it is largely dependent on the requirements of the study and the scale at which it is carried out. In a large area such as the KNP however, together with limited personnel, detailed evaluation of microhabitat at an extensive scale is impractical and is best left to specific, small-scale studies. In the VCA

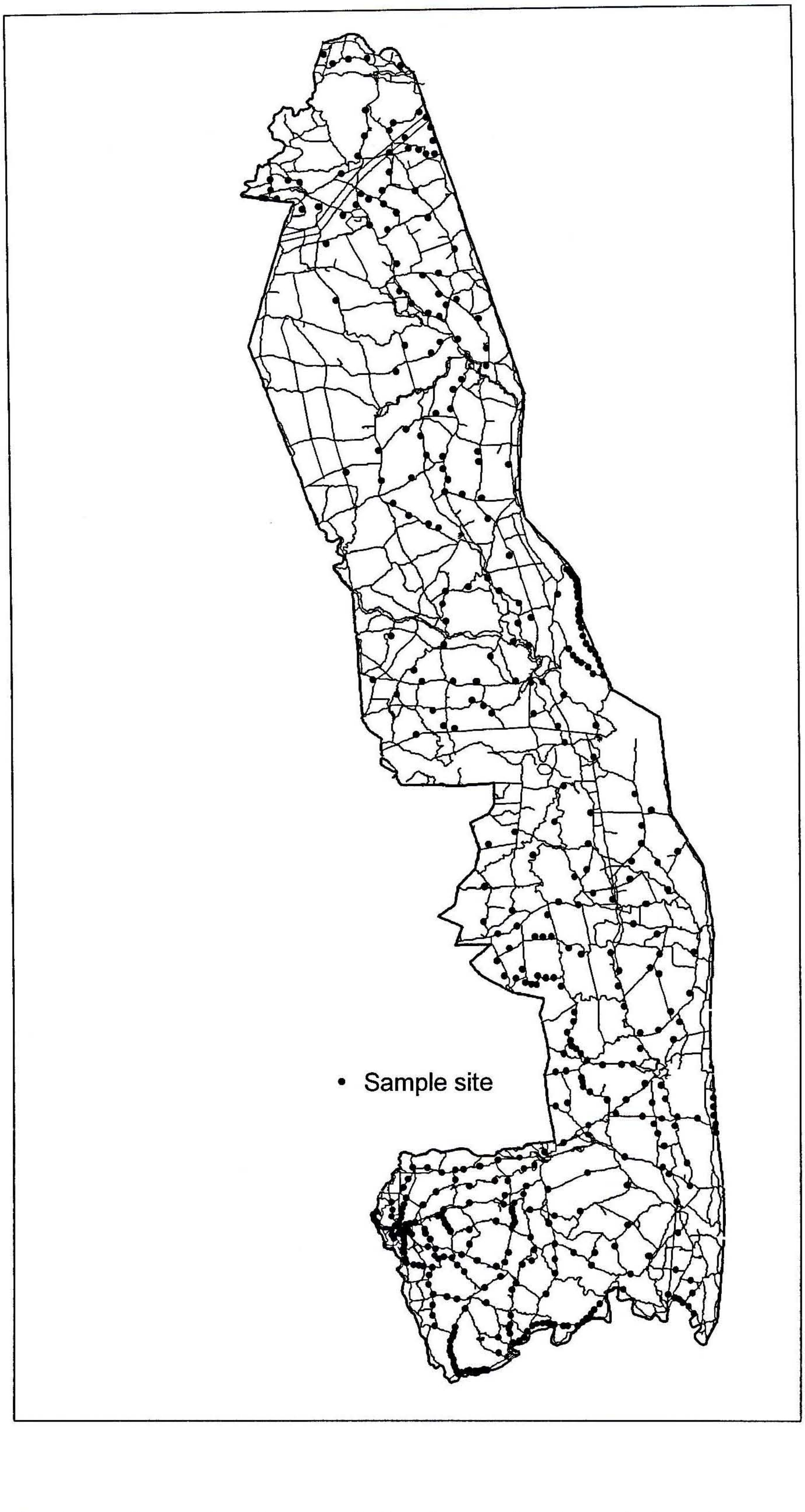


Figure 5.3. Distribution of sample sites used for the evaluation of the disc pasture meter calibration.

monitoring programme applied at the extensive scale over the entire KNP, it suffices to be able to describe uncompressed grass sward height in relatively broad terms.

It was consequently decided to investigate whether the DPM reading can be 'de-compressed' to calculate the sward height, thereby saving time and effort. For this purpose, at each sample point, six height measurements were randomly taken: three of the maximum height of the culm end-points (including the inflorescence, where this was present), and three to the top of the grass canopy (leaf table height). The means for each of these categories were then calculated. In most cases, the dominant grass species was also recorded.

Stewart *et al.* (2001) found the 'sward stick' to be the best method for recording the architecture of the sward surface, and hence invertebrate niches, but was poor for measuring short turf. Never the less, this requires an additional measurement to be made.

Jordaan *et al.* (1991) obtained highly significant correlations between tuft volume and above-ground phytomass of 22 grass species. Volume was calculated from tuft height, measured to the height of the highest leaf tip.

Data from those sample sites with a DPM height >260 mm were examined to determine if there are any common features which may distinguish these from sites with DPM heights of <260 mm. These are listed in Table 5.3. Mean stem and leaf table heights of the dominant grasses of outlier samples (Figure 5.2.) are given in Table 5.4, and compared with non-outliers. Outliers were chosen arbitrarily (subjectively) as those points not falling within the bulk of the point mass the scatter diagrams.

Statistical analyses

Double Normal model estimation

As stated above, it was suspected that two structurally different grass populations exist in the herbaceous stratum of the KNP. It was consequently decided to test for this. Frequency distributions (10 mm height class intervals) were calculated for compressed sward heights and double-normal model distributions were fitted to height frequencies by the method of maximum likelihood estimation (MLE; Derry *et al.* 1999) using the algorithm of Agha & Ibrahim (1984).

This is an iterative, statistical procedure which fits the best distribution to a set of data that may be representing two or more normally-distributed populations and is similar to a least squares estimation. The sub-sets are expected to have differing means and variances, the null hypothesis being that the two are the same. The procedure returns the alpha statistic, and mean and standard deviation of each population. These values were then applied in the Bayes Allocation rule to identify and separate the populations. Two populations were identified using this procedure: ≥20-200 mm and >200 mm (Figure 5.4).

Mean DPM values for 10 mm classes were calculated to increase precision. Square root transformation of each standing crop value was then undertaken to reduce bias caused by very high DPM height values.

It was realized from the outset however, that the disadvantage of averaging and square root transformation is that this reduces variance and the standard error of prediction, and hence tends to produce falsely low values for these parameters. At the same time, it should also be borne in mind that in the practical application of the DPM, a number of samples, generally ranging between 100 to 200, are taken and a single mean DPM height calculated. The effect of this is to reduce the variance and standard error even more than in the case of averaging within relatively narrow DPM height classes. This mean is then used in an equation to calculate standing crop.

The occurrence of two populations in the data set was confirmed with a Hockey Stick (or 'Broken Stick') regression using the S-Plus 2000 software (MathSoft 1999). This however showed the break-point in the data to be at 259 mm, which was rounded off to 260 mm (Figure 5.5.). The data set was then separated accordingly into two sub-sets and regressed using the CurveExpert 1.3 software (http://www.ebicom.net/). This tests each of over 30 data modeling equations (curve fits, including the linear family) against the data, using the Levenberg-Marquardt algorithm for quick, non-linear regression performance, and chooses the best fit. This software however does not provide the probability statistic (P).

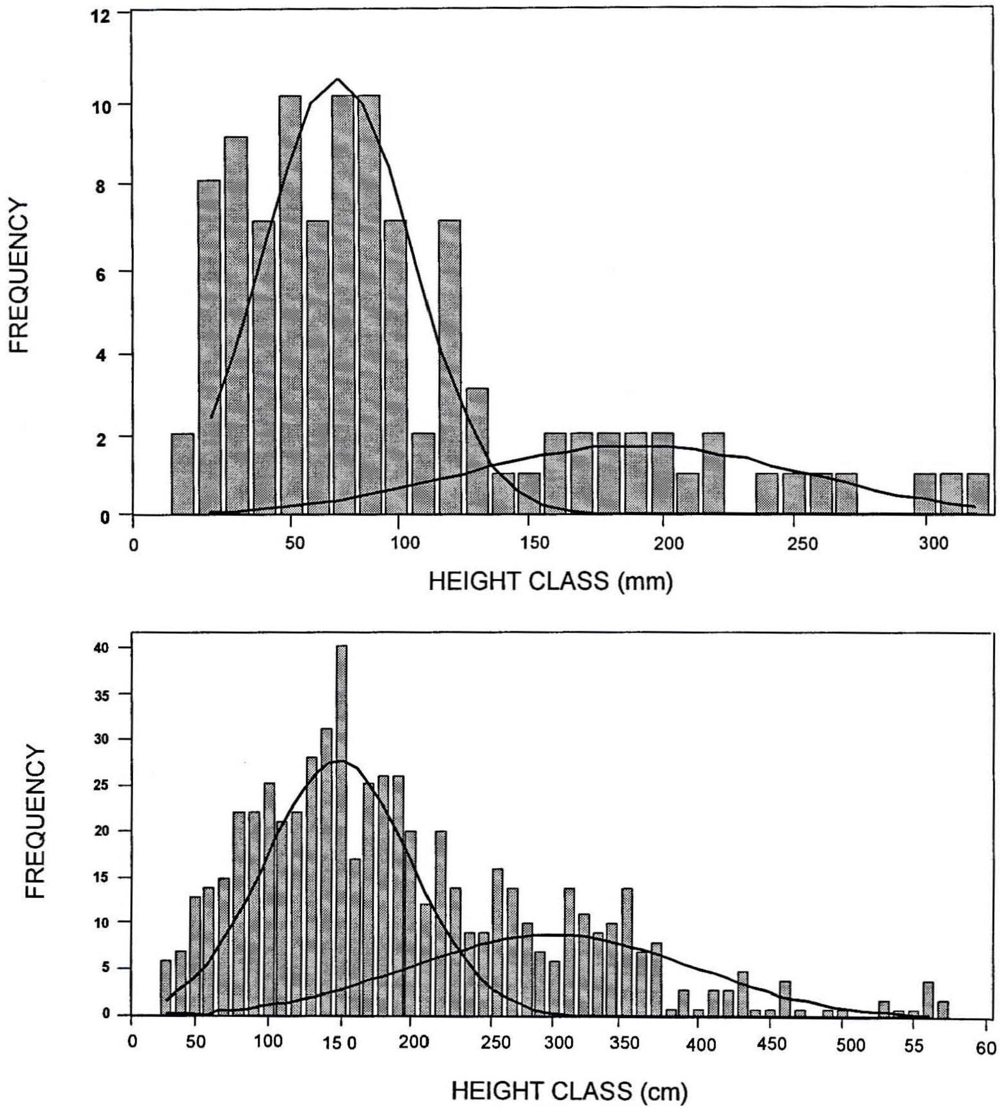


Figure 5.4. Frequency distribution of 10-mm DPM height classes (bars) and two normal populations (lines) after the application of MLE. Top: Trollope & Potgieter (1986); bottom: this study.

In the data of Trollope & Potgieter (1986), compressed DPM heights of >260 mm were recorded only four times, and range from 270 to 316 mm (mean 297 mm). The corresponding standing crop values ranged from 7 545 to 8 495 kg ha^{-1}, with a mean of 8 060 kg ha^{-1}.

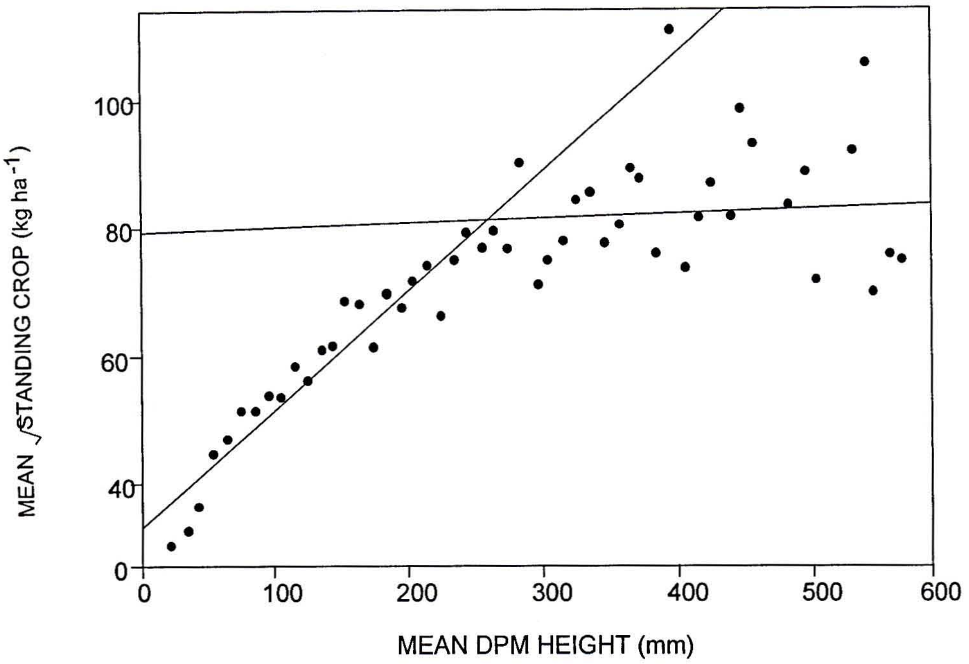


Figure 5.5. Broken stick regression showing the breakpoint in the data at 260 mm.

In the period 1989 to 1999 a total of 5 670 standing crop evaluations were undertaken. During this period, a mean DPM height of 260 mm was exceeded in only 18 cases (0.32% of all surveys), the highest mean DPM height being 347 mm, recorded in 1999 some 2 km NE of Gudzane windmill in the Nwanetsi section of the central district. Eleven of these 'tall' sites are included in this study (Table 5.3).

The data were sub-set and transformed as follows:

NOTES:

- A linear regression was fitted using least squares.
- DPMH = disc pasture meter height.
- Mean of standing crop and DPMH are the means of the standing crop and DPMH for that class interval, in all cases except D(c)(iii) being 10 mm. In the latter case, class intervals were 20 mm for DPMH >370 to 430 mm; 30 mm for DPMH >430 to 460 mm; and 40 mm for DPMH >460 to 580 mm. (These classes were widened in order to increase the number of samples for the means as in some of these cases, only a single sample was available for a particular 10 mm class).

A. ENTIRE DATA SET, UNPARTITIONED:

- i) Simple linear regression
- ii) Best model selection

B. ENTIRE DATA SET, SQUARE-ROOT TRANSFORMATION OF THE STANDING CROP; MEANS OF STANDING CROP AND DPMH CALCULATED FOR 10 MM CLASS INTERVALS:

- i) ≥20 ≤ 580 mm DPMH sub-set.

C. PARTITIONED BY MLE:

- a) Untransformed, no means calculated.
  - i) ≥20 to ≤200 mm DPMH sub-set.
  - ii) >200 mm DPMH sub-set.
- b) Square-root transformation of the standing crop; means of standing crop and DPM height calculated for 10 mm class intervals.
  - i) ≥20 to ≤200 mm DPMH sub-set.
  - ii) >200 mm DPMH sub-set.

D. PARTITIONED BY 'BROKEN STICK' REGRESSION:

- a) Untransformed, no means calculated.
  - i) ≥20 to ≤260 mm DPMH sub-set.
  - ii) ≥260 mm DPMH sub-set.
- b) Untransformed, means of standing crop and DPMH calculated for 10 mm class intervals.
  - i) ≥20 to ≤260 mm DPMH sub-set.
  - ii) ≥260 mm DPMH sub-set.
- c). Square-root transformation of the standing crop; means of standing crop and DPMH calculated for 10 mm class intervals.
  - i) ≥20 to 260≤mm DPMH sub-set.
  - ii) >260 mm DPMH sub-set.
  - iii) >260 to 370 mm DPMH with 10 mm class intervals, class intervals for DPM heights >370 mm variable in range - see Table 5.2, point C c) iii).

The original field data of Trollope & Potgieter (1986) are fortunately still available. Maximum likelihood estimation was consequently applied to this set to determine if it consists of more than one population. Square-root transformation of the standing crop was also applied.

The equation parameters determined by CurveExpert were then used in the non-linear regression facility of the Statgraphics Plus Version 2 for Windows (Manugistics 1996) to determine the coefficient of determination and other statistics. The probability statistic P was determined using the mean squares of the model and residual, D.f., and critical values of the F-distribution of a two-tailed test given in statistical tables (Rohlf & Sokal 1981).

5.4. RESULTS

A summary of best models selected and their statistics is presented in Table 5.2.

5.4.1. SIMPLE LINEAR REGRESSION

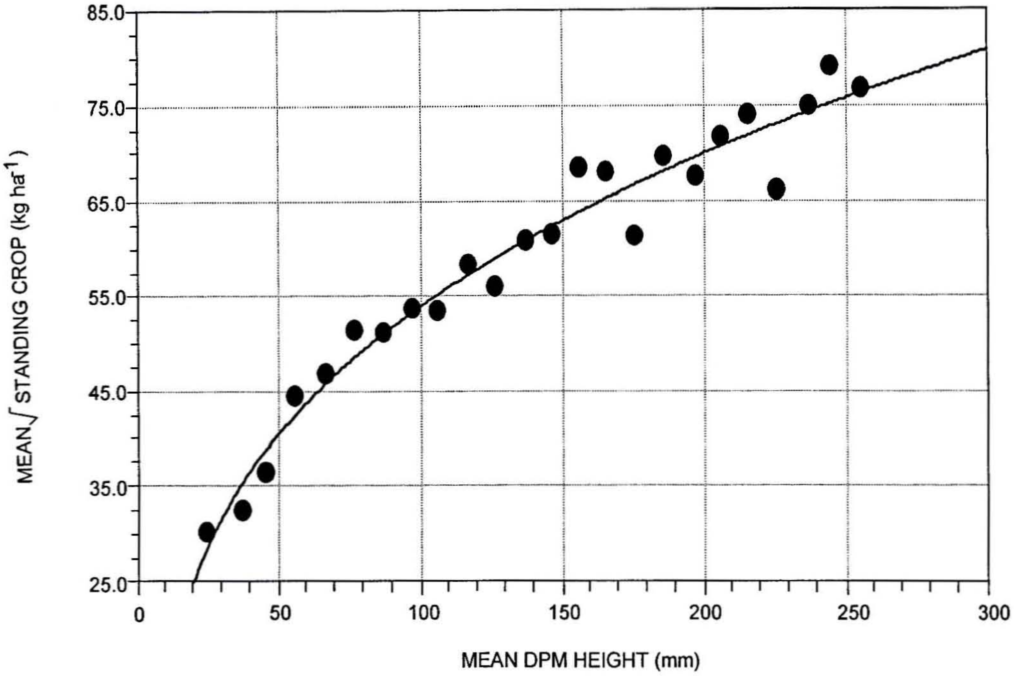
Simple linear regression with no transformation or averaging of the data produced a poor correlation between compressed DPM height and standing crop ($r = 0.605$; $r^2 = 0.367$; $P < 0.0001$). Using the best model selection facility of CurveExpert, this improved slightly ($r = 0.641$; $r^2 = 0.53$; $P < 0.0005$), with the Quadratic Fit being the best model fitted to the untransformed data.

Using the entire data set without any partitioning but with square-root transformation of standing crop, followed by averaging per 10 mm height class intervals, resulted in an improved correlation ($r = 0.948$; $r^2 = 0.88$; $P < 0.0005$; Hoerl Model; Figure 5.6).

5.4.2. DATA PARTITIONED BY MLE (≥20 TO 200 mm, AND >200 mm GROUPS)

Correlation of the untransformed sub-sets was reasonable to poor. For the ≥20 to 200 mm group, $r = 0.596$; $r^2 = 0.359$; $P < 0.0005$ (Saturation Growth Rate Model) and for the >200 mm group, $r = 0.237$; $r^2 = 0.310$; $P < 0.0005$ (Gaussian Model).

Square-root transformation of the standing crop, followed by averaging per 10 mm height class intervals resulted in a greatly improved correlation for the ≥20 to 200 mm DPM height range ($r = 0.979$; $r^2 = 0.948$; $P<0.0005$; Hoerl Model). The >200 mm sub-set however showed very little improvement with transformation ($r = 0.294$; $r^2 = 0.704$; $P<0.0005$, Exponential Association Model).



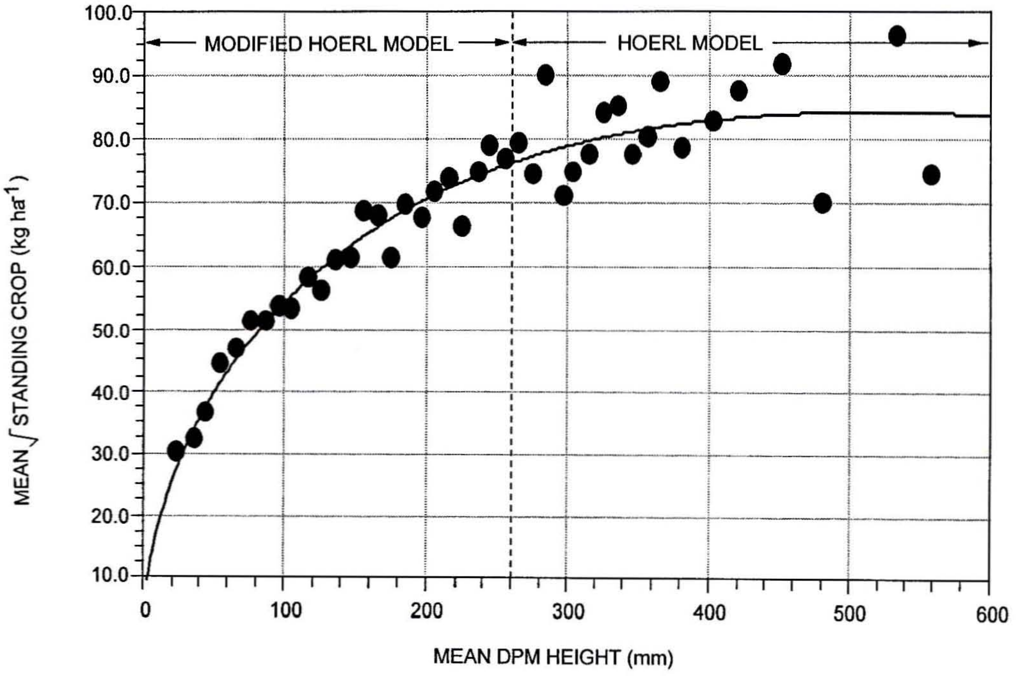


Figure 5.6. Modified Hoerl Model for mean DPM heights of ≤260 mm (top); and combined with the Hoerl Model for mean DPM heights >260 mm (bottom).

5.4.3. DATA PARTITIONED BY BROKEN-STICK REGRESSION (≥20 TO 260 mm, AND >260 mm GROUPS)

As was the case with the MLE sub-sets, untransformed data showed poor correlations for the ≥20 to ≤260 mm sub-set ($r = 0.605$; $r^2 = 0.367$; $P<0.0005$; Power Fit Model); and $r = 0.180$; $r^2 = 0.331$; $P<0.0005$ (3rd Degree Polynomial Fit) for the >260 mm sub-set. Mean DPMH and mean standing crop per height class however markedly improved correlation, particularly in the ≥20 to 260 mm sub-set ($r = 0.971$; $r^2 = 0.933$; $P<0.0005$; Power Fit Model). Correlation in the >260 mm sub-set remained poor ($r = 0.386$; $r^2 = 0.000$; $P<0.0005$; Gaussian Model).

Transformation (mean of the square-root transformation of standing crop) improved the correlation slightly for the ≥20 to 260 mm sub-set ($r = 0.979$; $r^2 = 0.951$; $P<0.0005$; Modified Hoerl Model; Figure 5.6).

In spite of transformation however, correlation in the >260 mm sub-set remained poor ($r = 0.483$; $r^2 = 0.091$; $P<0.0005$

5.4.4. CALCULATING STANDING CROP

To calculate standing crop, the Modified Hoerl Model equation (DPM values ≥20 to ≤260 mm) and the Hoerl Model equation DPM values >260 mm) are used. In both cases, square-root transformation of the standing crop was used to derive the equations. Their products must consequently be squared to obtain the standing crop in kg ha^{-1}. The equations can be difficult to use, particularly when only a calculator is available. A pre-calculated 'look-up table', either electronic or on paper, would thus be the most practical.

FOR MEAN DPM VALUES ≤260 MM (MODIFIED HOERL MODEL):

$$\text{kg ha}^{-1} = \left[26.6002\left(0.5745^{\frac{1}{x}}\right)x^{0.3324}\right]^2$$

FOR MEAN DPM VALUES >260 MM (HOERL MODEL):

$$\text{kg ha}^{-1} = \left[17.9889\left(0.9899^{x}\right)x^{0.5247}\right]^2$$

Maximum likelihood estimation analysis of the Trollope & Potgieter (1986) data also revealed two populations (Figure 5.4). The application of simple linear regression using CurveExpert to this data set without any transformation produced a correlation coefficient of 0.74; $r^2 = 0.549$; SEE= 2017; P=0.0000 (n = 104). Without any transformation, this improved considerably when CurveExpert was allowed to choose the best fit (Logisitic Model, r = 0.840; $r^2 = 0.704$; SEE = 1644.01; MAE = 1099.83; ME = 16.2849; P<0.0005):

$$y = \frac{a}{1 + be^{-cx}}$$

a = 7956.6105
b = 25.614378
c = 0.4112395

With square root transformation of the standing crop, the best model selection of CurveExpert was a 3rd degree Polynomial Fit (r = 0.8875; $r^2 = 78.6$; SEE = 11.0366; MAE = 8.08512; ME = -0.0000323; P<0.0005):

$$y = a + bx + cx^2 + dx^3 \ldots$$

a = -2.530689
b = 11.899664
c = -0.513237
d = 0.007278

The terms SEE, MAE and ME are explained as follows (Manugistics 1996):

SEE (Standard Error of Estimate):

This explains the value for the standard deviation of the residuals. This value can be used to construct prediction limits for new observations.

MAE (Mean Absolute Error):

The average of the absolute values of the residuals. If the result is a small value, performance can be predicted more precisely; if the result is a large value, a different model may be used.

ME (Mean Error):

The average of the residuals. The closer the ME is to 0, the less biased, or more accurate, the prediction.

A common characteristic of those sites (all on basalt) on which a mean DPM height >260 mm was recorded during field surveys (Table 5.3) is that they are dominated by *Panicum coloratum, P.maximum*, or *T. triandra;* grasses with robust or stiff culms when mature, in some cases with a relatively large number of culms per tuft, for example *T. triandra* and *C. ciliaris. Bothriochloa radicans* is also a stiff-culmed species, similar in structure to *C. ciliaris*.

The presence of *Urochloa mosambicensis* in ten of the eleven sites in Table 5.3. is noteworthy. Although the culms of this species are not as stiff as those of the above species, it very often produces an abnormally large number of culms from ground level, the tuft having an inverted campanulate (bell-shaped) growth form. Consequently, when the DPM falls on the tuft, the effect of a large number of culms appears to be the same as that of fewer but stiffer culms. It is interesting to note that 77.8% of the outliers are tall grass species usually associated with sourveld and 22.2% short species, the former consisting of species with numerous and/or stiff culms.

Working in Kenya, Kinyamario & Imbamba (1992) found that 68% of above-ground grass biomass occurred within 0-200 mm from the ground, 23% between 200-400 mm, and only 9% above 400 mm. This may possibly imply that as total (culm) height increases, a corresponding increase in biomass does not occur, i.e. the relation is not linear. If this is indeed the case, then an increasing DPM height should not be linearly related to grass biomass.

The ratio of standing crop to mean maximum and mean minimum heights was also calculated in order to determine whether this is constant or not, on the assumption that compression has an equal effect, i.e. linear, on all swards. If it is not, then the relation between DPM height and standing crop would then also not be linear. Although in statistical terms the relations are not strong, their significance is that they are not linear. In both cases, standing crop per mm of height, be it for maximum or minimum height, decreases as height increases.

Compression thus does *not* appear have an equal effect on all tufts or swards, i.e. less compression occurs per unit biomass as the number of stems or stem stiffness increases. The relation between mean DPM height and mean maximum and mean minimum height thus does not appear to be linear.

Table 5.2. Best model selection and model statistics for the calibration of the DPM. In all cases, $P<0.0005$

TREATMENT	BEST MODEL	r	r^2	SEE	MAE	ME	n
A. UNPARTITIONED							
A) UNTRANSFORMED							
i) Simple linear regression	Linear Fit	0.605	0.367	2075.93	-	-	605
ii) Best model selection	Quadratic Fit	0.641	0.530	2618.87	1790.87	-667.437	605
B) √STANDING CROP, MEAN DPMH							
i) ≥20 to ≤580 mm DPMH	Hoerl$_{\mathrm{I}}$	0.948	0.882	5.3086	3.76643	0.000914	42
B. PARTITIONED BY MLE							
A) UNTRANSFORMED							
i) ≥20 to ≤200 mm DPMH	Saturation Growth-Rate	0.596	0.359	1337.79	986.694	0.346769	380
ii) >200 mm DPMH	Gaussian Model$_{\mathrm{I}}$	0.237	0.003	2880.66	2168.77	-1.49385	225
B) √STANDING CROP, MEAN DPMH							
i) ≥20 to ≤200 mm DPMH	Hoerl$_{\mathrm{II}}$	0.979	0.948	2.6696	1.97645	-0.00609	18
ii) >200 mm DPMH	Exponential Association$_{\mathrm{I}}$	0.294	0.070	12.3868	8.00025	-0.00857	34
C. PARTITIONED BY BROKEN STICK REGRESSION							
A) UNTRANSFORMED							
i) ≥20 to ≤260 mm DPMH	Power Fit$_{\mathrm{I}}$	0.605	0.367	1634.35	1154.75	-0.59901	460
ii) >260 mm DPMH	3rd degree Polynomial Fit	0.180	0.033	2891.99	2169.5	-0.02470	145

Table 5.2. (continued)

B) MEAN DPMH AND STANDING CROP PER CLASS							
i) ≥20 to ≤260 mm DPMH (10 mm classes)	Power Fit$_{II}$	0.971	0.939	403.492	293.132	-3.28433	24
ii) >260 mm	Gaussian$_{II}$	0.386	0.000	2335.01	1625.02	-16.9401	28
C) √STANDING CROP, MEAN DPMH (10 MM CLASSES)							
i) ≥20 to ≤260 mm DPMH (10 mm classes)	Modified Hoerl	0.979	0.951	2.91935	2.12621	-0.00099	24
ii) >260 mm DPMH (10 mm classes)	Exponential Association$_{II}$	0.097	0.008	13.5778	9.06200	-0.00159	28
iii) >260 mm DPMH (10 mm classes for DPMH ≤370 mm; 20, 30 or 40 mm classes for DPMH >370 mm)	Sinusoidal Fit	0.483	0.091	7.87579	5.78989	0.000185	19

Table 5.2. (continued)

MODEL	EQUATION	COEFFICIENTS A	 b	 c	 d
Linear Fit	y = a+bx	1755.97	145.73		
Quadratic Fit	y = a+bx+cx^2	184.8282	314.42762	-3.4308248	
Hoerl$_{I}$	y_1 = a*(b^x)*(x^c)	17.98888	0.98990	0.52456	
Saturation Growth-Rate	y = ax/(b+x)	12865.873	32.384065		
Gaussian Model$_{I}$	y = a*exp((-(b-)^2)/(2*c^2))	7446.9141	44.142422	28.315964	
Hoerl$_{II}$	y_1 = a*(b^x)*(x^c)	18.450603	0.98679045	0.5279971	
Exponential Association$_{I}$	y_1 = a(1-exp(-bx)	84.949801	0.092744876		
Power Fit$_{I}$	y = ax^b	511.8546	0.76564866		
3rd degree Polynomial Fit	y = a+bx+cx^2+dx^3...	35972.129	-2563.8961	71.40451	-0.62665858
Power Fit$_{II}$	y_1 = ax^b	496.29206	0.77774242		
Gaussian$_{II}$	y_1 = a*exp((-(b-x)^2)/(2*c^2))	7667.836	39.600536	17.648207	
Modified Hoerl	y_1 = a*b^(1/x)*x^c	26.60023	0.57450	0.33235	
Exponential Association$_{II}$	y_1 = a(1-exp(-bx)	83.581018	0.11356139		
Sinusoidal Fit	y_1 = a+b*cos(cx+d)	81.225859	5.0316618	0.660741	8.923875

y = standing crop; y_1 = √Standing crop; x = mean DPM height

Table 5.3. Species composition of VCA sites included in this study with a mean DPM height >260 mm. Figure in parentheses is the percentage frequency of occurrence of the species.

YEAR	SITE NO	MEAN DPM HEIGHT (mm) FOR SITE	DOMINANT SPECIES (% FREQUENCY IN PARENTHESES)
1996	1705	303	*P. maximum* (44), *S. incrassata* (15), *U. mosambicensis* (15)
1996	1720	270	*P. maximum* (29), *P. coloratum* (26), *U. mosambicensis* (19)
1997	1705	276	*P. maximum* (32), *S. incrassata* (21), *U. mosambicensis* (21)
1999	1705	347	*P. maximum* (66), *P. coloratum* (16), *S. incrassata* (7), *U. mosambicensis* (6)
1999	1720	310	*P. coloratum* (33), *T. triandra* (24), *P. maximum* (17), *U. mosambicensis* (10), *B. radicans* (5)
1999	1721	267	*T. triandra* (30), *U. mosambicensis* (29), *B. radicans* (15), *P. maximum* (9), *P. coloratum* (9)
1999	1722	295	*T. triandra* (42), *P. coloratum* (22), *P. maximum* (15), *U. mosambicensis* (5), *B. radicans* (4)
1999	1726	279	*T. triandra* (32), *U. mosambicensis* (20), *P. maximum* (15), *P. coloratum* (6), *B. radicans* (4)
1999	1807	315	*T. triandra* (49), *P. coloratum* (29), *U. mosambicensis* (14), *P. maximum* (4), *B. radicans* (4)
1999	2307	268	*S. incrassata* (32), *P. coloratum* (20), *P. maximum* (18), *U. mosambicensis* (10)
1999	2364	271	*P. coloratum* (26), *C. ciliaris* (15), *T. triandra* (7), *P. maximum* (5),

Table 5.4. Characteristics of outlier samples shown in Figure 5.2, compared with non-outlier samples

SAMPLE NO	**SPECIES**	**MEAN STEM HEIGHT (mm)**	**MEAN LEAF HEIGHT (mm)**	**DPM HEIGHT (mm)**
9	*Andropogon gayanus*	1 393	1 393	465
33	*Urochloa oligoricha*	683	705	324
35	*Themeda triandra*	683	633	240
41	*Themeda triandra*	758	620	264
47	*Cechrus ciliaris*	928	818	323
98	*Bothriochloa radicans*	1 097	410	219
215	*Heteropogon contortus*	1 097	687	395
217	*Setaria sphacellata*	1 045	573	220
219	*Panicum maximum*	1 637	1 267	560
292	*Panicum maximum*	1 312	1 033	453
297	*Hyperthelia dissoluta*	2 030	1 247	253
317	*Hyperthelia dissoluta*	1 843	980	415
319	*Heteropogon contortus*	853	667	333
322	*Themeda triandra*	1 143	973	424
323	*Heteropogon contortus*	1 405	870	368
373	*Hyperthelia dissoluta*	1 248	1 248	285
489	*Themeda triandra*	1 150	940	560
581	*Cymbopogon excavatus*	520	520	249
MEANS: OUTLIERS		1 127	866	354
NON-OUTLIERS (n=587): MEANS		906	729	187
MEDIANS		891	703	165

Standing crop values for a DPM height range of 0-600 mm were calculated using the equation of Trollope & Potgieter (1986), and the equations developed in this study (Modified Hoerl and Hoerl models). Marked differences between these two approaches are evident (Figure 5.7), with that of Trollope & Potgieter (1986) increasing in a linear manner, whereas that determined by the Hoerl models levels off and in fact declines slightly beyond a peak of 7 109 kg ha^{-1} (515 to 518 mm DPM height). At this height, the Trollope & Potgieter (1986) equation produces a standing crop of 13 089 kg ha^{-1} (84.1% greater than that produced by the

Hoerl model). For DPM readings of ≥500 mm, mean standing crop calculated by the Trollope & Potgieter (1986) equation is 13 735 kg ha^{-1}. Yet ten samples collected during the fieldwork of this study and having a DPM height of ≥500 mm had a mean standing crop of 6 846 kg ha^{-1} (median of 6 830 kg ha^{-1}), ranging from 3 159 to 11 116 kg ha^{-1}.

It must also be remembered that the highest compressed DPM value used by Trollope & Potgieter (1986) was 316 mm. This represents the upper limit to which their calibration equation can be applied in practice. Nevertheless, for the purposes of comparison, this has been extended to 600 mm in Figure 5.7 to illustrate the increasing difference between standing crop values determined by this equation and by the Hoerl Model equations.

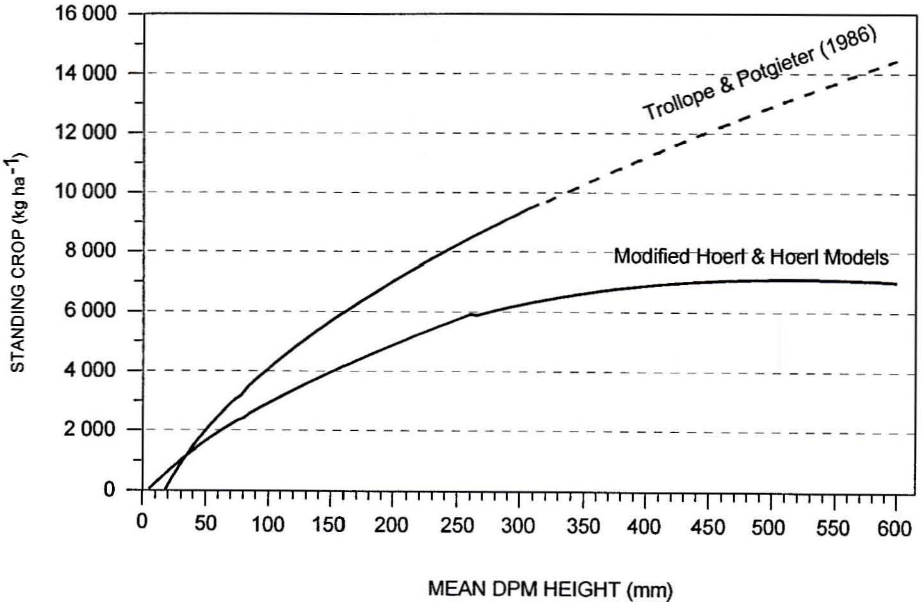


Figure 5.7. Comparison of standing crop calculated with the equation of Trollope *et al.* (1986), and with the Hoerl Model equations of this study. The broken line represents the extension of calculations beyond the calibration limits of the former equation.

A considerable number of studies have been undertaken on production of the grass sward in African savanna, though little information could be found on mean standing crop in relation to mean annual rainfall. This is shown in Figure 5.8 and is based on the information of Le Roux & Dannhauser (1999), Moyo & Campbell (1998); Moyo *et al.* (1998), Smit & Swart (1994), Tacheba & Mphinyane (1993) and Muir & Alage (2001).

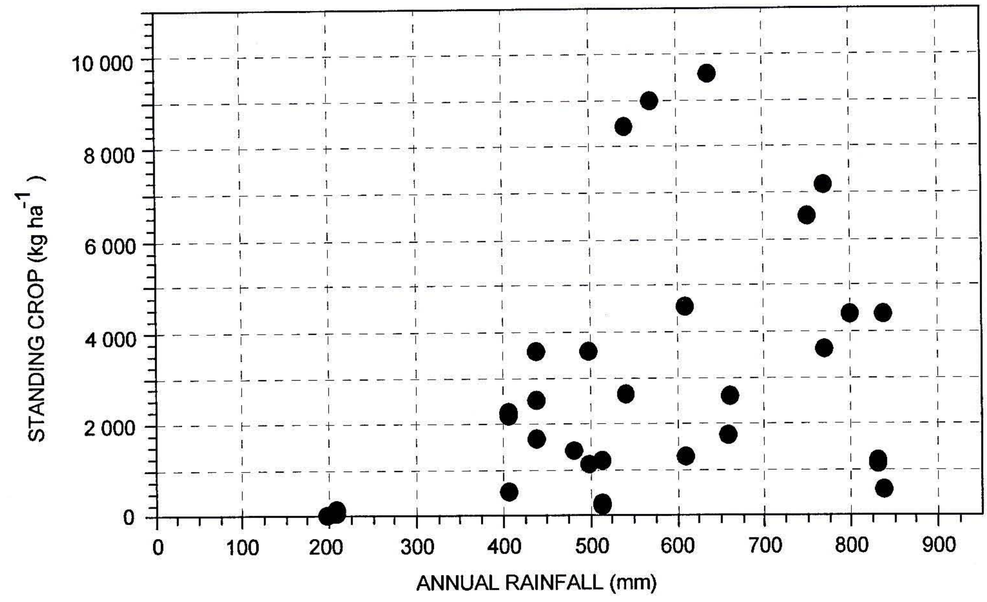


Figure 5.8. Scatter diagram of standing crop in relation to annual rainfall in various parts of African savanna.

Considerable variation in standing crop relative to annual rainfall is evident. This is due to a range in soil production potentials, herbivore stocking rates, veld condition, and in some cases, a composition consisting of one or two species only.

The three highest standing crop values of between 8 000 to 10 000 kg ha^{-1} in Figure 5.8 are those of a silt alluvial plain along the Nkomati River in Mozambique which has been cleared of most of the woody vegetation. It is dominated by *T. triandra* and *P. maximum*, and received a mean annual rainfall of 638 mm during the study period of 1993 to 1999 (Muir & Alage 2001).

In the KNP, the most extensive alluvial deposits occur along the Limpopo and Luvuvhu Rivers, the sediments flanking the Limpopo being mostly sandy while those of the Luvuvhu consisting of deep red silt (Venter 1990). Mean annual rainfall in this part of the KNP however ranges between some 410 and 450 mm. In addition, the alluvial deposits of the Luvuvhu are generally heavily utilized by herbivores. Consequently, although the soil production potential is high, the aridity of the area, together with heavy grazing, prevents this potential from being realized.

Unfortunately, only two VCA sites exist on the alluvial deposits along the Luvuvhu. Nevertheless, the highest standing crop recorded here was 3 890 kg ha^{-1} (in 1995). Although exceptionally heavy rains fell in 2000 (1 092 mm at the Pafuri ranger post and 988 mm at the Pafuri police station approximately 11 km further downstream), the resultant flooding deposited a thick layer of silt, completely suppressing growth; so much so that no VCA surveys could be undertaken. In the following year, only one site could be surveyed and produced a standing crop of a mere 177 kg ha^{-1}.

It is consequently clear from the above discussion that even with abundant rainfall, the production of this area is poor and has no similarity to that of the Nkomati River deposits.

In contrast to the Luvuvhu area, standing crop in the sourveld of Pretoriuskop reached the highest ever recorded in the 13 years of VCA monitoring during 2000 - a mean of 7 356 kg ha^{-1}, the site with the highest standing crop reaching 9 924 kg ha^{-1}. This is slightly less than the 10 295 kg ha^{-1} recorded in the Nwanetsi area on basalt during the previous year. (Unfortunately, the latter site was not surveyed in 2000). *[Note: all standing crop values given here were calculated using the equation of Trollope* & Potgieter *(1986)].*

Bell (1982) gives a range of 7 000 to 10 000 kg ha^{-1} for *Hyparrhenia* veld and 2 000 to 5 000 kg ha^{-1} for *T. triandra* and *Loudetia simplex* veld, though he does not state the rainfall for these areas. These species are common in the sourveld of the Pretoriuskop area of the KNP, which has a mean annual rainfall of 730 mm.

From the foregoing discussion therefore, it appears that a standing crop of almost 14 500 for a mean annual rainfall of some 750-800 mm is unattainable in the KNP, the highest possible probably being in the region of 7-8 000 kg ha^{-1} (using the revised equations of this study).

5.4.5. ESTIMATING CULM AND LEAF HEIGHTS FROM DPM HEIGHT

Simple regression without transformation produced poor correlations between DPM height and culm and leaf heights. For culm height, $r = 0.506$; $r^2 = 0.256$; SEE = 27.706; $P = 0.0000$ ($n = 605$). For leaf height $r = 0.420$; $r^2 = 0.177$; SEE = 27.755; $P = 0.0000$ ($n = 605$).

Mean DPM height and mean culm and leaf heights averaged for 10 mm-interval classes greatly improved the linear relations. For culm height $r = 0.8940$; $r^2 = 0.800$; SEE = 9.9090; P = 0.0000. For leaf height this improved to $r = 0.892$; $r^2 = 0.800$; SEE = 8.1238; P = 0.0000.

When CurveExpert was used to fit the best models to the data (Figure 5.9), a slight improvement in the correlation resulted in the case of the DPM-culm height relation. The Reciprocal Logarithm model was the best fit ($r = 0.923$; $r^2 = 0.829$; SEE = 0.47073; MAE = 0.358137; ME = 0.001214; $P<0.0005$ ($n=605$))

$$y=\frac{1}{a+b\ln x}$$

In the DPM-leaf height relation, the Rational Function was the best fit ($r = 0.957$; $r^2 = 0.893$; SEE = 0.37032; MAE = 0.26705; ME = .00950; $P<0.0005$).

$$y = \frac{a + bx}{1 + cx + dx^2}$$

It is therefore possible to predict culm and leaf heights from the mean DPM value. As is the case with the calibration of the DPM however, it must be remembered that the averaging and square root transformation of the data used in developing the equations give an artificially low estimate of standard error.

The equations derived from the above two models are given below. As is the case with standing crop, the products of these equations must be squared to derive culm and leaf table heights (in cm).

Mean culm height:

$$h_{culm}=\left[\frac{1}{0.1549-(0.0171\ln x)}\right]^2$$

h_{culm} = mean culm height (cm)

x = mean DPM height (cm)

Mean leaf height:

$$h_{\text{leaf}} = \left[\frac{-4.5815 + 8.8796\,x}{1 + (1.0263\,x) - 0.0036\,x^2} \right]^2$$

h_{leaf} = mean leaf height (cm)

x = mean DPM height (cm)

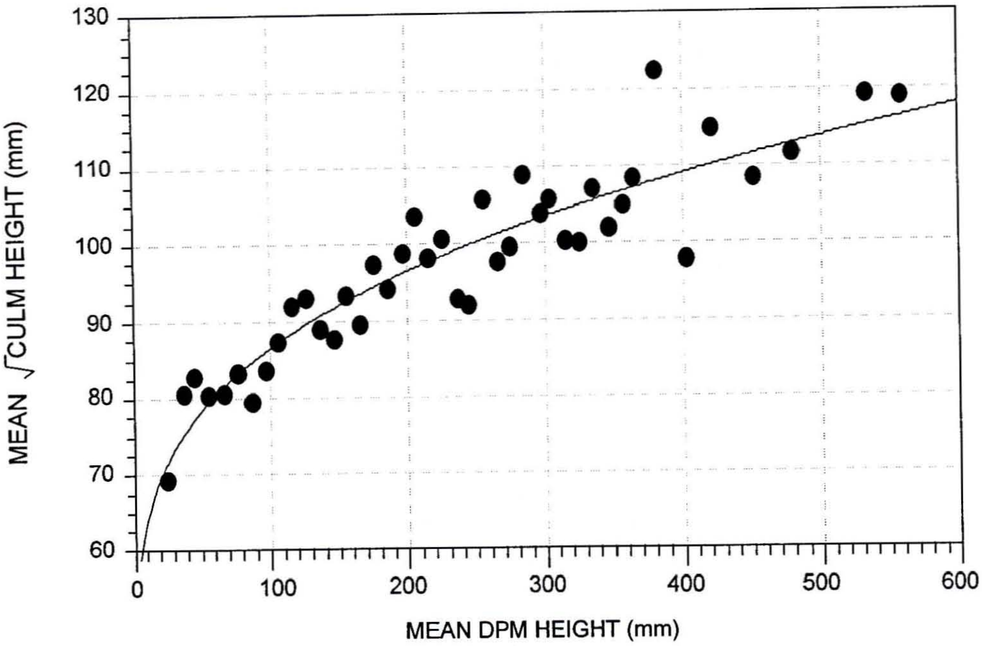
5.5. DISCUSSION AND CONCLUSIONS

As a simple comparative test of the compressibility of grass tufts with DPM values ≤260 mm and >260 mm, the uncompressed ratios of leaf table height to culm height were first calculated for the two categories. It is interesting to note that there is practically no difference between the two groups: 80.6% in the former case, and 79.6% in the latter.

The ratios of uncompressed to compressed heights for DPM values ≤260 mm and > 260 mm however differ considerably: in the former case, mean culm height was reduced by 83.1% and mean leaf table height by 79.0% to a compressed DPM height of 143 mm. For DPM values >260 mm, mean culm height was reduced by 69.4% and mean leaf table height by 61.1% to a compressed DPM height of 350 mm.

This is further evidence that regardless of the ratio between dry mass to compressed DPM height, taller grasses, especially those with stiffer culms, offer greater resistance to compression by the DPM. This will consequently have a weakening effect on the correlation between compressed DPM height and dry mass.

The evidence presented in this study shows that, at least in the KNP, the relation between compressed DPM height and standing crop is not linear but appears to be asymptotic at a height of approximately 510 mm. Moreover, beyond a DPM height of 260 mm, the correlation between this parameter and standing crop is very poor, apparently being strongly influenced by the structure of the grass plant. More specifically, tall grasses, or grasses with highly lignified culms appear to result in a weaker correlation.



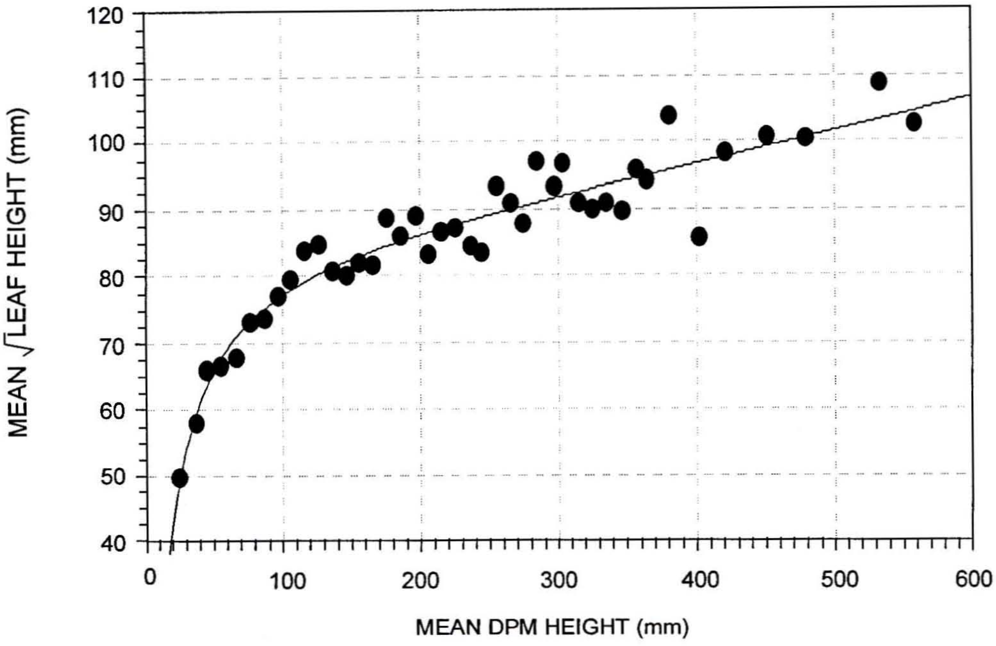


Figure 5.9. The Reciprocal Logarithm Model (top) and the Rational Function Model (bottom) for determining grass culm and leaf table heights, respectively.

Examples are many of the 'sour' species such as *H. dissoluta*, *Hyparrhenia* spp., *Andropogon* spp., *T. triandra* and some 'sweet' species such as *Cenchrus cliliaris, Panicum maximum* and *Setaria incrassata.* Another common feature of most of these grasses is that culms have a relatively large diameter of some three to six millimeters.

A comparison of the structure of these grasses with that of others having less lignified or 'softer' culms shows that they generally either carry less leaf material relative to the overall size (especially height) of the tuft (e.g. *H. dissoluta*), or where leaf material is abundant, there is also an abundance of hard culms (e.g. *C. ciliaris* and *T. triandra*). In either case, the effect of this is a disc settling height which is relatively higher than would be the case with less lignified tufts having a similar amount of leaf material.

This matter needs to be investigated in greater detail and may indicate that DPM surveys under these conditions may require the recording of the dominant species under the meter, and the application of a 'de-stiffening' factor in subsequent standing crop calculations in order to standardize DPM height readings.

This however is likely to present a number of complicating factors, one of them being a differing (increasing) degree of culm stiffness as tuft development progresses during the various phenological stages; from the supple growth of new material in spring, to maximum lignification and hence stiffness in the dry, dormant period. The development of a markedly different procedure and/or instrument for use in these situations is thus also a possibility.

Calibration of the DPM for natural (rangeland) conditions carries the inherent risk of having to deal with two 'short' and 'tall' components, resulting in a skewed distribution in the frequencies of height measurements (a "double normal distribution"). This apparently is a reflection of selective grazing, or markedly different characteristics in sward composition and sward structure, or both.

That this phenomenon has not been detected or recognised and dealt with in previous calibrations is reflected by rather poorly-motivated reasons for removing 'outliers' from the data set in order to improve correlation. While this procedure may be justified to meet very specific needs, under natural conditions in general, it is normally the objective to obtain an overall estimate of the standing crop as a whole, regardless of the presence or absence of "non representative" areas in the sward, "above-normal growth", or "unnaturally high levels of plant nutrients". For the manager who must use the instrument, these are vague concepts, which in practice generally are also difficult to recognise or identify in the field, particularly when a large number of surveys must be undertaken and within a limited time-span. The consequence is that such 'rules' are ignored, in turn leading to erroneous results. Exclusion of such samples under natural (rangeland) conditions is therefore questionable.

This matter needs further investigation to refine the DPM-standing crop relation, specifically to cater for such situations, which are particularly prevalent in the sourveld of the south-western corner of the KNP, or in cases where the mean compressed DPM height is >260 mm. A single calibration equation for the entire KNP is insufficient to cater for the marked differences in grass composition and structure present in the KNP. A separate calibration for each rainfall region does not however appear to be necessary.

The suitability of the field sampling procedure of Bransby & Tainton (1977) for the calibration of the DPM in tall grassveld also needs re-evaluation. In these situations, when the sleeve is placed over (past) the DPM and onto the underlying grass sward, a relatively large proportion of those culms which are forced to the side by the falling disc are clipped off and discarded - culms which initially fell within the diameter of the disc and are in fact still rooted under it.

The counter-argument is that overhanging stems of adjacent material are pushed down by the falling disc and incorporated in the sampling sleeve. This bias is therefore theoretically cancelled out. Nevertheless, the effects of this should be tested in order to improve estimates of standing crop.

Related to this is the sampling procedure of Trollope & Potgieter (1986). This also needs to be re-evaluated as it may prove to be more suited to rangeland conditions than that of Bransby & Tainton (1977), especially in cases where strongly-lignified grass culms are predominant.

The revised calibration equation for compressed DPM heights ≤260 mm derived from the Modified Hoerl Model needs to be validated for the KNP. Furthermore, there does not appear to be any reason why it cannot be applied successfully in other areas of the South African savanna biome were annual rainfall ranges from about 350 to 650 mm, provided its suitability outside the KNP is first confirmed by validation in the area where it is to be applied.

CHAPTER 6

CONCLUSIONS

Rainfall is a major driving force behind the diverse "facets and fluxes" of the KNP ecosystem and shows much variation, both spatially and temporally. The rainfall characteristics of the KNP not only have a major influence on the composition and distribution of the vegetation at the broader, park-wide scale, but also exert a major influence on its year-to-year dynamics, particularly on the herbaceous layer. Because of the size of the KNP, together with its diverse range in geology, soils and topography, these influences cannot reasonably be expected to be similar everywhere in a given year or even a part of a year.

6.1. DETERMINANTS OF NETT PRIMARY PRODUCTION AND NETT STANDING CROP

6.1.1. NETT PRIMARY PRODUCTION

In broad terms, there appears to be little difference between the primary and secondary determinants of nett primary production in the KNP and in other parts of the savanna biome.

Nett primary production on basalt is primarily dependent on the total number of raindays during the year, with a mean minimum of 58.5 days being required for maximum production. When more raindays occur and are preceded by more than 62 stress-free days during the growing season of two years before, coupled with an A horizon thickness of more than about 200 mm, production is at its highest. The proportion of perennials also has an influence but only at a low frequency of abundance of about 22%. Herbivores have no apparent influence, as measured in this study.

On granite, total annual rainfall is also the primary determinant of nett primary production. When this is less than about 490 mm, root stress becomes a critical factor: when stress-free days on average are less than 77.5, production is at its lowest, but, as long as rainfall is less than 490 mm, more stress-free days have little positive effect in improving production.

With total annual rainfall of more than 490 mm, distance to permanent drinking water plays a major role and if this is less than about 5.5 km, together with a base status fertility index of less than 2.9, production generally improves only slightly. The highest production is reached when distance to permanent drinking water is greater than about 5.5 km. Under stress-free conditions, herbivore abundance however does not appear to have any direct influence on production.

6.1.2. NETT STANDING CROP

Whether on basalt or granite, variables influencing nett standing crop are substantially more numerous, and with more complex interactions, than those determining nett primary production. On basalt, soil moisture must be sufficiently high to allow for unrestricted evapotranspiration. When this is less than about 203 mm during the growth period, the number of raindays becomes an important factor. If these are less than 37, and in spite of a high percentage of perennials, standing crop is at its lowest. With more than 37 raindays during the growth period, woody plant competition replaces the abundance of perennial grasses as the important criterion, and to a lesser degree, the time since the last burn. The tolerance for competition by woody plants appears to be very low. When soil moisture is limited a canopy cover of 57 m^{-2} (3.8%), together with a burning interval of less than 7.6 years has a substantial effect on nett standing crop. Herbivores appear to have a minor effect, though when they do exert an influence, this is at relatively low densities.

On granite, standing crop is primarily dependent on the year's total rainfall. When this is less than a mean of 556 mm, a low percentage of perennials and to a lesser extent, concentrate grazers appear to have a negative but minor influence and at very low densities. When rainfall exceeds 556 mm per year and stress-free days are more than 80.5, net standing crop can be expected to be at its highest, provided the period since the last burn was at least more than about 9 months.

6.1.3. CONCLUSIONS

The hypothesis that nett primary production in the KNP is influenced primarily by rainfall and soil properties; with composition, grazing and fire playing secondary roles, has been confirmed. In the case of nett standing crop, the primary determinants are broadly similar to those of production. The importance of fire, and more specifically, the period since the previous burn, is however relatively greater in the case of nett standing crop than in the case of nett primary production. Processes and interactions between variables are also a great deal more complex in the case of nett standing crop, be it on granite or basalt.

6.2. EVAPOTRANSPIRATION COMPARED TO RAINFALL, AS PREDICTORS OF PRODUCTION

The second hypothesis proposed that a closer correlation can be expected to exist between evapotranspiration and phytomass production, than between total annual rainfall and production; and that evapotranspiration can consequently be expected to be a better predictor of production than rainfall.

It was also stated that evaporation and the soil water balance are better indicators of soil moisture dynamics than is total rainfall; and that the temporal distribution of rainfall during the growth period, rather than the annual total, plays a more significant role in production.

The determination of evapotranspiration at the extensive level as applied in this study has the important advantage of providing a more detailed insight into the complex relations of the grass sward with its environment. Ideally, evapotranspiration should be measured at the individual, species level, though this is a very difficult undertaking.

In spite of the substantially better understanding obtained when evapotranspiration is used in combination with rainfall in analyses, its use is not absolutely essential, provided that a variety of rainfall parameters, in addition to the annual total, are used. Snyman & Fouché (1993) came to the same conclusion, namely that evapotranspiration has no apparent advantage over rainfall in the estimation of production in semi-arid areas, and is much more difficult to measure than rainfall.

The method eventually chosen in this component of the study, namely tree regression, does not support the explicit determination of correlations. It however identifies the relative importance of each variable, which proved to be a great deal more insightful than correlation procedures would have been.

6.2.1. CONCLUSIONS

The relative importance of rainfall characteristics proved more influential than did evapotranspiration parameters, thus tending to negate the hypothesis that evapotranspiration can be expected to be a better predictor of production than.

The determination of evapotranspiration and the associated parameters on the soil moisture balance however remain important criteria in that these identify the rainfall/soil moisture relations and interactions, as well as identifying moisture stress thresholds. This supports the sub-hypothesis that information on evapotranspiration is a better indicator of the soil water balance than rainfall is.

The simplified tree regressions based only on rainfall, composition and, in the case of nett standing crop, the burn interval, indicate that production in the broad sense can be predicted successfully without the use of evapotranspiration data, on the *proviso* that in addition to annual rainfall, information on the temporal distribution of the rainfall and its frequency is known and taken into account.

It is consequently concluded that, at least in the Lowveld savanna ecosystem, evapotranspiration is not a better predictor of grass production that rainfall is.

6.3. COMPOSITION

6.3.1. PERENNIALS

The major determinant of perennial grass composition on basalt is soil moisture content. When this occurs in abundance to allow unrestricted evapotranspiration to take place during the growth period, perennials are at their highest abundance. When evapotranspiration is less than 180 mm, root stress becomes a critical factor. In the absence of evapotranspiration data, the number of raindays during the preceding dormant period is the key factor, implying that soil moisture content at the start of the growing season is of major importance, provided this is followed up by at least 28.5 raindays in the growth period.

On granite, perennial grasses are even more dependent on soil moisture than those on basalt. The total number of raindays during the preceding dormant period is a key determinant, followed by the rainfall of the previous year's growth period and the number of raindays of the current growth period. Other variables interact in complex ways but play relatively minor roles in perennial composition on both basalt and granite with herbivore abundance on both basalt and granite apparently showing little or no effect when soil moisture is adequate.

6.3.2. DECREASERS

Decreasers on basalt are primarily dependent on the number of raindays and hence soil moisture content during the year. When these are less than 61, the number of raindays during the growth period are important. If the total number of raindays exceed 61, then the percentage clay content of the A horizon has an important influence. Other factors play minor or even insignificant roles, though herbivore abundance under conditions of soil water stress does have considerable influence, particularly concentrate and mixed feeders, and at relatively low or very low densities.

On granite, the number of raindays during the growth period is the most important determinant of the proportion of Decreasers. When these are less than 30.5, total rainfall during the preceding dormant period and herbivores have an influence, though of a relatively minor nature. When raindays exceed 30.5 on average, other rainfall properties become important, with herbivore abundance again being relatively unimportant at higher soil moisture levels.

6.3.3. CONCLUSIONS

It is consequently concluded that rainfall in its various forms and manifestations is without doubt the primary determinant of grass production, standing crop, and composition, the latter both in terms of perennials or Decreasers. Secondary determinants, in varying degrees of importance, are the thickness and base status of the A horizon, distance to permanent drinking water, and competition by woody plants. In all cases, when little or no stress (particularly soil moisture stress) is exerted by the environment, herbivore abundance is insignificant or plays a relatively minor role at the scale of this study.

Evidence presented in this study shows that Decreasers decrease primarily as a result of environmental factors and more specifically, fluctuations in rainfall, and not, as the original definition states, purely as a result of over- or under-utilization by herbivores. It is furthermore apparent that when a certain critical level in moisture stress is exceeded, herbivore pressure plays an increasingly important role in altering grass species composition. Moreover, when this stage is reached, it appears that these changes in composition occur at very low herbivore densities. This is in agreement with the view of O'Reagain & Turner (1992) that there appears to be a threshold stocking rate above which degradation occurs.

More specifically, it is apparent that herbivores exert a negative influence on Decreasers when the total number of raindays in a year are less than 61 in the case of basalt, and when the total number of raindays during the growth period of the previous year are less than 30.5 in the case of granite. Composition of the grass sward in the KNP can thus be expected to follow annual rainfall in terms of annual variation, with year-to-year trends ultimately reflecting wet and dry rainfall cycles.

It is also concluded that the defining criteria for the Decreaser-Increaser groups are incomplete and need to be revised to reflect the influences of environmental factors, especially those of erratic rainfall, in combination with the effects of herbivores at widely-differing densities.

6.4. GENERAL CONCLUSIONS

This study has focused on only two classificatory groups, namely perennials and Decreasers, and on an extensive area. There is clearly a need to undertake similar work on the other groups and sub-groups as well and ultimately, on the classification of the grass species themselves.

The tree regression procedure is well suited to the analysis of complex ecological processes and interactions, both of a quantitative and qualitative nature. It is a powerful yet simple and effective tool to use and produces results that are otherwise not easily discernible or easy to interpret with linear regression and some other statistical procedures. The technique also has potential for use in developing models as aids in decision-support systems for management purposes.

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APPENDIX 1

IMPUTED AND COMPUTED DATA, AND EQUATIONS FOR THE CALCULATION OF EVAPOTRANSPIRATION

Imputed and computed data, and the equations used in the calculation of reference and crop evapotranspiration are given in the following tables.

Table A1. Estimated densities of root and canopy cover of trees, bushes and shrubs

PLANT TYPE	ESTIMATED SURFACE AREAS (m^{-1})	
	CANOPY	ROOT
TREE	10.8	268.8
BUSH	3.7	91.6
SHRUB	0.7	18.1

SIZE CLASS	DENSITY CLASS	FACTOR	TOTAL NUMBER ON SITE	DENSITY (PLANTS ha^{-1})	SURFACE AREAS (m^{-1})	
					CANOPY	ROOT
TREES	Very open	22.2	3.0	20	32.3	806.4
	Open	18.5	4.4	29	47.3	1182.7
	Moderate	14.8	6.9	46	74.2	1854.7
	Dense	11.1	12.2	81	131.2	3279.4
	Very dense	7.4	27.4	183	294.6	7365.1
BUSHES	Very open	12.9	9.0	60	32.9	824.9
	Open	10.8	13.0	87	47.6	1190.9
	Moderate	8.6	20.3	135	74.3	1859.7
	Dense	6.5	36.0	240	131.8	3298.0
	Very dense	4.3	81.2	542	297.2	7438.7
SHRUBS	Very open	5.7	46.6	311	33.6	843.5
	Open	4.8	66.6	444	48.0	1205.5
	Moderate	3.8	104.0	694	74.9	1882.4
	Dense	2.9	184.7	1232	133.0	3343.1
	Very dense	1.9	415.6	2772	299.2	7522.4

Table A2. Estimated phenological stages and duration (days) of the grass stratum for three Acocks veld types

LOWVELD

PHENOLOGICAL STAGE	CONDITION			MEAN (DAYS)
	GOOD	MODERATE	POOR	
DORMANT$_{I}$	1 Jul-15Oct	1 Jul-15 Oct	1 Jul-31 Oct	112.3
	[1]01-107	01-107	01-123	
	[2]107	107	123	
INITIATION	16 Oct-31 Oct	16 Oct-31 Oct	1 Nov-15 Nov	15.7
	108-123	108-123	124-138	
	16	16	15	
DEVELOPMENT	1 Nov-30 Nov	1 Nov-30 Nov	16 Nov-30 Nov	25.0
	124-153	124-153	139-153	
	30	30	15	
MID SEASON	1 Dec-15 Mar	1 Dec-29 Feb	1 Dec-14 Feb	91.0
	154-259	154-244	154-229	
	106	91	76.0	
LATE SEASON	16 Mar-30 Apr	1 Mar-31 Mar	15 Feb-29 Feb	30.7
	260-305	245-275	230-244	
	46	31	15	
DORMANT$_{II}$	1 May-30 Jun	1 Apr-30 Jun	1 Mar-30 Jun	91.3
	306-366	276-366	245-366	
	61	91	122	
TOTAL DAYS ACTIVE	198	168	121	162.4
TOTAL DAYS DORMANT	168	198	245	203.6

ARID LOWVELD & MOPANIVELD

PHENOLOGICAL STAGE	CONDITION			MEAN (DAYS)
	GOOD	MODERATE	POOR	
DORMANT$_{I}$	1 Jul-15 Oct	1 Jul-31 Oct	1 Jul-31 Oct	117.7
	01-107	01-123	01-123	
	107	123	123	
INITIATION	16 Oct-31 Oct	1 Nov-15 Nov	1 Nov-15 Nov	15.3
	108-123	124-138	124-138	
	16	15	15	
DEVELOPMENT	1 Nov-30 Nov	16 Nov-30 Nov	16 Nov-30 Nov	20.0
	124-153	139-153	139-153	
	30	15	15	
MID SEASON	1 Dec-29 Feb	1 Dec-14 Feb	1 Dec-31 Jan	76.3
	154-244	154-229	154-215	
	91	76	62	
LATE SEASON	1 Mar-31 Mar	15 Feb-29 Feb	1 Feb-14 Feb	20.0
	245-275	230-244	216-229	
	31	15	14	
DORMANT$_{II}$	1 Apr-30 Jun	1 Mar-30 Jun	15 Feb-30 Jun	116.7
	276-366	245-366	230-366	
	91	122	137	
TOTAL DAYS ACTIVE	168	121	106	131.6
TOTAL DAYS DORMANT	198	245	260	234.4

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[1] Climyear day

[2] Duration (number of days)

Table A3. Estimated basic minimum and maximum aerial cover values for a year with average rainfall (aerial cover includes grass aerial cover and litter cover) [-]

ACOCKS VELD TYPE	VELD CONDITION	BASALT			GRANITE		
		UNBURNT		BURNT	UNBURNT		BURNT
		MAXIMUM	MINIMUM		MAXIMUM	MINIMUM	
LOWVELD	GOOD	0.90	0.70	0.80	0.80	0.65	0.75
	MODERATE	0.75	0.55	0.70	0.70	0.50	0.65
	POOR	0.60	0.35	0.55	0.50	0.35	0.45
ARID LOWVELD	GOOD	0.75	0.55	0.70	0.65	0.45	0.60
	MODERATE	0.65	0.45	0.60	0.50	0.30	0.45
	POOR	0.50	0.35	0.45	0.30	0.20	*
MOPANI VELD	GOOD	0.80	0.60	0.70	0.70	0.50	0.65
	MODERATE	0.70	0.50	0.65	0.50	0.30	0.40
	POOR	0.55	0.35	0.50	0.25	0.15	*

*Arid Lowveld and Mopani Veld in poor condition do not normally produce adequate standing crop to burn cleanly.

Table A4. Equation statistics ($y = a + fx$) for calculating estimated daily values of total ground cover (f_c) for three Acocks veld types on basalt and granite. UBNT = unburnt, BNT = burnt; INT = Intercept; X_a = first day of period, X_b = last day of period

LOWVELD ON BASALT

PHENOLOGICAL STAGE	PARAMETER	VELD CONDITION					
		GOOD		MODERATE		POOR	
		UBNT	BNT	UBNT	BNT	UBNT	BNT
$\text{DECLINE}_{\text{I}}$	INT (a)	79.7	77.2	63.9	61.5	46.7	44.2
	SLOPE (f)	-0.093	-0.070	-0.087	-0.066	-1.096	-0.077
	DAY RANGE ($\geq X_a$ - $\leq X_b$)	1-107	1-107	1-107	1-107	1-123	1-123
INITIATION & DEVELOPMENT	INT (a)	23.5	-197.7	8.5	67.5	-102.5	-225.5
	SLOPE (f)	0.435	1.848	0.435	1.522	0.833	1.833
	DAY RANGE ($\geq X_a$ - $\leq X_b$)	107-153	107-153	107-153	107-153	123-153	123-153
PEAK (MID SEASON)	INT (a)	90	85	75	70	60	55
	DAY RANGE ($\geq X_a$ - $\leq X_b$)	153-259	153-259	153-244	153-244	153-229	153-229
$\text{DECLINE}_{\text{II}}$ (LATE SEASON)	INT (a)	65.2	103.1	96.2	86.1	82.0	72.6
	SLOPE (f)	-0.093	-0.070	-0.087	-0.066	-0.096	-0.077
	DAY RANGE ($\geq X_a$ - $\leq X_b$)	259-366	259-366	244-366	244-366	229-366	229-366

Table A4 (continued)

LOWVELD ON GRANITE

PHENOLOGICAL STAGE	PARAMETER	VELD CONDITION					
		GOOD		MODERATE		POOR	
		UBNT	BNT	UBNT	BNT	UBNT	BNT
DECLINE$_{I}$	INT (a)	73.2	69.8	59.0	56.7	42.1	39.8
	SLOPE (f)	-0.070	-0.047	-0.087	-0.067	-0.058	-0.038
	DAY RANGE (≥x_a - ≤x_b)	1-107	1-107	1-107	1-107	1-123	1-123
INITIATION & DEVELOPMENT	INT (a)	30.1	-174.4	3.5	-151.2	-26.5	-184.5
	SLOPE (f)	0.326	1.630	0.435	1.413	0.500	1.500
	DAY RANGE (≥x_a - ≤x_b)	107-153	107-153	107-153	107-153	123-153	123-153
PEAK (MID SEASON)	INT (a)	80	75	70	65	50	45
	DAY RANGE (≥x_a - ≤x_b)	153-259	153-259	153-244	153-244	153-229	153-229
DECLINE$_{II}$ (LATE SEASON)	INT (a)	98.1	87.2	91.2	81.3	63.3	53.7
	SLOPE (f)	-0.070	-0.047	-0.087	-0.067	-0.058	-0.038
	DAY RANGE (≥x_a - ≤x_b)	259-366	259-366	244-366	244-366	229-366	229-366

ARID LOWVELD ON BASALT

PHENOLOGICAL STAGE	PARAMETER	VELD CONDITION					
		GOOD		MODERATE		POOR	
		UBNT	BNT	UBNT	BNT	UBNT	BNT
DECLINE$_{I}$	INT (a)	64.1	62.6	54.2	51.7	41.7	39.3
	SLOPE (f)	-0.087	-0.066	-0.077	-0.058	-0.055	-0.037
	DAY RANGE (≥x_a - ≤x_b)	1-107	1-107	1-123	1-123	1-123	1-123
INITIATION & DEVELOPMENT	INT (a)	8.5	-162.9	-37.0	-246.0	-26.5	-184.5
	SLOPE (f)	0.435	1.522	0.667	2.000	0.500	1.500
	DAY RANGE (≥x_a - ≤x_b)	107-153	107-153	123-153	123-153	123-153	123-153
PEAK (MID SEASON)	INT (a)	75	70	65	60	50	45
	DAY RANGE (≥x_a - ≤x_b)	153-244	253-244	153-229	153-229	153-215	153-215
DECLINE$_{II}$ (LATE SEASON)	INT (a)	96.2	86.1	82.6	73.3	61.8	53.0
	SLOPE (f)	-0.087	-0.066	-0.077	-0.058	-0.055	-0.037
	DAY RANGE (≥x_a - ≤x_b)	244-366	244-366	229-366	229-366	215-366	215-366

ARID LOWVELD ON GRANITE

PHENOLOGICAL STAGE	PARAMETER	VELD CONDITION					
		GOOD		MODERATE		POOR	
		UBNT	BNT	UBNT	BNT	UBNT	BNT
DECLINE$_{I}$	INT (a)	54.1	51.7	39.3	36.8	24.4	Does not normally produce adequate standing crop to burn 'cleanly'
	SLOPE (f)	-0.087	-0.066	-0.077	-0.058	-0.037	
	DAY RANGE (≥x_a - ≤x_b)	1-107	1-107	1-123	1-123	1-123	
INITIATION & DEVELOPMENT	INT (a)	-1.6	-139.5	-52.0	-184.5	-21.0	
	SLOPE (f)	0.435	1.304	0.667	1.500	0.333	
	DAY RANGE (≥x_a - ≤x_b)	107-153	107-153	123-153	123-153	123-153	
PEAK (MID SEASON)	INT (a)	65	60	50	45	30	
	DAY RANGE (≥x_a - ≤x_b)	153-244	153-244	153-229	153-229	153-215	
DECLINE$_{II}$ (LATE SEASON)	INT (a)	86.2	76.1	67.6	58.3	38.0	
	SLOPE (f)	-0.087	-0.066	-0.077	-0.058	-0.037	
	DAY RANGE (≥x_a - ≤x_b)	244-366	244-366	229-366	229-366	215-366	

Table A4 (continued)

MOPANIVELD ON BASALT

PHENOLOGICAL STAGE	PARAMETER	VELD CONDITION					
		GOOD		MODERATE		POOR	
		UBNT	BNT	UBNT	BNT	UBNT	BNT
DECLINE$_{\text{I}}$	INT (a)	69.0	64.4	59.1	56.7	43.8	41.7
	SLOPE (f)	-0.087	-0.044	-0.077	-0.058	-0.073	-0.055
	DAY RANGE ($\geq x_a$ - $\leq x_b$)	1-107	1-107	1-123	1-123	1-123	1-123
INITIATION & DEVELOPMENT	INT (a)	33.5	-162.9	-32.0	-266.5	-47.0	-205.0
	SLOPE (f)	0.435	1.522	0.667	2.167	0.667	1.667
	DAY RANGE ($\geq x_a$ - $\leq x_b$)	107-153	107-153	123-153	123-153	123-153	123-153
PEAK (MID SEASON)	INT (a)	80	70	70	65	55	50
	DAY RANGE ($\geq x_a$ - $\leq x_b$)	153-244	153-244	153-229	153-229	153-215	153-215
DECLINE$_{\text{II}}$ (LATE SEASON)	INT (a)	101.2	80.7	87.6	78.3	70.7	61.8
	SLOPE (f)	-0.087	-0.044	-0.077	-0.058	-0.073	-0.055
	DAY RANGE ($\geq x_a$ - $\leq x_b$)	244-366	244-366	229-366	229-366	215-366	215-366

MOPANIVELD ON GRANITE

PHENOLOGICAL STAGE	PARAMETER	VELD CONDITION					
		GOOD		MODERATE		POOR	
		UBNT	BNT	UBNT	BNT	UBNT	BNT
DECLINE$_{\text{I}}$	INT (a)	59.1	56.8	39.4	34.7	19.7	Does not normally produce adequate standing crop to burn 'cleanly'
	SLOPE (f)	-0.087	-0.066	-0.077	-0.039	-0.037	
	DAY RANGE ($\geq x_a$ - $\leq x_b$)	1-107	1-107	1-123	1-123	1-123	
INITIATION & DEVELOPMENT	INT (a)	3.5	-151.2	-52.0	-164.0	-26.0	
	SLOPE (f)	0.435	1.413	0.667	1.333	0.333	
	DAY RANGE ($\geq x_a$ - $\leq x_b$)	107-153	107-153	123-153	123-153	123-153	
PEAK (MID SEASON)	INT (a)	70	65	50	40	25	
	DAY RANGE ($\geq x_a$ - $\leq x_b$)	153-244	153-244	153-229	153-229	153-215	
DECLINE$_{\text{II}}$ (LATE SEASON)	INT (a)	91.2	81.1	67.6	48.9	33.0	
	SLOPE (f)	-0.087	-0.066	-0.077	-0.039	-0.037	
	DAY RANGE ($\geq x_a$ - $\leq x_b$)	244-366	244-366	229-366	229-366	215-366	

Table A5. Estimated cover adjustment factors for five rainfall classes [-]

RAINFALL CLASS	% OF MEAN ANNUAL RAINFALL	COVER ADJUSTMENT FACTOR
DROUGHT-STRICKEN	<25	0.15
	>25-35	0.15
	>35-45	0.20
	>45-55	0.30
	>55-65	0.45
	>65-75	0.65
BELOW AVERAGE	>75-85	0.80
	>85-95	0.92
AVERAGE	>95-105	1.00
ABOVE AVERAGE	>105-115	1.05
	>115-125	1.07
ABUNDANT RAIN	>125-135	1.08
	>135-145	1.09
	>145-155	1.10
	>155	1.10

Table A6. Equation statistics ($y = a + fx$) for calculating estimated daily values of total litter cover for three Acocks veld types. Cover of burnt veld adjusted to 0. UBNT = unburnt, BNT = burnt; INT = Intercept; X_a = first day of period, X_b = last day of period

DEVELOPMENTAL STAGE	**PARAMETER**	**VELD TYPE**			
		LOWVELD & ARID LOWVELD		MOPANIVELD	
		UBNT	BNT	UBNT	BNT
DEPOSITION$_I$	INT (a)	17.0	17.0	16.5	16.5
	SLOPE (f)	0.038	0.038	0.032	0.038
	DAY RANGE ($\geq x_a$ - $\leq x_b$)	1-77	1-45	1-107	1-45
PEAK	INT (a)	20.0	0.0	20.0	0.0
	DAY RANGE ($\geq x_a$ - $\leq x_b$)	77-138	46-307	107-168	46-307
DECOMPOSITION	INT (a)	27.8	Does not normally produce adequate standing crop to burn 'cleanly'	34.9	Does not normally produce adequate standing crop to burn 'cleanly'
	SLOPE (f)	-0.056		-0.087	
	DAY RANGE ($\geq x_a$ - $\leq x_b$)	138-228		168-228	
PRODUCTION	INT (a)	15.0		15.0	
	DAY RANGE ($\geq x_a$ - $\leq x_b$)	228-306		228-306	
DEPOSITION$_{II}$	INT (a)	3.3	3.3	4.9	4.9
	SLOPE (f)	0.038	0.038	0.033	0.033
	DAY RANGE ($\geq x_a$ - $\leq x_b$)	306-366	306-366	306-366	306-366

Table A7. Mean monthly basal crop coefficients of the ACRU 'Compoveg' file [-]

	ACOCKS VELD TYPE		
MONTH	LOWVELD	ARID LOWVELD	MOPANI VELD
JANUARY	0.70	0.60	0.52
FEBRUARY	0.70	0.60	0.52
MARCH	0.70	0.60	0.50
APRIL	0.60	0.50	0.40
MAY	0.50	0.45	0.38
JUNE	0.45	0.38	0.33
JULY	0.40	0.32	0.30
AUGUST	0.45	0.38	0.35
SEPTEMBER	0.58	0.40	0.40
OCTOBER	0.65	0.45	0.45
NOVEMBER	0.70	0.50	0.48
DECEMBER	0.70	0.60	0.50

Table A8. Estimated basal crop coefficients, K_c (Adapted from the ACRU model, Shulze 1995) [-]

ACOCKS VELD TYPE	VELD CONDITION	PHENOLOGICAL PERIOD		
		INITIATION	MID SEASON	LATE SEASON
LOWVELD	GOOD	0.40	0.70	0.45
	MODERATE	0.30	0.60	0.40
	POOR	0.25	0.50	0.35
ARID LOWVELD	GOOD	0.30	0.60	0.40
	MODERATE	0.25	0.50	0.35
	POOR	0.20	0.45	.030
MOPANI VELD	GOOD	0.30	0.55	0.35
	MODERATE	0.25	0.50	0.30
	POOR	0.20	0.45	0.25

Table A9. Weighting values for wind direction and calm conditions used in the estimation of daily total hours of sunshine duration [-]

WIND SPEED >0,0 m s^{-1}		**WIND SPEED = 0,0 m s^{-1} (CALM CONDITIONS)**	
WIND DIRECTION	**WEIGHTING**	**CLOUD COVER (OCTAVES)**	**WEIGHTING**
N	7	8	0
NE	5	7	0
E	0	6	1
SE	0	5	2
S	1	4	4
SW	5	3	8
W	7	2	9
NW	10	1	10
-	-	0	10

Table A10. Equation statistics ($y = a + fx$) for calculating estimated daily values of basal grass crop coefficients (K_c) for three Acocks veld types. INT = Intercept; x_a and x_b= First and last days in range respectively

PHENOLOGICAL STAGE	**PARAMETER**	**VELD TYPE & CONDITION**								
		LOWVELD			ARID LOWVELD			MOPANIVELD		
		GOOD	MOD.	POOR	GOOD	MOD.	POOR	GOOD	MOD.	POOR
DORMANT$_{I}$	INT (a)	0.40	0.30	0.25	0.30	0.25	0.20	0.30	0.25	0.20
	DAY RANGE $(\geq x_a - \leq x_b)$	1-107	1-107	1-107	1-107	1-123	1-123	1-107	1-123	1-123
INITIATION	INT (a)	0.40	0.30	0.25	0.30	0.25	0.20	0.30	0.25	0.20
	DAY RANGE $(\geq x_a - \leq x_b)$	107-123	107-123	123-138	107-123	123-138	123-138	107-123	123-138	123-138
DEVELOPMENT	INT (a)	-0.84	-0.94	-2.25	-0.94	-2.25	-2.30	-0.82	-2.25	-2.30
	SLOPE (f)	0.010	0.010	0.018	0.010	0.018	0.018	0.009	0.018	0.018
	DAY RANGE $(\geq x_a - \leq x_b)$	123-153	123-153	138-153	123-153	138-153	138-153	123-153	138-153	138-153
MID SEASON	INT (a)	0.70	0.60	0.50	0.60	0.50	0.45	0.55	0.50	0.45
	DAY RANGE $(\geq x_a - \leq x_b)$	153-259	153-244	153-229	153-244	153-229	153-215	153-244	153-229	153-215
LATE SEASON	INT (a)	2.38	2.97	4.32	2.97	4.32	4.30	2.53	4.32	4.30
	SLOPE (f)	-0.0065	-0.0097	-0.0167	-0.0097	-0.0167	-0.0179	-0.0081	-0.0167	-0.0179
	DAY RANGE $(\geq x_a - \leq x_b)$	259-305	244-275	229-244	244-275	229-244	215-229	244-275	229-244	215-229
DORMANT$_{II}$	INT (a)	0.40	0.30	0.25	0.30	0.25	0.20	0.30	0.25	0.20
	DAY RANGE $(\geq x_a - \leq x_b)$	305-366	275-366	244-366	275-366	244-366	229-366	275-366	244-366	229-366

Table A11. Regression equations for estimating daily maximum, minimum, dry bulb and wet bulb temperatures using values from nearby stations. P (Intercept) in most cases <0.00001. For TX_{LEV} $P<0.5986$; for TW_{LEV14} $P=0.02411$; for TD_{MOP14} $P = 0.00399$; for TW_{PRE14} $P = 0.00028$; for TN_{SHI} $P = 0.04333$. P (slope) in all cases <0.00001. See bottom of table for explanation of abbreviations

STATION	Equation	r	r^2 (%)	S.E.E.	D.f.
BERG EN DAL					
TX_{BDL}	$2.465 + 0.982(TX_{PRE})$	0.962	92.45	1.31	2 323
TN_{BDL}	$4.470 + 0.769(TN_{SKZ})$	0.954	91.09	1.46	2 355
TD_{BDL08}	$1.885 + 0.976(TD_{PRE08})$	0.929	86.34	1.72	2 380
TW_{BDL08}	$4.615 + 0.759(TW_{SKZ08})$	0.952	90.54	1.32	2 361
TD_{BDL14}	$2.584 + 0.964(TD_{PRE14})$	0.949	89.96	1.53	2 676
TW_{BDL14}	$3.478 + 0.867(TW_{PRE14})$	0.919	84.52	1.34	4 662
LETABA					
TX_{LET}	$1.538 + 0.977(TX_{SAT})$	0.937	87.81	1.73	6 633
TN_{LET}	$1.953 + 0.918(TN_{SHI})$	0.944	89.02	1.88	7 294
TD_{LET08}	$1.288 + 0.935(TD_{SHI08})$	0.920	84.61	2.16	5 478
TW_{LET08}	$1.731 + 0.919(TW_{SHI08})$	0.924	85.37	1.87	5 022
TD_{LET14}	$0.976 + 0.992(TD_{SAT14})$	0.935	87.48	1.75	5 138
TW_{LET14}	$3.057 + 0.912(TW_{SKZ14})$	0.802	64.24	2.19	5 703
LEVUBU					
TX_{LEV}	$-0.114 + 0.909(TX_{PUN})$	0.940	88.32	1.68	2 036
TN_{LEV}	$-0.803 + 0.926(TN_{PUN})$	0.931	86.72	1.46	2 025
TD_{LEV08}	$3.408 + 0.699(TD_{SHI08})$	0.900	81.04	1.86	5 556
TW_{LEV08}	$1.749 + 0.778(TW_{SHI08})$	0.922	85.06	1.63	5 359
TD_{LEV14}	$0.897(TD_{PUN14})$	0.949	89.96	1.53	2 676
TW_{LEV14}	$0.209 + 0.919(TW_{PHA14})$	0.917	84.00	1.34	7 498
LOWER SABIE					
TX_{OSA}	$1.695 + 0.956TX_{SKZ})$	0.973	94.61	1.08	2 427
TN_{OSA}	$4.128 + 0.812(TN_{SKZ})$	0.956	91.40	1.54	2 427
TD_{OSA08}	$4.725 + 0.831(TD_{SKZ08})$	0.947	89.63	1.70	2 552
TW_{OSA08}	$3.841 + 0.847(TW_{SKZ08})$	0.964	92.87	1.26	2 390
TD_{OSA14}	$1.496 + 0.962(TD_{SKZ14})$	0.968	93.65	1.19	2 378
TW_{OSA14}	$5.468 + 0.820(TW_{PRE14})$	0.911	82.93	1.34	2 391
MOPANI					
TX_{MOP}	$0.453 + 0.960(TX_{SHI})$	0.955	91.20	1.50	2 473
TN_{MOP}	$3.126 + 0.811(TN_{LET})$	0.964	92.95	1.30	2 610
TD_{MOP08}	$4.727 + 0.788(TD_{LET08})$	0.920	84.54	1.91	2 408
TW_{MOP08}	$3.742 + 0.806(TW_{LET08})$	0.928	86.07	1.60	2 187
TD_{MOP14}	$0.485 + 0.977(TD_{LET14})$	0.964	92.88	1.34	2 283
TW_{MOP14}	$2.280 + 0.908(TW_{LET14})$	0.873	76.25	1.67	2 124
PAFURI POLICE STATION					
TX_{PAP}	$2.283 + 0.939(TX_{SHI})$	0.959	91.92	1.39	1 653
TN_{PAP}	$1.051 + 0.994(TN_{SHI})$	0.957	91.65	1.87	1 755
TD_{PAP08}	$1.742 + 0.945(TD_{SHI08})$	0.938	88.03	1.99	1 765
TW_{PAP08}	$1.748 + 0.928(TW_{SHI08})$	0.943	88.90	1.70	1 615
TD_{PAP14}	$3.548 + 0.898(TD_{SHI14})$	0.942	88.72	1.61	1 599
TW_{PAP14}	$6.065 + 0.7469(TW_{PUN14})$	0.872	76.03	1.50	1 561

Table A11 (continued)

PHALABORWA					
TX_{PHA}	$0.513 + 0.939(TX_{LET})$	0.990	97.81	0.70	6 530
TN_{PHA}	$5.299 + 0.701(TN_{LET})$	0.934	87.26	1.66	2 080
TD_{PHA08}	$3.036 + 0.779(TD_{LET08})$	0.928	86.02	1.70	3 447
TW_{PHA08}	$2.315 + 0.796(TW_{LET08})$	0.931	86.67	1.51	3 227
TD_{PHA14}	$1.272 + 0.895(TD_{LET14})$	0.933	87.14	1.71	3 253
TW_{PHA14}	$2.959 + 0.915(TW_{LEV14})$	0.917	84.00	1.34	7 498
PRETORIUSKOP					
TX_{PRE}	$-1.121 + 0.957(TX_{SKZ})$	0.968	93.67	1.18	2 481
TN_{PRE}	$6.121 + 0.592(TN_{SKZ})$	0.913	83.35	1.66	7 482
TD_{PRE08}	$6.689 + 0.643(TD_{SKZ08})$	0.877	76.89	2.09	5 966
TW_{PRE08}	$4.515 + 0.715(TW_{SKZ08})$	0.923	85.26	1.59	5 627
TD_{PRE14}	$-0.746 + 0.948(TD_{SKZ14})$	0.953	90.75	1.43	5 871
TW_{PRE14}	$-0.806 + 0.979(TW_{SKZ14})$	0.880	77.34	1.72	2 390
PUNDA MARIA					
TX_{PUN}	$-1.055 + 0.980(TX_{SHI})$	0.952	90.68	1.16	1 912
TN_{PUN}	$3.065 + 0.937(TN_{LEV})$	0.931	86.72	1.47	2 024
TD_{PUN08}	$4.847 + 0.915(TD_{LEV08})$	0.893	79.66	1.98	5 962
TW_{PUN08}	$5.914 + 0.778(TW_{LEV08})$	0.888	78.77	1.81	1 616
TD_{PUN14}	$4.353 + 0.943(TD_{LEV14})$	0.922	84.94	1.94	5 472
TW_{PUN14}	$6.905 + 0.787(TW_{PUN08})$	0.749	56.17	2.71	5 699
SATARA					
TX_{SAT}	$1.817 + 0.945(TX_{SKZ})$	0.943	88.95	1.56	7 026
TN_{SAT}	$2.901 + 0.801(TN_{LET})$	0.941	88.56	1.62	7 010
TD_{SAT08}	$7.347 + 0.681(TD_{LET08})$	0.886	78.48	1.97	5 651
TW_{SAT08}	$7.325 + 0.680(TW_{SKZ08})$	0.909	82.70	1.64	5 390
TD_{SAT14}	$2.017 + 0.939(TD_{SKZ14})$	0.942	88.74	1.57	5 500
TW_{SAT14}	$1.957 + 0.946(TW_{SKZ14})$	0.842	70.87	1.94	5 362
SHIMUWINI					
TX_{SHM}	$0.799 + 0.970(TX_{LET})$	0.972	94.51	1.16	2 383
TN_{SHM}	$0.800 + 0.957(TN_{LET})$	0.976	95.15	1.27	2 501
TD_{SHM08}	$1.851 + 0.913(TD_{LET08})$	0.956	91.47	1.60	2 294
TW_{SHM08}	$1.323 + 0.924(TW_{LET08})$	0.955	91.15	1.43	1 954
TD_{SHM14}	$1.586 + 0.943(TD_{LET14})$	0.970	93.99	1.18	1 638
TW_{SHM14}	$2.218 + 0.897(TW_{LET14})$	0.913	83.33	1.29	1 514
SHINGWEDZI					
TX_{SHI}	$3.684 + 0.926(TX_{PUN})$	0.953	90.76	1.50	5 910
TN_{SHI}	$-0.138 + 0.969(TN_{LET})$	0.943	89.06	1.93	7 493
TD_{SHI08}	$2.004 + 0.905(TD_{LET08})$	0.920	84.61	2.13	5 478
TW_{SHI08}	$1.063 + 0.925(TW_{LET08})$	0.925	85.59	1.87	4 885
TD_{SHI14}	$4.129 + 0.907(TD_{PUN14})$	0.929	86.31	1.81	5 100
TW_{SHI14}	$5.835 + 0.816(TW_{LEV14})$	0.815	66.42	1.94	4 778
SIRHENI					
TX_{SIR}	$2.353 + 0.960(TX_{PUN})$	0.968	93.72	1.29	2 364
TN_{SIR}	$0.973 + 0.924(TN_{SHI})$	0.963	92.79	1.56	2 541
TD_{SIR08}	$1.653 + 0.904(TD_{SHI08})$	0.942	88.86	1.81	2 560
TW_{SIR08}	$2.008 + 0.889(TW_{SHI08})$	0.942	88.65	1.62	2 324
TD_{SIR14}	$2.310 + 0.964(TD_{PUN14})$	0.953	90.84	1.58	2 233
TW_{SIR14}	$5.784 + 0.753(TW_{PUN14})$	0.833	69.41	1.77	2 178

Table A11 (continued)

SKUKUZA					
TX_{SKZ}	$3.174 + 0.964(TX_{PRE})$	0.957	91.62	1.38	7 047
TN_{SKZ}	$-4.878 + 1.209(TN_{SAT})$	0.936	87.53	2.20	6 934
TD_{SKZ08}	$-1.043 + 0.968(TD_{LET08})$	0.920	84.59	2.30	5 820
TW_{SKZ08}	$-2.966 + 1.193(TW_{PRE08})$	0.923	85.26	2.06	5 627
TD_{SKZ14}	$3.380 + 0.958(TD_{PRE14})$	0.952	90.59	1.45	5 194
TW_{SKZ14}	$4.178 + 0.7613(TW_{SAT14})$	0.843	71.10	1.74	5 553
TALAMATI					
TX_{TAL}	$0.500 + 0.969(TX_{SAT})$	0.983	95.49	0.98	2 539
TN_{TAL}	$0.773 + 0.901(TN_{SKZ})$	0.960	92.08	1.62	2 455
TD_{TAL08}	$-2.931 + 1.071(TD_{SAT08})$	0.939	88.13	1.70	2 511
TW_{TAL08}	$4.823 + 0.750(TW_{SKZ08})$	0.947	89.60	1.39	2 394
TD_{TAL14}	$0.742 + 0.948(TD_{SKZ14})$	0.962	92.52	1.27	2 417
TW_{TAL14}	$1.341 + 0.891(TW_{SKZ14})$	0.812	76.01	1.62	2 307

TEMPERATURES: TM = Maximum temperature; TN = Minimum temperature; TD = Dry bulb temperature; TW = Wet bulb temperature. *STATIONS*: BDL = Berg en dal; LET = Letaba; LEV = Levubu; OSA = Lower Sabie; MOP = Mopani; PAP = Pafuri Police Station; PHA = Phalaborwa; PRE = Pretoriuskop; PUN = Punda Maria; SAT = Satara; SHM = Shimuwini; SHI = Shingwedzi; SIR = Sirheni; SKZ = Skukuza; TAL = Talamati.

Table A12. Sub-equations for the calculation of reference evapotranspiration (ET_o) and crop evapotranspiration (ET_c), after Allen *et al.* (1996; 1998). All parameters are described in Table A13)

EQUATIONS FOR THE CALCULATION OF REFERENCE EVAPOTRANSPIRATION (ET_o)

Sunset hour angle (ω_s)	$\omega_s = \arccos[-\tan(\varphi)\tan(\delta)]$
Latitude (φ)	$\varphi = \frac{\pi}{180}(\text{decimal degrees}))$
Solar declination (δ)	$\delta = 0.409 \sin\left(\frac{2\pi}{365}J - 1.39\right)$
Daylength (N)	$N = \frac{24}{\pi}\omega_s$
Inverse relative distance Earth-Sun (d_r)	$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365}J\right)$
Extraterrestrial radiation (R_a)	$R_a = \frac{24(60)}{\pi} G_{sc}\, d_r \left[\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)\right)$
Solar or (shortwave) radiation (R_s)	$R_s = \left(a_s + b_s \frac{n}{N}\right) R_a$
Net solar or net shortwave radiation (R_{ns})	$R_{ns} = (1 - \alpha) R_s$
Clear-sky solar radiation (R_{so})	$R_{so} = (a_s + b_s) R_a$
Actual vapour pressure (e_a)	$e_a = e^{\circ}(T_{wet}) - \gamma_{psy}(T_{dry} - T_{wet})$
Net outgoing longwave radiation (R_{nl})	$R_{nl} = \sigma \left[\frac{T_{max,K}^4 + T_{min,K}^4}{2}\right]\left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35 \frac{R_s}{R_{so}} - 0.35\right)$
Net radiation (R_n)	$R_n = R_{ns} - R_{nl}$
Maximum and minimum saturation vapour pressure ($e^{o}T$)	$e^{\circ}(T) = 0.6108 \exp\left[\frac{17.27\, T_{max}}{T_{max} + 237.3}\right]$ and $e^{\circ}(T) = 0.6108 \exp\left[\frac{17.27\, T_{min}}{T_{min} + 237.3}\right]$
Mean vapour pressure (e_s)	$e_s = \frac{e^{\circ}(T_{max}) + e^{\circ}(T_{min})}{2}$
Atmospheric pressure (P)	$p = 101.3\left(\frac{293 - 0.006z}{293}\right)^{5.26}$
Psychrometric constant (γ)	$\gamma = \frac{c_p P}{\varepsilon\lambda} = 0.665 \times 10^{-3} P$
Slope of the saturation vapour pressure curve (Δ)	$\Delta = \frac{4098\left[0.6108 \exp\left(\frac{17.27\,T}{T + 237.3}\right)\right]}{(T + 237.3)^2}$

Reference crop evaporation (ET_o)	$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{965}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)}$

EQUATIONS FOR THE CALCULATION AND ADJUSTMENT OF CROP COEFFICIENTS AND CALCULATION OF CROP EVAPOTRANSPIRATION (ET_c)

Potential rate of evapotranspiration (E_{so})	$E_{so} = 1.15 ETo$
Time when stage 1 drying is completed (t_l)	$t_l = REW/E_{so}$
Total evaporable water (TEW)	$TEW = 1000(\theta_{FC} - 0.5\theta_{WP})Z_e$
Crop coefficient during the initial growth stage (stage 2) ($K_{c\ ini}$)	$K_{c\ ini} = \frac{TEW - (TEW - REW)\exp\left(\frac{-(t_w - t_1)E_{so}\left(1 + \frac{REW}{TEW - REW}\right)}{TEW}\right)}{t_w ET_o}$
Maximum value of the crop coefficient following rain ($K_{c\ max}$)	$K_{c\ max} = \max\left(\left\{1.2 + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3}\right\}, \{K_{cb} + 0.05\}\right)$
Basal crop coefficient during the mid-season growth stage when plant density and/or leaf area are lower than for full cover conditions. ($K_{cb\ mid\ adj}$). *In cases where only estimates of the fraction of the soil surface effectively covered by vegetation are available, this equation is used (Allen et al.1998)*	$K_{cb\ mid\ adj} = K_{c\ min} + (K_{cb\ full} - K_{c\ min})\left(\min\left(1.2f_c, \left(f_{c\ eff}\left(\frac{1}{1+h}\right)\right)\right)\right)$
Basal crop coefficient for the end of the late season ($K_{cb\ full}$). *For natural vegetation, can be approximated as a function of climate and mean plant height for areas of vegetation that are greater than a few hectares.*	$K_{cb\ full} = K_{cb(end)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3}$
The potential maximum retention after runoff begins (S)	$S = \frac{1000}{CN} - 10$
Surface runoff (RO)	$RO = \frac{(P - 0.2S)^2}{(P + 0.8S)}$
Soil evaporation reduction coefficient (K_r)	For $DEW_{e,I-1}$>REW: $K_r = \frac{TEW - D_{e,i-1}}{TEW - REW}$ For $DEW_{e,i-1}$≤REW: $K_r = 1$ ($K_r = 0$ when TEW is at its maximum)
Soil evaporation coefficient (K_e)	$K_e = K_r(K_{c\ max} - K_{cb}) \le f_{ew} K_{c\ max}$

Cumulative depth of evaporation following complete wetting from the exposed and wetted fraction of the topsoil at the end of day i ($D_{e,i}$)	$D_{e,i} = D_{e,i-1} - (P_i - RO_i) - \frac{I_i}{f_w} + \frac{E_i}{f_{ew}} + DP_{e,i}$
Deep percolation loss from the topsoil layer on day i if soil water content exceeds field capacity ($DP_{e,i}$)	$DP_{e,i} = (P_i - RO_i) + \frac{I_i}{f_w} - D_{e,i-1}$
Deep percolation following heavy rain (or irrigation) (DP_i)	$DP_i = (P_i - RO_i) + I_i - ET_{c,i} - D_{r,i-1} \geq 0$
Total Available Water (TAW)	$TAW = 1000\ (\theta_{FC} - \theta_{WP})Z_r$
Readily Available Water (RAW)	$RAW = p * TAW$
Initial depletion from the root zone (to initiate calculations) ($D_{r,i-1}$)	$D_{r,i-1} = 1000(\theta_{FC} - \theta_{i-1})Z_r$
Daily water balance of the root zone, expressed in terms of depletion at the end of each day ($D_{r,i}$)	$D_{r,i} = D_{r,i-1} - (P - RO)_i - I_i - CR_i + ET_{c,i} + DP_i$
Water stress coefficient (K_s)	For D_r >RAW: $K_s = \frac{TAW - D_r}{TAW - RAW} = \frac{TAW - D_r}{(1-p)TAW}$ For D_r <RAW: $K_s = 1$
Crop evapotranspiration under non-standard conditions ($ET_{c\ adj}$)	$ET_{c\ adj} = (K_s K_{cb} + K_e)ET_o$

Table A13. List of symbols and acronyms used in the reference and crop evapotranspiration equations (Allen *et al.* 1998)

SYMBOL	PARAMETER	UNIT
a_s & b_s	Regression constants Angstrom constants), expressing the fraction of extraterrestrial radiation reaching the earth on an overcast day (n=0). Values for Nelspruit were used: a_s =21, b_s=65 (Smithers & Schulze 1995)	-
a_s+b_s	Fraction of extraterrestrial radiation reaching the earth on a clear day (n=N)	-
CN	Curve number (Table A20)	-
c_p	Specific heat at constant pressure for average atmospheric conditions (=1.013 10^{-3})	MJ kg^{-1} $°C^{-1}$
CR_i	Capillary rise from the groundwater table on day i	mm
D_e	Cumulative depth of evaporation (depletion) from the soil surface layer	mm
$D_{e,\ i}$	Cumulative depth of evaporation following complete wetting From the exposed and wetted fraction of the topsoil at the end of day i	mm
$D_{e,\ i-1}$	The cumulative depth of evaporation (depletion) from the soil Surface layer at the end of day $_{i-1}$ (the previous day)	mm
DP	Deep percolation	mm
DP_e	Deep percolation from the evaporation layer	mm
$DP_{e,i}$	Deep percolation loss from the topsoil layer on day i if soil Water content exceeds field capacity	mm
DP_i	Water loss out of the root zone by deep percolation on day i	mm
D_r	Cumulative depth of evapotranspiration (depletion) from the root zone	mm
d_r	Inverse relative distance Earth-Sun	-
$D_{r,i}$	Cumulative depth of evaporation (depletion) from root zone at the end of day i	mm
$D_{r,i-1}$	Water content in the root zone at the end of the previous day, i-1 (Table A25)	mm
E_i	Evaporation on day i (i.e. $E_i = K_eET_o$)	mm day^{-1}
e_a	Actual vapour pressure	kPa
E_{so}	Potential rate of evapotranspiration	mm d^{-1}
e_s	Mean saturation vapour pressure for a given time period	kPa
e_s-e_a	Saturation vapour pressure deficit	kPa
ET	Evapotranspiration	mm day^{-1}
$ET_{c,i}$	Crop evapotranspiration on day i	mm
ET_c	Crop evapotranspiration under standard conditions	mm day^{-1}
$ET_{c\ adj}$	Crop evapotranspiration under non-standard conditions	mm day^{-1}
ET_o	Reference crop evapotranspiration; mean ET_o during the initial period (Table A17)	mm day^{-1}
e°(T)	Saturation vapour pressure at air temperature T	kPa
f_c	Fraction of soil surface covered by vegetation (as observed from Overhead; Tables A3-A6)	-
$f_{c\ eff}$	The effective fraction of the soil surface covered by vegetation (=0.01-1; Tables A3-A6)	-
1-f_c	Exposed soil fraction (Tables A3-A6)	-

Table A13 (continued)

f_{ew}	Fraction of soil that is both exposed and wetted, i.e. the fraction of the soil from which most evaporation occurs (= 0.01 -1; Tables A3-A6)	-
f_w	Fraction of soil surface wetted by rain or irrigation (=0.01 -1; Tables A3-A6)	-
G	Soil heat flux density	MJ m^{-2} day^{-1}
g	Gravitational acceleration	m s^{-2}
G_{sc}	Solar constant (=0.0820)	MJ m^{-2} min^{-1}
h	Mean maximum plant height during the period of calculation (initial, development, mid-season, or late-season; Table A18)	m
I_i	Irrigation depth on day i that infiltrates the soil	mm
J	Number of the day in the year (the *nth* day of the year)	-
K_c	Crop coefficient (Tables A8 & 10)	-
$K_{c\ end}$	Crop coefficient at end of the late season growth stage	-
$K_{c\ ini}$	Crop coefficient during the initial growth stage	-
$K_{c\ max}$	Maximum value of crop coefficient (following rain or irrigation)	-
$K_{c\ mid}$	Crop coefficient during the mid-season growth stage	-
$K_{c\ min}$	Minimum value of crop coefficient (dry soil with no ground cover)	-
K_{cb}	Basal crop coefficient (Tables A8 & A10)	-
$K_{cb\ end}$	Basal crop coefficient at end of the late season growth stage	-
$K_{cb\ full}$	Basal crop coefficient during mid-season (at peak plant size or height) for vegetation with full ground cover of LAI >3	-
$K_{cb\ ini}$	Basal crop coefficient during the initial growth stage	-
$K_{cb\ mid\ adj}$	Adjusted basal crop coefficient during the mid-season growth stage	-
K_e	Soil evaporation coefficient	-
K_r	Soil evaporation reduction coefficient	-
K_s	Water stress coefficient	-
max() or min()	Maximum (or minimum) value of the parameters in brackets {} that are separated by a comma	-
N	Maximum possible sunshine duration in a day, daylight hours	hour
n	Actual duration of sunshine in a day	hour
n/N	Relative sunshine duration	-
P	Rainfall , atmospheric pressure	mm, kPa
P_i	Precipitation on day i, i.e. daily precipitation	mm
p	Evaporation depletion factor, a function of the evaporation power of the atmosphere. Average fraction of TAW that can be depleted from the root zone before moisture stress(i.e. reduction in ET) occurs (=0-1; Table A24)	-
R_a	Extraterrestrial radiation	MJ m^{-2} day^{-1}
RAW	Readily available soil water of the root zone (Table A23)	mm
REW	Readily evaporable water (i.e. maximum depth of water that can be evaporated from the soil surface layer without restriction during stage 1; Table A14)	mm
RH	Relative humidity	%
RH_{max}	Daily maximum relative humidity	%

Table A13 (continued)

RH_{mean}	Daily mean relative humidity	%
RH_{min}	Mean minimum daily relative humidity during the mid-season (Table A19)	%
R_l	Longwave radiation	$MJ\ m^{-2}\ day^{-1}$
R_n	Net radiation at the crop surface	$MJ\ m^{-2}\ day^{-1}$
R_{nl}	Net longwave radiation	$MJ\ m^{-2}\ day^{-1}$
R_{ns}	Net solar or shortwave radiation	$MJ\ m^{-2}\ day^{-1}$
RO	Surface runoff	mm
RO_i	Runoff from the soil surface on day i	mm
R_s	Incoming solar or shortwave radiation (measured or calculated)	$MJ\ m^{-2}\ day^{-1}$
R_{so}	Clear-sky solar or clear-sky shortwave radiation	$MJ\ m^{-2}\ day^{-1}$
R_s/R_{so}	Relative solar or relative shortwave radiation (limited to ≤ 1.0)	-
S	The potential maximum retention after runoff begins, related to the soil and cover conditions of the watershed through the curve number (CN)	-
T	Air temperature	°C
TAW	Total available soil water of the root zone (Table A21)	mm
T_{dew}	Dewpoint temperature	°C
T_{dry}	Temperature of dry bulb	°C
T_{wet}	Temperature of wet bulb	°C
$T_{dry} - T_{wet}$	Wet bulb depression	°C
TEW	Total evaporable water (i.e. maximum depth of water that can be evaporated from the soil surface layer when the topsoil has initially been completely wetted (Table A14)	mm
T_k	Air temperature	K
T_{max}	Daily maximum air temperature	°C
$T_{max,K}$	Maximum absolute temperature during the 24-hour period (K = °C + 273.16)	K
T_{mean}	Daily mean air temperature	°C
T_{min}	Daily minimum air temperature	°C
$T_{min,K}$	Minimum absolute temperature during the 24-hour period (K = °C + 273.16)	K
t_w	Mean interval between wetting events (Table A15)	days
T_{wet}	Temperature of wet bulb	°C
t_1	Time when stage 1 drying is completed	hour
u_2	Mean wind speed at 2m height during the mid-season (Table A19)	$m\ s^{-1}$
Z_e	Depth of surface soil layer subjected to drying by evaporation; Where unknown, a value of 0.10 to 0.15 m is recommended by Allen *et al.* (1998). In this study, a standard depth of 0.15 m was used (Table A14)	m
Z_r	Rooting depth (Table A22)	m
z	Elevation, height above sea level	m
α	Albedo or canopy reflection coefficient, 0.23 for the hypothetical grass reference crop	-
γ	Psychrometric constant	kPa $°C^{-1}$
γ_{psy}	Psychrometric constant of the instrument	kPa $°C^{-1}$

Table A13 (continued)

Δ	Slope of the saturation vapour pressure curve	kPa °C^{-1}
δ	Solar declination	radians
ε	Ratio of molecular weight of water vapour to dry air (=0.622)	-
θ	Soil water content	m^{3} (water) m^{-3} (soil)
θ_{FC}	Soil water content at field capacity (Table A14)	m^{3} (water) m^{-3} (soil)
θ_{WP}	Soil water content at wilting point (Table A14)	m^{3} (water) m^{-3} (soil)
θ_{i-1}	Average soil water content for the effective root zone	m^{3} (water) m^{-3} (soil)
λ	Latent heat of vapourization, (=2.45)	MJ kg^{-1}
σ	Stefan-Boltzman constant (=4.903 10^{-9})	MJ K^{-4} m^{-2} day^{-1}
φ	Latitude	radians
ω	Solar time angle at midpoint of hourly or shorter period	radians
ω_{S}	Sunset hour angle	radians

Table A14. Soil water content at field capacity (θ_{FC}), wilting point (θ_{WP}), readily evaporable water (REW) and total evaporable water (TEW) for various soil texture classes. Depth of surface soil layer subjected to drying by evaporation (Z_e) is unknown and therefore set at 0.15 m for all classes (Allen *et al.* 1998)

SOIL TEXTURE CLASS	**SOIL WATER CONTENT AT FIELD CAPACITY ($m^{-3}\ m^{-3}$)**	**SOIL WATER CONTENT AT WILTING POINT ($m^{-3}\ m^{-3}$)**	**READILY EVAPORABLE WATER (mm)**	**TOTAL EVAPORABLE WATER (mm)**
	θ_{FC}	θ_{WP}	[2]REW	TEW
CLAY	0.360	0.220	10.0	37.5
LOAM	0.250	0.120	9.0	28.5
SAND	0.120	0.045	4.5	14.6
LOAMY SAND	0.150	0.065	6.0	13.1
SANDY LOAM	0.230	0.110	8.0	26.3
SILTY LOAM	0.290	0.150	9.5	32.3
SANDY CLAY LOAM	[1]0.254	[1]0.159	[1]9.5	26.2
CLAY LOAM	[1]0.312	[1]0.195	[1]9.5	32.2
SILTY CLAY LOAM	0.335	0.205	9.5	34.9
SANDY CLAY	[1]0.323	[1]0.228	[1]9.5	31.4
SILTY CLAY	0.360	0.230	10.0	36.8

[1]After Schulze, Angus & Guy (1995). [2] REW class mid-points (Allen *et al.* 1998).

Table A15. Mean interval between wetting events (t_w) [days]

ACOCKS VELD TYPE	WEATHER STATION	PHENOLOGICAL STAGE					
		DORMANT$_{I}$	INITIATION	DEVELOPMENT	MID SEASON	LATE SEASON	DORMANT$_{II}$
LOWVELD	BDL	14.3	5.8	4.1	4.0	5.3	8.6
	OSA	13.2	5.4	4.1	3.6	4.8	12.5
	PRE	10.7	4.3	3.2	2.9	4.2	13.8
	SKZ	12.4	5.5	3.2	3.6	4.4	11.5
ARID LOWVELD	LET	19.5	7.2	4.4	4.6	5.3	13.7
	OSA	12.5	5.0	3.9	3.6	3.9	9.3
	SAT	20.4	9.2	4.1	4.3	5.1	13.5
	SHM	20.7	7.8	4.6	5.6	7.7	15.9
	SKZ	11.8	4.6	3.2	3.6	3.8	8.6
	TAL	14.2	5.9	3.6	3.7	4.2	10.3
MOPANI VELD	LET	19.5	7.2	4.4	4.6	5.3	13.7
	MOP	20.9	7.8	4.7	5.2	6.5	14.2
	PAP	29.9	9.8	4.9	5.3	6.0	18.7
	PUN	14.7	5.6	4.0	4.1	5.5	13.8
	SHI	18.7	8.9	5.7	5.3	5.8	16.5
	SHM	20.7	7.8	4.6	5.6	7.7	15.9
	SIR	15.9	7.9	5.4	4.7	5.8	13.6

BDL = Berg en dal; LET = Letaba; OSA = Lower Sabie; MOP = Mopani; PAP = Pafuri police station; PRE = Pretoriuskop; PUN = Punda Maria; SAT = Satara; SHI = Shingwedzi; SHM = Shimuwini; SIR = Sirheni; SKZ = Skukuza; TAL = Talamati.

Table A16. Monthly DPM adjustment factors for peaks in February, March and April (After Grunow *et al.* (1980) [-]

MONTH	FACTOR FOR PEAK IN:			
	JANUARY	FEBRUARY	MARCH	APRIL
OCTOBER	1.950	2.836	3.391	3.120
NOVEMBER	1.219	1.950	2.836	3.391
DECEMBER	1.013	1.219	1.950	2.836
JANUARY	1.000	1.013	1.219	1.950
FEBRUARY	1.114	1.000	1.013	1.219
MARCH	1.444	1.114	1.000	1.013
APRIL	1.835	1.444	1.114	1.000
MAY	2.364	1.835	1.444	1.114
JUNE	2.786	2.364	1.835	1.444
JULY	3.120	2.786	2.364	1.835
AUGUST	3.391	3.120	2.786	2.364
SEPTEMBER	2.836	3.391	3.120	2.786

Table A17. Mean ET_O during the 'initial' phenological stage [mm]

ACOCKS VELD TYPE	STATION	VELD CONDITION GOOD	MODERATE	POOR
LOWVELD	BDL	3.8	3.8	4.0
	OSA	3.9	3.8	4.3
	PRE	3.7	3.7	3.9
	SKZ	3.8	3.7	3.9
ARID LOWVELD	LET	4.6	4.8	4.8
	OSA	3.9	4.3	4.3
	SAT	4.4	4.6	4.6
	SHM	4.7	4.9	4.9
	SKZ	3.8	3.9	3.9
	TAL	4.0	4.1	4.1
MOPANI VELD	LET	4.6	4.8	4.8
	MOP	4.4	4.8	4.8
	PAP	4.9	5.3	5.3
	PUN	4.4	4.6	4.6
	SHI	4.9	5.1	5.1
	SHM	4.7	4.9	4.9
	SIR	4.6	4.8	4.8

Table A18. Estimated mean maximum grass height (h) for unburnt and burnt veld on basalt and granite [m]

UNBURNT VELD (All veld types)

PHENOLOGICAL STAGE	BASALT GOOD	MODERATE	POOR	GRANITE GOOD	MODERATE	POOR
DORMANT_I	0.40	0.30	0.20	0.30	0.20	0.10
INITIATION	0.40	0.30	0.20	0.30	0.20	0.10
DEVELOPMENT	0.50	0.40	0.30	0.40	0.30	0.20
MID SEASON	0.70	0.60	0.50	0.60	0.50	0.40
LATE SEASON	0.60	0.50	0.40	0.50	0.40	0.30
DORMANT_II	0.50	0.40	0.30	0.40	0.30	0.20

BURNT VELD (All veld types)

PHENOLOGICAL STAGE		BASALT GOOD	MODERATE	POOR	GRANITE GOOD	MODERATE	POOR
DORMANT_I	[1]PRE-BURN	0.40	0.30	0.20	0.30	0.20	0.10
	[2]POST-BURN	0.00 (107)	0.00 (107)	0.00 (123)	0.00 (107)	0.00 (107)	0.00 (123)
INITIATION		0.15	0.15	0.10	0.15	0.10	0.10
DEVELOPMENT		0.40	0.30	0.30	0.30	0.20	0.10
MID SEASON		0.70	0.60	0.50	0.60	0.50	0.40
LATE SEASON		0.60	0.50	0.40	0.50	0.40	0.30
DORMANT_II		0.50	0.40	0.30	0.40	0.30	0.20

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[1] In all cases, climyear day = 1 to 45.

[2] In all cases, climyear day is from 46 onwards to day given in parentheses, i.e. 107 or 123. In the case of Mopani veld in moderate or poor condition, on basalt or granite, to climyearday 123.

Table A19. Mean daily minimum relative humidity (%RH$_{MIN}$)and mean daily wind speed (u$_2$, m s^{-1}) at 2 m above ground level for the initiation, development, mid and late season phenological stages

VELD TYPE	STN	COND	INITIATION		DEVELOPMENT		MID SEASON		LATE SEASON	
			%RH$_{MIN}$	u$_{2ms}$	%RH$_{MIN}$	u$_{2ms}$	%RH$_{MIN}$	u$_{2ms}$	%RH$_{MIN}$	u$_{2ms}$
LOWVELD	BDL	GOOD	44.6	1.0	47.2	0.9	49.8	0.8	48.5	0.6
		MOD	44.5	0.6	47.2	0.9	49.6	0.9	51.5	0.6
		POOR	45.4	0.9	48.9	0.9	49.5	0.8	50.0	0.9
	OSA	GOOD	39.7	1.0	40.1	0.9	45.9	0.8	44.0	0.6
		MOD	39.7	1.0	40.1	0.9	45.8	0.9	46.7	0.6
		POOR	38.8	0.9	41.4	0.9	45.6	0.9	46.7	0.9
	PRE	GOOD	46.1	1.1	49.5	1.0	53.0	0.9	52.2	0.6
		MOD	46.1	1.1	49.5	1.0	52.9	0.9	54.5	0.7
		POOR	47.3	0.9	51.7	1.0	52.7	0.9	53.5	0.8
	SKZ	GOOD	43.0	1.1	45.0	1.0	48.2	0.9	46.1	0.6
		MOD	43.0	1.1	45.0	1.0	48.1	0.9	49.3	0.7
		POOR	43.7	0.9	46.4	1.0	48.1	0.9	48.2	0.9
ARID LOWVELD	LET	GOOD	42.5	1.3	44.3	1.2	48.3	1.0	48.1	0.9
		MOD	41.7	1.2	47.0	1.2	48.3	1.1	48.5	1.0
		POOR	41.7	1.2	47.0	1.2	48.1	1.1	49.4	1.1
	OSA	GOOD	39.7	1.0	40.1	0.9	45.8	0.9	46.5	0.6
		MOD	39.8	0.9	41.4	0.9	45.6	0.9	46.8	0.9
		POOR	38.8	0.9	41.4	0.9	45.2	0.9	47.4	0.8
	SAT	GOOD	45.1	1.2	46.2	1.0	51.4	0.9	52.3	0.7
		MOD	44.4	1.0	47.9	1.0	51.1	0.9	53.1	0.9
		POOR	44.4	1.0	47.9	1.0	51.8	0.9	51.8	0.9
	SHM	GOOD	42.9	1.3	44.9	1.2	48.3	1.0	48.4	0.8
		MOD	42.2	1.2	47.6	1.2	48.4	1.0	47.9	1.0
		POOR	42.2	1.2	47.6	1.2	48.1	1.0	49.6	1.1
	SKZ	GOOD	43.0	1.1	45.0	1.0	48.1	0.9	49.3	0.7
		MOD	43.7	0.9	46.4	1.0	48.1	0.9	48.2	0.9
		POOR	43.7	0.9	46.4	1.0	48.1	0.9	48.0	0.9
	TAL	GOOD	42.4	1.2	43.2	1.0	48.0	0.9	48.3	0.7
		MOD	41.7	1.0	44.8	1.0	47.9	0.9	48.0	0.9
		POOR	41.7	1.0	44.8	1.0	47.9	0.9	48.0	0.9
MOPANI VELD	LET	GOOD	42.5	1.3	44.3	1.2	48.3	1.0	48.1	0.9
		MOD	41.7	1.2	47.0	1.2	48.3	1.1	48.5	1.0
		POOR	41.7	1.2	47.0	1.2	48.1	1.1	49.4	1.1
	MOP	GOOD	44.7	1.3	46.4	1.2	49.9	1.1	50.9	0.9
		MOD	43.5	1.2	49.3	1.2	49.9	1.1	50.0	1.0
		POOR	43.5	1.2	49.3	1.2	49.6	1.1	51.2	1.1
	PAP	GOOD	41.3	1.5	41.7	1.3	45.0	1.2	46.6	1.0
		MOD	40.2	1.3	43.2	1.3	44.8	1.2	46.0	1.1
		POOR	40.2	1.3	43.2	1.3	44.2	1.2	47.4	1.2
	PUN	GOOD	45.9	1.5	48.0	1.3	51.4	1.2	51.7	1.0
		MOD	46.4	1.3	49.7	1.3	51.5	1.2	51.0	1.1
		POOR	46.4	1.3	49.7	1.3	51.1	1.2	53.3	1.2
	SHI	GOOD	41.1	1.4	41.6	1.2	45.9	1.1	47.6	0.9
		MOD	39.9	1.2	43.3	1.2	45.5	1.1	48.4	1.0
		POOR	39.9	1.2	43.3	1.2	45.1	1.1	47.1	1.1
	SHM	GOOD	42.9	1.3	44.9	1.2	48.3	1.0	48.4	0.8
		MOD	42.2	1.2	47.6	1.2	48.4	1.0	47.9	1.0
		POOR	42.2	1.2	47.6	1.2	48.1	1.0	49.6	1.1
	SIR	GOOD	44.0	1.5	44.0	1.3	49.2	1.1	50.8	0.9
		MOD	42.5	1.3	45.4	1.3	49.0	1.1	50.2	1.1
		POOR	42.5	1.3	45.4	1.3	48.6	1.1	50.7	1.2

BDL = Berg en dal; LET = Letaba; OSA = Lower Sabie; MOP = Mopani; PAP = Pafuri police station; PRE = Pretoriuskop; PUN = Punda Maria; SAT = Satara; SHI = Shingwedzi; SHM = Shimuwini; SIR = Sirheni; SKZ = Skukuza; TAL = Talamati.

Table A20. Curve Numbers (CN) for the calculation of surface runoff (RO) from veld in good, moderate or poor condition on different soil texture classes. All values determined according to the procedures of Allen *et al.* (1996) [-]

SOIL TEXTURE CLASS	CN NUMBER FOR VELD CONDITION CLASS		
	GOOD	MODERATE	POOR
CLAY	79	82	86
LOAM	58	65	73
SAND	35	43	57
LOAMY SAND	35	43	57
SANDY LOAM	35	43	57
SILTY LOAM	58	65	73
SANDY CLAY LOAM	72	76	82
CLAY LOAM	79	82	86
SILTY CLAY LOAM	79	82	86
SANDY CLAY	79	82	86
SILTY CLAY	79	82	86

Table A21. Total available soil water of the root zone (TAW) (= $1000(\theta_{FC} - \theta_{WP})*Z_r$) [mm]

SOIL TEXTURE CLASS	BASALT			GRANITE		
	GOOD	MODERATE	POOR	GOOD	MODERATE	POOR
CLAY	70.0	35.00	14.0	84.0	42.0	21.0
LOAM	65.0	32.50	13.0	78.0	39.0	19.5
SAND	37.5	18.75	7.5	45.0	22.5	11.3
LOAMY SAND	42.5	21.25	8.5	51.0	25.5	12.8
SANDY LOAM	60.0	30.00	12.0	72.0	36.0	18.0
SILTY LOAM	70.0	35.00	14.0	84.0	42.0	21.0
SANDY CLAY LOAM	47.5	23.75	9.5	57.0	28.5	14.3
CLAY LOAM	58.5	29.25	11.7	70.0	35.0	17.6
SILTY CLAY LOAM	65.0	32.50	13.0	78.0	39.0	19.5
SANDY CLAY	47.5	23.75	9.5	57.0	28.5	14.3
SILTY CLAY	65.0	32.50	13.0	78.0	39.0	19.5

Table A22. Estimated effective rooting depth (Z_r); i.e. depth where ≥80% of the root mass is located [m]

GEOLOGY	VELD CONDITION		
	GOOD	MODERATE	POOR
BASALT	0.50	0.25	0.10
GRANITE	0.60	0.30	0.15

Table A23. Readily available soil water of the root zone, RAW (= p*TAW) [mm]

SOIL TEXTURE CLASS	BASALT GOOD	 MODERATE	 POOR	GRANITE GOOD	 MODERATE	 POOR
CLAY	37.8	18.9	7.6	45.4	22.7	11.3
LOAM	39.0	19.5	7.8	46.8	23.4	11.7
SAND	24.8	12.4	5.0	29.7	14.9	7.5
LOAMY SAND	27.6	13.8	5.5	33.2	16.6	8.3
SANDY LOAM	37.8	18.9	7.6	45.4	22.7	11.3
SILTY LOAM	42.0	21.0	8.4	50.4	25.2	12.6
SANDY CLAY LOAM	28.5	14.3	5.7	34.2	17.1	8.6
CLAY LOAM	35.1	17.7	7.0	42.0	21.0	10.6
SILTY CLAY LOAM	39.0	19.5	7.8	46.8	23.4	11.7
SANDY CLAY	27.1	13.5	5.4	32.5	16.3	8.2
SILTY CLAY	36.4	18.2	7.3	43.7	21.8	10.9

Table A24. Average depletion fraction (p) of TAW that can be depleted from the root zone before moisture stress (reduction in ET) occurs. For fine-textured soils, p is reduced by 5-10%, increased by 5-10% for coarse soils, and unchanged for medium textured soils (Allen *et al.* 1998). Default value of p for extensive grazing is 0.60 (Allen *et al.* 1998) [-]

	TEXTURE GROUP FINE			MEDIUM						COARSE		
TEXTURE CLASS	CLAY	SILTY CLAY	SANDY CLAY	LOAM	SILY LOAM	SILT	CLAY LOAM	SANDY CLAY LOAM	SILTY CLAY LOAM	SANDY LOAM	LOAMY SAND	SAND
% adj.	-10	-7.5	-5	0	0	0	0	0	0	+5	+7.5	+10
p	0.54	0.56	0.57	0.60	0.60	0.60	0.60	0.60	0.60	0.63	0.65	0.66

Table A25. Root zone depletion (i.e. cumulative depth of evapotranspiration from the root zone, $D_{r,\,i-1}$) at the end of day 1 (start of the climatic year, 1 July; i.e. start of daily calculations for the climatic year) [mm]

SOIL TEXTURE CLASS	GEOLOGY AND VELD CONDITION BASALT GOOD	 MODERATE	 POOR	 GRANITE GOOD	 MODERATE	 POOR
CLAY	24.5	12.3	4.9	29.4	14.7	7.4
LOAM	22.8	11.4	4.6	27.3	13.7	6.8
SAND	13.1	6.6	2.6	15.8	7.9	4.0
LOAMY SAND	14.9	7.4	3.0	17.9	8.9	4.5
SANDY LOAM	21.0	12.3	4.2	25.2	12.6	6.3
SILTY LOAM	24.5	12.3	4.9	29.4	14.7	7.4
SANDY CLAY LOAM	16.6	8.3	3.3	20.0	10.0	5.0
CLAY LOAM	20.5	10.2	4.1	24.5	12.3	6.2
SILTY CLAY LOAM	22.8	11.4	4.6	27.3	13.7	6.8
SANDY CLAY	16.6	8.3	3.3	20.0	10.0	5.0
SILTY CLAY	22.8	11.4	4.6	27.3	13.7	6.8

APPENDIX 2

TREE REGRESSION REPORTS

EXPLANATORY NOTES FOR INTERPRETTING THE REPORTS

- In growing a tree, the binary partitioning algorithm recursively splits the data in each mode until either the node is homogenous or the node contains too few observations, ≤5, by default.
- The minimum number of observations used in the analyses is 10, and the minimum deviation calculated is 0.1
- "node), split, n, deviance, yval, *denotes terminal node" This represents the sequence in which the results for each node is given:
  - *"node)"* is the *nth* number node, starting with the root (parent) node, the latter always being the first node.
  - *"split"* partitions the total number of observations
  - *"deviance",* the measure of heterogeneity used in the tree-growing algorithm.
  - *"yval"* The y value at the particular split.
  - *"*denotes terminal node"* Node which is not split, the last node, denoted by an asterisk.

(Mathsoft 1999)

1. NETT PRIMARY PRODUCTION (MEAN DPM HEIGHT)

FIGURE 4.11: PRODUCTION ON BASALT, INCLUDING ET VARIABLES

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Variables actually used in tree construction:
[1] "DAYYR"    "DAYGRO"    "PEREN"
[4] "PH.A"     "THICK.A"   "KS1GRO.2"
Number of terminal nodes:  9
Residual mean deviance:  7.488 = 471.8 / 63
Distribution of residuals:
Min.    1st Qu.        Median Mean          3rd Qu.        Max.
-8.371  -0.8542        0.07    -8.018e-017  1.13           12.93

node), split, n, deviance, yval, * denotes terminal node

 1) root 72 2646.000  7.564
   2) DAYYR<58.45 54  266.400  5.000
     4) DAYGRO<30 38   49.140  4.071
       8) PEREN<22 7    1.769  2.914 *
       9) PEREN>22 31   35.890  4.332
        18) PH.A<6.035 10    3.861  3.630 *
        19) PH.A>6.035 21   24.750  4.667 *
     5) DAYGRO>30 16  106.600  7.206
      10) THICK.A<0.1955 11   40.350  6.064
        20) KS1GRO.2<76.5 5    8.592  4.560 *
        21) KS1GRO.2>76.5 6   11.030  7.317 *
      11) THICK.A>0.1955 5   20.330  9.720 *
   3) DAYYR>58.45 18  960.100 15.260
     6) KS1GRO.2<62 5   38.460  8.300 *
     7) KS1GRO.2>62 13  586.700 17.930
      14) THICK.A<0.1975 7  291.400 21.770 *
      15) THICK.A>0.1975 6   71.570 13.450 *
```

FIGURE 4.11: PRODUCTION ON BASALT, EXCLUDING ET VARIABLES

```
Variables actually used in tree construction:
[1] "DAYYR"   "DAYGRO"  "PEREN"    "PH.A"
[5] "THICK.A" "RFGRO.2"
Number of terminal nodes:  9
Residual mean deviance:  9.324 = 587.4 / 63
Distribution of residuals:
Min.    1st Qu.        Median          Mean          3rd Qu. Max.
```

```
-8.383 -0.7917        -0.02333        -1.172e-016     0.8089  13.72

node), split, n, deviance, yval, * denotes terminal node

 1) root 72 2646.000  7.564
   2) DAYYR<58.45 54  266.400  5.000
     4) DAYGRO<30 38   49.140  4.071
       8) PEREN<22 7    1.769  2.914 *
       9) PEREN>22 31   35.890  4.332
        18) PH.A<6.035 10    3.861  3.630 *
        19) PH.A>6.035 21   24.750  4.667 *
     5) DAYGRO>30 16  106.600  7.206
      10) THICK.A<0.1955 11   40.350  6.064
        20) RFGRO.2<593 5    8.592  4.560 *
        21) RFGRO.2>593 6   11.030  7.317 *
      11) THICK.A>0.1955 5   20.330  9.720 *
   3) DAYYR>58.45 18  960.100 15.260
     6) DAYYR<69.85 12  331.100 12.390
      12) RFGRO.2<354.25 6   67.270  8.883 *
      13) RFGRO.2>354.25 6  116.100 15.900 *
     7) DAYYR>69.85 6  333.700 20.980 *
```

FIGURE 4.12: PRODUCTION ON GRANITE, INCLUDING ET VARIABLES

```
Variables actually used in tree construction:
[1] "RFYR"        "KS1GRO"      "ETDOR"
[4] "BURN.INTER" "DIST.H2O"     "BSFI"
[7] "ETGRO.2"     "SOILFERT"    "DAYYR.3"
Number of terminal nodes:  11
Residual mean deviance:  4.837 = 343.4 / 71
Distribution of residuals:
Min.    1st Qu.         Median          Mean            3rd Qu.         Max.
-6.1    -0.8917         -0.1167         2.437e-017      0.6375          8.36

node), split, n, deviance, yval, * denotes terminal node

  1) root 82 1434.000  6.889
    2) RFYR<489.1 39  124.700  4.149
      4) KS1GRO<77.5 27   37.990  3.289
        8) ETDOR<61.6 7   11.890  4.686 *
        9) ETDOR>61.6 20    7.660  2.800 *
      5) KS1GRO>77.5 12   21.860  6.083
       10) BURN.INTER<0.52 6   12.090  6.817 *
       11) BURN.INTER>0.52 6    3.315  5.350 *
    3) RFYR>489.1 43  751.100  9.374
      6) DIST.H2O<5.4475 35  427.400  8.363
       12) BSFI<2.8829 30  197.700  7.617
         24) RFYR<574.65 14   16.660  6.279
           48) ETGRO.2<296.4 9    7.040  5.733 *
           49) ETGRO.2>296.4 5    2.132  7.260 *
         25) RFYR>574.65 16  134.000  8.788
           50) SOILFERT<3.215 5   42.490 11.480 *
           51) SOILFERT>3.215 11   38.810  7.564
            102) DAYYR.3<53.35 6   11.470  8.967 *
            103) DAYYR.3>53.35 5    1.348  5.880 *
       13) BSFI>2.8829 5  112.800 12.840 *
      7) DIST.H2O>5.4475 8  131.200 13.800 *
```

FIGURE 4.12: PRODUCTION ON GRANITE, EXCLUDING ET VARIABLES

```
Variables actually used in tree construction:
[1] "RFYR"      "RFGRO.1"  "PEREN"
[4] "RFYR.3"    "DIST.H2O" "BSFI"
[7] "DAYDOR"    "SOILFERT" "DAYYR.3"
Number of terminal nodes:  11
Residual mean deviance:  4.882 = 346.6 / 71
Distribution of residuals:
Min.    1st Qu.         Median  Mean            3rd Qu.         Max.
-6.1    -0.955          -0.15   -1.625e-016     0.805           8.36

node), split, n, deviance, yval, * denotes terminal node
  1) root 82 1434.000  6.889
    2) RFYR<489.1 39  124.700  4.149
      4) RFGRO.1<368.3 20   10.410  2.895 *
```

```
      5) RFGRO.1>368.3 19   49.780  5.468
       10) PEREN<75 14   21.370  4.857
         20) RFYR.3<606.75 6    3.813  5.633 *
         21) RFYR.3>606.75 8   11.240  4.275 *
       11) PEREN>75 5    8.528  7.180 *
    3) RFYR>489.1 43  751.100  9.374
      6) DIST.H2O<5.4475 35  427.400  8.363
       12) BSFI<2.8829 30  197.700  7.617
         24) RFYR<574.65 14   16.660  6.279
           48) DAYDOR<16.5 6    4.788  5.717 *
           49) DAYDOR>16.5 8    8.560  6.700 *
         25) RFYR>574.65 16  134.000  8.788
           50) SOILFERT<3.215 5   42.490 11.480 *
           51) SOILFERT>3.215 11   38.810  7.564
            102) DAYYR.3<53.35 6   11.470  8.967 *
            103) DAYYR.3>53.35 5    1.348  5.880 *
       13) BSFI>2.8829 5  112.800 12.840 *
      7) DIST.H2O>5.4475 8  131.200 13.800 *
```

2. NETT STANDING CROP (MEAN DPM HEIGHT)

FIGURE 4.13: STANDING CROP ON BASALT, INCLUDING ET VARIABLES

```
Regression tree:
Variables actually used in tree construction:
 [1] "ETGRO"       "DAYYR"       "PEREN"
 [4] "KS1GRO.1"    "EFF.DPTH"    "RFGRO.3"
 [7] "THICK.A"     "WDYCANO"     "RFYR.1"
[10] "BURN.INTER"  "KSZGRO.3"    "BULKMAS.2"
[13] "ORG.CARBON"  "RFGRO.1"     "RFYR"
[16] "MIXMAS.1"    "CONCMAS"     "KS1GRO.2"
[19] "ETGRO.2"     "DAYDOR"      "DAYYR.2"
[22] "BURN.FREQ"   "BULKMAS.1"   "SKURT"
[25] "VAR"         "KS1GRO.3"
Number of terminal nodes:  34
Residual mean deviance:  5.738 = 1957 / 341
Distribution of residuals:
Min.           1st Qu.        Median Mean        3rd Qu.        Max.
 -7.817        -1.352         -0.052 1.125e-016  1.273          6.92

node), split, n, deviance, yval, * denotes terminal node

  1) root 375 10550.000  8.266
    2) ETGRO<203.45 220  2442.000  5.687
      4) DAYYR<36.85 113   676.700  4.412
        8) PEREN<80 91   304.500  3.804
         16) KS1GRO.1<9.5 5    13.290  7.080 *
         17) KS1GRO.1>9.5 86   234.500  3.614
           34) EFF.DPTH<0.565 67   156.700  3.282
             68) RFGRO.3<350.9 50    48.500  2.852 *
             69) RFGRO.3>350.9 17    71.700  4.547 *
           35) EFF.DPTH>0.565 19    44.430  4.784 *
        9) PEREN>80 22   199.400  6.927
         18) THICK.A<0.227 17    91.200  5.853 *
         19) THICK.A>0.227 5    21.830 10.580 *
      5) DAYYR>36.85 107  1388.000  7.033
       10) WDYCANO<57.22 18   371.300 10.040
         20) RFYR.1<233.4 5    86.910 15.180 *
         21) RFYR.1>233.4 13   101.400  8.062 *
       11) WDYCANO>57.22 89   821.400  6.425
         22) BURN.INTER<7.585 56   336.400  5.493
           44) KSZGRO.3<10.5 34    97.760  4.715 *
           45) KSZGRO.3>10.5 22   186.200  6.695
             90) ETGRO<113.2 9     9.309  4.789 *
             91) ETGRO>113.2 13   121.500  8.015
              182) BULKMAS.2<26.18 6    13.850  5.667 *
              183) BULKMAS.2>26.18 7    46.210 10.030 *
         23) BURN.INTER>7.585 33   353.900  8.006
           46) ORG.CARBON<0.285 8    27.120  4.700 *
           47) ORG.CARBON>0.285 25   211.400  9.064
             94) EFF.DPTH<0.585 19   122.700  8.147
              188) RFGRO.1<390.65 14    46.580  7.400 *
              189) RFGRO.1>390.65 5    46.370 10.240 *
```

```
              95) EFF.DPTH>0.585 6    22.190 11.970 *
   3) ETGRO>203.45 155  4564.000 11.930
     6) RFYR<587.4 115  2493.000 10.660
      12) PEREN<84.5 61   982.600  8.659
        24) BURN.INTER<5.63 37   515.900  7.186
          48) MIXMAS.1<56 24   181.200  5.788
            96) CONCMAS<13.7775 14    75.960  6.979 *
            97) CONCMAS>13.7775 10    57.560  4.120 *
          49) MIXMAS.1>56 13   201.000  9.769
            98) KS1GRO.2<67.5 7    28.010  6.814 *
            99) KS1GRO.2>67.5 6    40.570 13.220 *
        25) BURN.INTER>5.63 24   262.800 10.930
          50) RFGRO.1<435.5 19    99.120 10.100 *
          51) RFGRO.1>435.5 5   100.900 14.080 *
      13) PEREN>84.5 54   991.000 12.920
        26) ORG.CARBON<0.16 11   206.000 17.050
          52) ETGRO.2<191.2 6    80.910 14.520 *
          53) ETGRO.2>191.2 5    40.710 20.080 *
        27) ORG.CARBON>0.16 43   549.700 11.860
          54) DAYDOR<6 5   108.300 17.680 *
          55) DAYDOR>6 38   249.900 11.100
           110) DAYYR.2<38.35 9    69.400  9.022 *
           111) DAYYR.2>38.35 29   129.800 11.740
             222) BURN.FREQ<6.89 23    70.450 11.240 *
             223) BURN.FREQ>6.89 6    31.270 13.670 *
     7) RFYR>587.4 40  1356.000 15.570
      14) ETGRO.2<139.25 6   105.400  8.383 *
      15) ETGRO.2>139.25 34   886.200 16.840
        30) BULKMAS.1<220.06 29   618.000 17.980
          60) SKURT<-0.59375 9   118.600 14.370 *
          61) SKURT>-0.59375 20   329.100 19.610
           122) VAR<4.74485 7     8.394 16.430 *
           123) VAR>4.74485 13   212.100 21.320
             246) KS1GRO.3<80.5 5    66.710 24.640 *
             247) KS1GRO.3>80.5 8    55.540 19.240 *
        31) BULKMAS.1>220.06 5    10.100 10.200 *
```

FIGURE 4.14: STANDING CROP ON BASALT, EXCLUDING ET VARIABLES

```
Regression tree:
Variables actually used in tree construction:
 [1] "DAYGRO"     "BURN.INTER" "PEREN"
 [4] "DAYYR"      "EFF.DPTH"   "BARE"
 [7] "CONCMAS.2"  "BULKMAS.3"  "THICK.A"
[10] "RFGRO"      "MIXMAS.1"   "RFGRO.1"
[13] "RFYR"       "ORG.CARBON" "SKURT"
[16] "OTHERS"     "VAR"        "WDYCANO"
[19] "PH.A"       "RFYR.3"     "SSKEW"
[22] "DAYYR.3"
Number of terminal nodes:  34
Residual mean deviance:  5.734 = 1955 / 341
Distribution of residuals:
Min.    1st Qu. Median         Mean           3rd Qu.                Max.
 -6.187 -1.411  0.02857        -7.342e-017    1.292                  11.37

node), split, n, deviance, yval, * denotes terminal node

  1) root 375 10550.000  8.266
    2) DAYGRO<28.5 230  2925.000  5.958
      4) BURN.INTER<8.69 200  2070.000  5.445
        8) PEREN<89.5 187  1408.000  5.125
         16) DAYYR<36.85 105   500.000  4.162
           32) PEREN<72.5 90   275.800  3.823
             64) EFF.DPTH<0.565 67   165.500  3.381
              128) BARE<4.5 39   107.700  3.982
                256) CONCMAS.2<6.3825 15    62.840  4.987 *
                257) CONCMAS.2>6.3825 24    20.220  3.354 *
              129) BARE>4.5 28    24.070  2.543 *
             65) EFF.DPTH>0.565 23    58.930  5.113 *
           33) PEREN>72.5 15   152.000  6.193
             66) BULKMAS.3<16.33 6    42.730  9.267 *
             67) BULKMAS.3>16.33 9    14.820  4.144 *
         17) DAYYR>36.85 82   686.100  6.359
           34) THICK.A<0.222 73   549.800  6.766
             68) PEREN<49.5 59   321.600  6.112
              136) RFGRO<334.05 29    79.420  5.169 *
```

```
              137) RFGRO>334.05 30   191.500  7.023
                274) PEREN<36 18   103.500  7.972 *
                275) PEREN>36 12    47.460  5.600 *
             69) PEREN>49.5 14    96.600  9.521 *
           35) THICK.A>0.222 9    26.060  3.056 *
        9) PEREN>89.5 13   367.800 10.040
         18) MIXMAS.1<85.75 7   192.000 13.230 *
         19) MIXMAS.1>85.75 6    21.390  6.317 *
      5) BURN.INTER>8.69 30   451.300  9.380
       10) DAYGRO<24.5 18   139.100  7.239
         20) RFGRO.1<345.1 10    60.300  5.570 *
         21) RFGRO.1>345.1 8    16.180  9.325 *
       11) DAYGRO>24.5 12   105.800 12.590
         22) BULKMAS.3<95.075 7    20.650 14.330 *
         23) BULKMAS.3>95.075 5    34.510 10.160 *
    3) DAYGRO>28.5 145  4453.000 11.930
      6) RFYR<580.5 99  2310.000 10.520
       12) BARE<0.5 73  1515.000 11.890
         24) ORG.CARBON<0.16 16   340.600 15.990
           48) SKURT<-0.3829 8   114.000 12.890 *
           49) SKURT>-0.3829 8    72.890 19.090 *
         25) ORG.CARBON>0.16 57   830.000 10.740
           50) MIXMAS.1<58 35   264.900  9.426
            100) OTHERS<5.5 21    99.710 10.860 *
            101) OTHERS>5.5 14    56.890  7.271 *
           51) MIXMAS.1>58 22   408.800 12.830
            102) BURN.INTER<5.06 14   162.400 10.910
              204) SKURT<-0.68685 8    95.890 12.390 *
              205) SKURT>-0.68685 6    25.980  8.950 *
            103) BURN.INTER>5.06 8   105.600 16.180 *
       13) BARE>0.5 26   274.400  6.677
         26) VAR<5.7334 21   140.700  5.600
           52) PEREN<69 12    47.170  4.192 *
           53) PEREN>69 9    38.040  7.478 *
         27) VAR>5.7334 5     7.020 11.200 *
      7) RFYR>580.5 46  1526.000 14.950
       14) PEREN<75.5 22   513.900 11.970
         28) WDYCANO<144.625 17   279.700 13.660
           56) PH.A<6.28 8   120.200 16.270 *
           57) PH.A>6.28 9    56.540 11.340 *
         29) WDYCANO>144.625 5    20.050  6.220 *
       15) PEREN>75.5 24   638.100 17.680
         30) RFYR.3<561.2 18   315.200 19.600
           60) SSKEW<-0.06015 13   133.000 18.030
            120) DAYYR.3<39.85 8     6.089 16.010 *
            121) DAYYR.3>39.85 5    42.190 21.260 *
           61) SSKEW>-0.06015 5    66.990 23.680 *
         31) RFYR.3>561.2 6    58.370 11.930 *
```

FIGURE 4.15: STANDING CROP ON GRANITE, INCLUDING ET VARIABLES

```
Regression tree:
Variables actually used in tree construction:
 [1] "RFYR.1"     "RFYR"       "FORBS"
 [4] "PEREN"      "KS1GRO.1"   "BULKMAS.1"
 [7] "CONCMAS.3"  "AVGKSGRO"   "KSZGRO.2"
[10] "MIXMAS.2"   "KS1GRO"     "ANN"
[13] "BURN.INTER" "DAYYR.1"    "PH.A"
[16] "MIXMAS.1"   "MIXMAS.3"   "ETGRO.1"
Number of terminal nodes:  27
Residual mean deviance:  1.84 = 504.2 / 274
Distribution of residuals:
Min.    1st Qu. Median          Mean          3rd Qu.        Max.
-3.86   -0.8154 -0.1125         1.918e-016    0.776          4.033

node), split, n, deviance, yval, * denotes terminal node

  1) root 301 4336.000  6.310
    2) RFYR.1<556.3 209 1263.000  4.800
      4) RFYR<364.45 68   86.840  2.987
        8) FORBS<10.5 26   34.270  3.715 *
        9) FORBS>10.5 42   30.220  2.536 *
      5) RFYR>364.45 141  845.200  5.674
       10) PEREN<22.5 21   21.810  2.948 *
       11) PEREN>22.5 120  639.900  6.152
         22) KS1GRO.1<59.5 46  136.800  5.061
```

```
          44) BULKMAS.1<157.615 39   89.330  4.674
            88) CONCMAS.3<7.045 7    9.594  3.171 *
            89) CONCMAS.3>7.045 32   60.470  5.003
             178) AVGKSGRO<0.285 7    6.417  6.357 *
             179) AVGKSGRO>0.285 25   37.630  4.624 *
          45) BULKMAS.1>157.615 7    9.169  7.214 *
        23) KS1GRO.1>59.5 74  414.400  6.830
          46) KSZGRO.2<2.5 61  276.900  6.389
            92) CONCMAS.3<16.99 31  144.300  7.358
             184) MIXMAS.2<105.75 22   50.940  6.377
               368) PEREN<66.5 11   29.700  5.573 *
               369) PEREN>66.5 11    6.996  7.182 *
             185) MIXMAS.2>105.75 9   20.460  9.756 *
            93) CONCMAS.3>16.99 30   73.350  5.387
             186) KS1GRO<69.5 6    3.708  3.283 *
             187) KS1GRO>69.5 24   36.470  5.912 *
          47) KSZGRO.2>2.5 13   69.880  8.900
            94) KS1GRO<91.5 7   21.380  7.643 *
            95) KS1GRO>91.5 6   24.530 10.370 *
   3) RFYR.1>556.3 92 1514.000  9.739
     6) KS1GRO<80.5 35  286.800  7.000
      12) ANN<6.5 23  119.600  8.435
        24) BURN.INTER<2.535 5    2.188  5.720 *
        25) BURN.INTER>2.535 18   70.360  9.189
          50) RFYR<460.85 13   46.490  8.531
           100) DAYYR.1<70.15 7   10.830  7.471 *
           101) DAYYR.1>70.15 6   18.630  9.767 *
          51) RFYR>460.85 5    3.600 10.900 *
      13) ANN>6.5 12   29.110  4.250 *
     7) KS1GRO>80.5 57  803.300 11.420
      14) BURN.INTER<0.785 6    2.313  5.967 *
      15) BURN.INTER>0.785 51  601.400 12.060
        30) PH.A<6.06 46  429.400 12.620
          60) PH.A<5.725 40  287.300 12.030
           120) MIXMAS.1<210 34  200.200 11.440
             240) PH.A<5.37 17   62.880 10.240
               480) MIXMAS.3<31.5 6   17.630 11.830 *
               481) MIXMAS.3>31.5 11   21.570  9.364 *
             241) PH.A>5.37 17   88.380 12.640
               482) ETGRO.1<267.65 7    7.397 14.740 *
               483) ETGRO.1>267.65 10   28.120 11.160 *
           121) MIXMAS.1>210 6    8.233 15.370 *
          61) PH.A>5.725 6   34.490 16.570 *
        31) PH.A>6.06 5   27.710  6.960 *
```

FIGURE 4.16: STANDING CROP ON GRANITE, EXCLUDING ET VARIABLES

```
Regression tree:
Variables actually used in tree construction:
 [1] "RFYR.1"     "RFYR"       "FORBS"
 [4] "PEREN"      "BULKMAS.1"  "BSFI"
 [7] "CLAY"       "DAYGRO.3"   "MIXMAS.2"
[10] "ORG.CARBON" "RFGRO"      "ANN"
[13] "BURN.INTER" "SSKEW"      "PH.A"
[16] "MIXMAS.1"   "BULKMAS.3"  "MIXMAS"
[19] "DAYGRO.1"
Number of terminal nodes:  25
Residual mean deviance:  2.147 = 592.7 / 276
Distribution of residuals:
Min.           1st Qu.        Median  Mean          3rd Qu.        Max.
 -5.886        -0.8357        -0.1143 9.738e-017    0.7846         5.014

node), split, n, deviance, yval, * denotes terminal node

  1) root 301 4336.000  6.310
    2) RFYR.1<556.3 209 1263.000  4.800
      4) RFYR<364.45 68   86.840  2.987
        8) FORBS<10.5 26   34.270  3.715 *
        9) FORBS>10.5 42   30.220  2.536 *
      5) RFYR>364.45 141  845.200  5.674
       10) PEREN<22.5 21   21.810  2.948 *
       11) PEREN>22.5 120  639.900  6.152
         22) RFYR.1<384.05 64  227.800  5.406
           44) BULKMAS.1<140.09 55  135.100  4.975
             88) BSFI<2.56 42   84.540  4.548
              176) CLAY<29.5 32   48.710  4.919
```

```
               352) DAYGRO.3<45 22   22.370  4.541 *
               353) DAYGRO.3>45 10   16.280  5.750 *
             177) CLAY>29.5 10   17.320  3.360 *
            89) BSFI>2.56 13   18.150  6.354 *
          45) BULKMAS.1>140.09 9   19.840  8.044 *
        23) RFYR.1>384.05 56  335.900  7.004
          46) BULKMAS.1<53.3775 29  201.800  7.934
            92) MIXMAS.2<83.25 21   95.320  6.929
             184) ORG.CARBON<0.66 11   41.050  5.764 *
             185) ORG.CARBON>0.66 10   22.930  8.210 *
            93) MIXMAS.2>83.25 8   29.490 10.580 *
          47) BULKMAS.1>53.3775 27   81.930  6.004
            94) BSFI<2.075 14   32.780  7.021 *
            95) BSFI>2.075 13   19.030  4.908 *
   3) RFYR.1>556.3 92 1514.000  9.739
     6) RFGRO<306.4 27  205.300  6.689
      12) ANN<9.5 17   88.020  8.088
        24) BURN.INTER<2.535 5    2.188  5.720 *
        25) BURN.INTER>2.535 12   46.100  9.075
          50) SSKEW<-0.24465 6    8.348 10.580 *
          51) SSKEW>-0.24465 6   10.450  7.567 *
      13) ANN>9.5 10   27.450  4.310 *
     7) RFGRO>306.4 65  953.000 11.010
      14) BURN.INTER<0.785 7    9.357  5.557 *
      15) BURN.INTER>0.785 58  710.800 11.660
        30) PH.A<6.04 52  507.500 12.250
          60) PH.A<5.73 45  342.500 11.730
           120) MIXMAS.1<210 39  242.700 11.170
             240) BULKMAS.3<50.945 21  102.700  9.976
               480) MIXMAS<29.25 7   11.510 12.210 *
               481) MIXMAS>29.25 14   38.550  8.857 *
             241) BULKMAS.3>50.945 18   75.260 12.560
               482) DAYGRO.1<46.5 7   23.140 14.200 *
               483) DAYGRO.1>46.5 11   21.360 11.520 *
           121) MIXMAS.1>210 6    8.233 15.370 *
          61) PH.A>5.73 7   74.910 15.590 *
        31) PH.A>6.04 6   31.600  6.600 *
```

3. COMPOSITION

FIGURE 4.17: PERENNIALS ON BASALT, INCLUDING ET VARIABLES

```
Regression tree:
Variables actually used in tree construction:
 [1] "ETGRO"      "KS1GRO"     "CONCMAS.1"
 [4] "RFYR"       "PH.A"       "CONCMAS"
 [7] "RFGRO.1"    "RFDOR"      "MIXMAS"
[10] "RFGRO.3"    "ETGRO.1"    "ETGRO.3"
[13] "DIST.H2O"   "KS1GRO.3"   "AVGKSGRO.2"
[16] "AVGKSGRO.1"
Number of terminal nodes:  21
Residual mean deviance:  75.35 = 26970 / 358
Distribution of residuals:
Min.    1st Qu         Median         Mean           3rd Qu.        Max.
-23     -5.947         0.5            1.237e-015     6.057          23.06

node), split, n, deviance, yval, * denotes terminal node

 1) root 379 315300.0 56.780
   2) ETGRO<180.05 202 108400.0 36.970
     4) KS1GRO<9.5 19   3800.0 82.000
       8) CONCMAS.1<49.45 14    885.4 88.430 *
       9) CONCMAS.1>49.45 5    716.0 64.000 *
     5) KS1GRO>9.5 183  62090.0 32.300
      10) ETGRO<121.4 106  18590.0 21.320
        20) RFYR<211.25 12   3433.0 43.920
          40) PH.A<6.845 7    527.4 55.290 *
          41) PH.A>6.845 5    734.0 28.000 *
        21) RFYR>211.25 94   8251.0 18.440
          42) CONCMAS<4.06 35   2466.0 22.940 *
          43) CONCMAS>4.06 59   4653.0 15.760
            86) RFGRO.1<161.65 16    443.8  9.375 *
            87) RFGRO.1>161.65 43   3313.0 18.140
             174) RFGRO.1<297.8 19    780.9 23.950 *
```

```
              175) RFGRO.1>297.8 24   1384.0 13.540 *
       11) ETGRO>121.4 77  13160.0 47.400
         22) RFDOR<44 7   1064.0 75.570 *
         23) RFDOR>44 70   5983.0 44.590
           46) MIXMAS<132.75 55   3755.0 46.380
             92) RFGRO.3<340.05 35   2069.0 43.740 *
             93) RFGRO.3>340.05 20   1016.0 51.000 *
           47) MIXMAS>132.75 15   1400.0 38.000 *
    3) ETGRO>180.05 177  37100.0 79.400
      6) ETGRO.1<205 82  19180.0 72.590
       12) ETGRO<217.95 14   1672.0 49.500 *
       13) ETGRO>217.95 68   8509.0 77.340
         26) ETGRO.3<111.75 10    674.5 65.500 *
         27) ETGRO.3>111.75 58   6192.0 79.380
           54) CONCMAS<53.275 49   4368.0 81.390
            108) DIST.H2O<3.231 17    918.9 75.060 *
            109) DIST.H2O>3.231 32   2406.0 84.750 *
           55) CONCMAS>53.275 9    550.2 68.440 *
      7) ETGRO.1>205 95  10840.0 85.270
       14) KS1GRO.3<60.5 40   4687.0 80.150
         28) AVGKSGRO.2<0.355 19   1660.0 75.630 *
         29) AVGKSGRO.2>0.355 21   2288.0 84.240 *
       15) KS1GRO.3>60.5 55   4340.0 89.000
         30) AVGKSGRO.1<0.445 20   1888.0 83.300 *
         31) AVGKSGRO.1>0.445 35   1431.0 92.260 *
```

FIGURE 4.18: PERENNIALS ON BASALT, EXCLUDING ET VARIABLES

```
Regression tree:
Variables actually used in tree construction:
 [1] "DAYDOR"     "DAYGRO.1"   "RFGRO"
 [4] "DAYYR.1"    "MIXMAS.2"   "CCFI"
 [7] "THICK.A"    "RFYR"       "SKURT"
[10] "DAYYR"      "DAYGRO.2"   "DAYGRO"
[13] "PH.A"       "BURN.INTER" "DAYGRO.3"
[16] "MIXMAS"     "SSKEW"      "CONCMAS.3"
Number of terminal nodes:  25
Residual mean deviance:  116.1 = 41090 / 354
Distribution of residuals:
Min.    1st Qu.        Median         Mean           3rd Qu.        Max.
-38     -6.811         -0.5625        -2.737e-015    6.361          40

node), split, n, deviance, yval, * denotes terminal node

  1) root 379 315300.0 56.78
    2) DAYDOR<11.5 245 152400.0 69.11
      4) DAYGRO.1<18.5 65  32900.0 38.92
        8) RFGRO<343.9 48  15240.0 29.88
         16) DAYYR.1<37.25 40   5726.0 25.05
           32) RFGRO<261.05 21   1815.0 31.43 *
           33) RFGRO>261.05 19   2112.0 18.00 *
         17) DAYYR.1>37.25 8   3922.0 54.00 *
        9) RFGRO>343.9 17   2636.0 64.47 *
      5) DAYGRO.1>18.5 180  38930.0 80.01
       10) DAYGRO.1<24.5 59  13620.0 70.64
         20) DAYDOR<6.5 31   2940.0 79.94 *
         21) DAYDOR>6.5 28   5036.0 60.36
           42) MIXMAS.2<42.5 18   1975.0 54.22 *
           43) MIXMAS.2>42.5 10   1164.0 71.40 *
       11) DAYGRO.1>24.5 121  17610.0 84.58
         22) CCFI<2.3989 9   1960.0 66.78 *
         23) CCFI>2.3989 112  12570.0 86.01
           46) THICK.A<0.111 5    165.2 68.40 *
           47) THICK.A>0.111 107  10780.0 86.83
             94) RFYR<269.05 13   1347.0 78.92 *
             95) RFYR>269.05 94   8508.0 87.93
              190) SKURT<-0.98725 9   1082.0 77.22 *
              191) SKURT>-0.98725 85   6287.0 89.06
                382) DAYYR<73.55 80   4623.0 89.80
                  764) DAYGRO.2<24 19   1194.0 83.89 *
                  765) DAYGRO.2>24 61   2560.0 91.64 *
                383) DAYYR>73.55 5    916.8 77.20 *
    3) DAYDOR>11.5 134  57580.0 34.25
      6) DAYGRO<28.5 111  30660.0 29.32
       12) DAYGRO.1<21.5 45   7774.0 21.00
         24) PH.A<6.925 31   5268.0 25.29
```

```
           48) BURN.INTER<3.6 15   2356.0 32.47 *
           49) BURN.INTER>3.6 16   1416.0 18.56 *
         25) PH.A>6.925 14    671.5 11.50 *
       13) DAYGRO.1>21.5 66  17650.0 35.00
         26) DAYGRO<15.5 21   6226.0 23.76
           52) DAYGRO.3<23 15   1631.0 15.33 *
           53) DAYGRO.3>23 6    864.8 44.83 *
         27) DAYGRO>15.5 45   7530.0 40.24
           54) MIXMAS<155.25 34   4060.0 43.65
            108) SSKEW<-0.28145 27   2927.0 40.96 *
            109) SSKEW>-0.28145 7    188.0 54.00 *
           55) MIXMAS>155.25 11   1860.0 29.73 *
      7) DAYGRO>28.5 23  11250.0 58.00
       14) DAYGRO<47 16   5747.0 48.25
         28) CONCMAS.3<9.67 11   1982.0 57.27 *
         29) CONCMAS.3>9.67 5    899.2 28.40 *
       15) DAYGRO>47 7    509.4 80.29 *
```

FIGURE 4.19: PERENNIALS ON GRANITE, INCLUDING ET VARIABLES

```
Regression tree:
Variables actually used in tree construction:
 [1] "ETGRO"      "KSZGRO"     "RFGRO.1"
 [4] "CONCMAS.2"  "CONCMAS"    "VAR"
 [7] "MIXMAS.1"   "CCFI"       "DAYYR.2"
[10] "KS1GRO"     "SKURT"      "AVGKSGRO.3"
[13] "EFF.DPTH"   "RFDOR"      "DAYGRO.1"
[16] "CONCMAS.1"  "CFVAR"      "AVGKSGRO"
Number of terminal nodes:  23
Residual mean deviance:  59.86 = 16700 / 279
Distribution of residuals:
Min.   1st Qu.        Median         Mean           3rd Qu.        Max.
-26.4  -4.551         -0.03333       -2.106e-015    4.761          23

node), split, n, deviance, yval, * denotes terminal node

  1) root 302 145700.0 50.43
    2) ETGRO<193.1 127  35250.0 32.21
      4) KSZGRO<0.5 56  13680.0 43.04
        8) RFGRO.1<481.05 49   7575.0 46.78
         16) CONCMAS.2<54.62 44   3748.0 49.39
           32) CONCMAS<38.51 39   2560.0 47.72
             64) VAR<5.05395 26   1006.0 44.54 *
             65) VAR>5.05395 13    764.9 54.08 *
           33) CONCMAS>38.51 5    233.2 62.40 *
         17) CONCMAS.2>54.62 5    886.8 23.80 *
        9) RFGRO.1>481.05 7    618.9 16.86 *
      5) KSZGRO>0.5 71   9838.0 23.68
       10) ETGRO<143.4 53   3260.0 20.38
         20) MIXMAS.1<81 33   2233.0 22.70
           40) CCFI<1.70145 24    848.6 20.12 *
           41) CCFI>1.70145 9    802.2 29.56 *
         21) MIXMAS.1>81 20    556.9 16.55 *
       11) ETGRO>143.4 18   4302.0 33.39
         22) DAYYR.2<43.5 10    806.0 45.00 *
         23) DAYYR.2>43.5 8    462.9 18.88 *
    3) ETGRO>193.1 175  37750.0 63.65
      6) ETGRO<266.8 91  20300.0 57.22
       12) KS1GRO<56.5 25   2278.0 73.44
         24) SKURT<-0.14605 5    662.8 62.20 *
         25) SKURT>-0.14605 20    825.8 76.25 *
       13) KS1GRO>56.5 66   8957.0 51.08
         26) AVGKSGRO.3<0.545 55   3704.0 47.55
           52) EFF.DPTH<0.445 26   1310.0 43.62 *
           53) EFF.DPTH>0.445 29   1632.0 51.07
            106) RFDOR<64.8 14    317.2 55.36 *
            107) RFDOR>64.8 15    816.9 47.07 *
         27) AVGKSGRO.3>0.545 11   1140.0 68.73 *
      7) ETGRO>266.8 84   9606.0 70.62
       14) DAYYR.2<74.05 77   6734.0 71.95
         28) DAYGRO.1<23.5 5    881.2 57.40 *
         29) DAYGRO.1>23.5 72   4721.0 72.96
           58) CONCMAS.1<47.4 66   3797.0 72.05
            116) CONCMAS.1<14.575 26   1649.0 75.23
              232) CFVAR<34.2432 14    526.4 79.79 *
              233) CFVAR>34.2432 12    492.9 69.92 *
```

```
          117) CONCMAS.1>14.575 40   1713.0 69.97
            234) AVGKSGRO<0.535 29   1107.0 72.10 *
            235) AVGKSGRO>0.535 11    128.5 64.36 *
         59) CONCMAS.1>47.4 6    264.0 83.00 *
       15) DAYYR.2>74.05 7   1240.0 56.00 *
```

FIGURE 4.20: PERENNIALS ON GRANITE, EXCLUDING ET VARIABLES

```
Regression tree:
Variables actually used in tree construction:
 [1] "DAYDOR"     "RFGRO.1"    "DAYGRO"
 [4] "RFYR.1"     "DAYYR.2"    "BURN.INTER"
 [7] "RFDOR"      "BULKMAS.3"  "DAYYR.3"
[10] "BULKMAS.1"  "BURN.FREQ"  "SSKEW"
[13] "RFGRO"      "MIXMAS.2"   "DAYYR"
[16] "MIXMAS"     "THICK.A"    "EFF.DPTH"
[19] "BSFI"       "PH.A"       "SKURT"
[22] "CONCMAS.3"  "BULKMAS"
Number of terminal nodes:  31
Residual mean deviance:  71.35 = 19330 / 271
Distribution of residuals:
Min.    1st Qu.         Median  Mean          3rd Qu.        Max.
-27.42  -5.457          0       -1.506e-015   5.449          23.53

node), split, n, deviance, yval, * denotes terminal node

  1) root 302 145700.00 50.43
    2) DAYDOR<10.5 139  49470.00 60.83
      4) RFGRO.1<189.7 16   2009.00 24.94
        8) DAYGRO<14 6     80.83 13.83 *
        9) DAYGRO>14 10    744.40 31.60 *
      5) RFGRO.1>189.7 123  24170.00 65.50
       10) RFYR.1<476 62  11820.00 59.32
         20) DAYYR.2<69.65 53   8912.00 56.68
           40) DAYDOR<9.5 46   6473.00 59.17
             80) BURN.INTER<2.525 18   1038.00 65.72 *
             81) BURN.INTER>2.525 28   4167.00 54.96
              162) RFDOR<37.15 5    163.20 70.40 *
              163) RFDOR>37.15 23   2553.00 51.61
                326) BULKMAS.3<46.955 9    338.00 43.67 *
                327) BULKMAS.3>46.955 14   1283.00 56.71 *
           41) DAYDOR>9.5 7    271.40 40.29 *
         21) DAYYR.2>69.65 9    360.90 74.89 *
       11) RFYR.1>476 61   7581.00 71.77
         22) DAYYR.3<58.7 28   1749.00 76.96
           44) BULKMAS.1<25.4175 9    420.00 84.33 *
           45) BULKMAS.1>25.4175 19    608.70 73.47 *
         23) DAYYR.3>58.7 33   4436.00 67.36
           46) BURN.FREQ<6.96 28   2429.00 70.14
             92) DAYYR.3<71.9 17   1338.00 65.71 *
             93) DAYYR.3>71.9 11    240.00 77.00 *
           47) BURN.FREQ>6.96 5    578.80 51.80 *
    3) DAYDOR>10.5 163  68430.00 41.56
      6) DAYGRO<38.5 119  32420.00 35.13
       12) SSKEW<-0.39835 21   3587.00 49.52
         24) RFGRO<310 8   1518.00 39.62 *
         25) RFGRO>310 13    803.10 55.62 *
       13) SSKEW>-0.39835 98  23550.00 32.04
         26) MIXMAS.2<20.25 28   4642.00 40.64
           52) DAYYR<29.05 8    756.00 29.00 *
           53) DAYYR>29.05 20   2368.00 45.30
            106) MIXMAS<45 8    222.00 53.50 *
            107) MIXMAS>45 12   1250.00 39.83 *
         27) MIXMAS.2>20.25 70  16000.00 28.60
           54) THICK.A<0.259 56  10350.00 25.59
            108) EFF.DPTH<0.385 39   7062.00 29.56
              216) BSFI<1.9552 6    821.30 15.33 *
              217) BSFI>1.9552 33   4804.00 32.15
                434) PH.A<5.065 9    670.20 22.44 *
                435) PH.A>5.065 24   2968.00 35.79
                  870) SKURT<-0.22325 12    583.70 29.17 *
                  871) SKURT>-0.22325 12   1331.00 42.42 *
            109) EFF.DPTH>0.385 17   1262.00 16.47 *
           55) THICK.A>0.259 14   3113.00 40.64
            110) MIXMAS.2<63 6    180.80 24.83 *
            111) MIXMAS.2>63 8    308.00 52.50 *
```

```
7) DAYGRO>38.5 44  17740.00 58.98
 14) RFDOR<167.7 26   2106.00 72.35
   28) CONCMAS.3<31.265 16   1465.00 75.69
     56) DAYYR<57.4 11    822.70 79.55 *
     57) DAYYR>57.4 5    118.80 67.20 *
   29) CONCMAS.3>31.265 10    176.00 67.00 *
 15) RFDOR>167.7 18   4272.00 39.67
   30) BULKMAS<35.7875 8    362.90 50.88 *
   31) BULKMAS>35.7875 10   2100.00 30.70
     62) RFGRO<335.85 5    279.20 42.60 *
     63) RFGRO>335.85 5    404.80 18.80 *
```

FIGURE 4.21: DECREASERS ON BASALT, INCLUDING ET VARIABLES

```
Regression tree:
Variables actually used in tree construction:
 [1] "DAYYR.2"    "ETGRO"      "ETGRO.1"
 [4] "BURN.FREQ" "KSZGRO"     "MIXMAS"
 [7] "ETGRO.2"    "EFF.DPTH"   "CONCMAS"
[10] "BSFI"       "WDYCANO"    "ETDOR"
[13] "VAR"        "DIST.H2O"   "RFGRO"
[16] "CONCMAS.3" "BULKMAS.1" "RFYR.2"
[19] "KS1GRO.3"   "BULKMAS"    "AVGKSGRO"
[22] "DAYGRO.1"   "CONCMAS.1" "KS1GRO.2"
[25] "CLAY"       "MIXMAS.1"   "SSKEW"
Number of terminal nodes:  31
Residual mean deviance:  121.9 = 42420 / 348
Distribution of residuals:
Min.    1st Qu.        Median          Mean          3rd Qu.        Max.
-47.5   -6.174         -1.19           4.593e-016    5.536          45.67

node), split, n, deviance, yval,* denotes terminal node

  1) root 379 252100.0 27.370
    2) DAYYR.2<61.3 329 152200.0 22.270
      4) ETGRO<177.35 183  32940.0 12.390
        8) ETGRO.1<185.7 152  18110.0  9.947
         16) BURN.FREQ<4.01 8   3568.0 31.000 *
         17) BURN.FREQ>4.01 144  10800.0  8.778
           34) KSZGRO<12.5 58   6060.0 12.710
             68) MIXMAS<12 16   2037.0 18.750 *
             69) MIXMAS>12 42   3216.0 10.400
              138) ETGRO.2<178.35 33   1335.0  8.182 *
              139) ETGRO.2>178.35 9   1120.0 18.560 *
           35) KSZGRO>12.5 86   3240.0  6.128
             70) BURN.FREQ<6.895 66   1936.0  4.576 *
             71) BURN.FREQ>6.895 20   619.8 11.250 *
        9) ETGRO.1>185.7 31   9465.0 24.390
         18) EFF.DPTH<0.535 18   4456.0 15.720
           36) CONCMAS<4.655 5    936.8 34.800 *
           37) CONCMAS>4.655 13    999.1  8.385 *
         19) EFF.DPTH>0.535 13   1787.0 36.380 *
      5) ETGRO>177.35 146  79010.0 34.650
       10) BSFI<2.65225 91  36990.0 27.290
         20) WDYCANO<40.75 8   3874.0 54.500 *
         21) WDYCANO>40.75 83  26620.0 24.660
           42) ETDOR<33.95 21   4242.0 38.760
             84) VAR<4.16445 5   1389.0 53.400 *
             85) VAR>4.16445 16   1446.0 34.190 *
           43) ETDOR>33.95 62  16790.0 19.890
             86) DIST.H2O<5.7565 44  12450.0 23.860
              172) RFGRO<472.05 27   3820.0 17.370
                344) CONCMAS.3<6.835 6    392.0 32.000 *
                345) CONCMAS.3>6.835 21   1777.0 13.190 *
              173) RFGRO>472.05 17   5686.0 34.180
                346) BULKMAS.1<127.462 11   2556.0 42.730
                  692) RFYR.2<375.3 6    983.3 51.330 *
                  693) RFYR.2>375.3 5    595.2 32.400 *
                347) BULKMAS.1>127.462 6    851.5 18.500 *
             87) DIST.H2O>5.7565 18   1936.0 10.170 *
       11) BSFI>2.65225 55  28920.0 46.840
         22) KS1GRO.3<59.5 34  14950.0 38.320
           44) BULKMAS<16.7275 11   3231.0 55.640
             88) AVGKSGRO<0.5 5   770.8 42.800 *
             89) AVGKSGRO>0.5 6   949.3 66.330 *
           45) BULKMAS>16.7275 23   6847.0 30.040
```

```
             90) BULKMAS.1<64.9825 16   3702.0 36.190
              180) DAYGRO.1<21.5 7   1009.0 25.140 *
              181) DAYGRO.1>21.5 9   1176.0 44.780 *
             91) BULKMAS.1>64.9825 7   1160.0 16.000 *
         23) KS1GRO.3>59.5 21   7511.0 60.620
           46) CONCMAS.1<1.7925 7    437.4 78.290 *
           47) CONCMAS.1>1.7925 14   3796.0 51.790
             94) KS1GRO.2<72.5 9    686.2 44.560 *
             95) KS1GRO.2>72.5 5   1793.0 64.800 *
    3) DAYYR.2>61.3 50  34960.0 60.960
      6) CLAY<29.5 6    193.5 11.500 *
      7) CLAY>29.5 44  18090.0 67.700
       14) MIXMAS.1<191.25 38   8001.0 72.660
         28) SSKEW<-0.32055 7    877.7 56.430 *
         29) SSKEW>-0.32055 31   4863.0 76.320
           58) CONCMAS.1<89.23 24   1958.0 81.000 *
           59) CONCMAS.1>89.23 7    579.4 60.290 *
       15) MIXMAS.1>191.25 6   3249.0 36.330 *
```

FIGURE 4.22: DECREASERS ON BASALT, EXCLUDING ET VARIABLES

```
Regression tree:
Variables actually used in tree construction:
 [1] "DAYYR.2"   "DAYGRO"    "EFF.DPTH"
 [4] "BULKMAS.3" "MIXMAS"    "CLAY"
 [7] "SKURT"     "BULKMAS"   "DAYYR"
[10] "MIXMAS.2"  "BSFI"      "DAYGRO.2"
[13] "RFDOR"     "DAYGRO.1"  "RFGRO"
[16] "SILT"      "BURN.FREQ" "CONCMAS.1"
[19] "RFYR"      "WDYCANO"   "THICK.A"
[22] "MIXMAS.1"  "SSKEW"
Number of terminal nodes:  33
Residual mean deviance:  141.3 = 48880 / 346
Distribution of residuals:
Min.    1st Qu.        Median         Mean           3rd Qu.        Max.
-35.14  -6.742         -1             7.733e-016     6.598          50.2

node), split, n, deviance, yval, * denotes terminal node

 1) root 379 252100.0 27.370
    2) DAYYR.2<61.3 329 152200.0 22.270
      4) DAYGRO<28.5 216  73660.0 16.580
        8) EFF.DPTH<0.535 146  35510.0 12.470
         16) BULKMAS.3<19.3225 30  11200.0 24.170
           32) MIXMAS<2 7   1856.0 47.000 *
           33) MIXMAS>2 23   4588.0 17.220
             66) CLAY<45 13    988.8 10.690 *
             67) CLAY>45 10   2326.0 25.700 *
         17) BULKMAS.3>19.3225 116  19140.0  9.440
           34) SKURT<1.0202 111  11600.0  8.297
             68) BULKMAS<11.9775 21   4468.0 17.760
              136) DAYYR<39.2 10   1853.0 26.900 *
              137) DAYYR>39.2 11   1021.0  9.455 *
             69) BULKMAS>11.9775 90   4815.0  6.089
              138) MIXMAS.2<466.75 85   2653.0  5.329
                276) DAYYR<40.55 71   1360.0  4.268 *
                277) DAYYR>40.55 14    806.9 10.710 *
              139) MIXMAS.2>466.75 5   1280.0 19.000 *
           35) SKURT>1.0202 5   4177.0 34.800 *
        9) EFF.DPTH>0.535 70  30530.0 25.160
         18) BSFI<2.975 55  14600.0 18.960
           36) DAYGRO.2<19 26   1757.0  9.769 *
           37) DAYGRO.2>19 29   8679.0 27.210
             74) RFDOR<105.8 22   3575.0 22.450
              148) MIXMAS.2<0.75 6    141.3  9.333 *
              149) MIXMAS.2>0.75 16   2014.0 27.380 *
             75) RFDOR>105.8 7   3045.0 42.140 *
         19) BSFI>2.975 15   6078.0 47.870
           38) DAYYR<38.25 8   2976.0 58.750 *
           39) DAYYR>38.25 7   1072.0 35.430 *
      5) DAYGRO>28.5 113  58140.0 33.150
       10) DAYGRO.1<22.5 42  13290.0 21.670
         20) RFGRO<481.05 20   2241.0 13.850 *
         21) RFGRO>481.05 22   8718.0 28.770
           42) SILT<6.5 6    707.5 13.500 *
           43) SILT>6.5 16   6086.0 34.500
```

```
             86) BURN.FREQ<6.83 9   1571.0 45.890 *
             87) BURN.FREQ>6.83 7   1847.0 19.860 *
       11) DAYGRO.1>22.5 71  36040.0 39.940
         22) CONCMAS.1<2.3825 13   3519.0 65.690
           44) RFYR<557.1 8     913.5 74.750 *
           45) RFYR>557.1 5     898.8 51.200 *
         23) CONCMAS.1>2.3825 58  21970.0 34.170
           46) WDYCANO<40.75 5   1097.0 64.400 *
           47) WDYCANO>40.75 53  15870.0 31.320
             94) THICK.A<0.143 16   4139.0 21.690
              188) RFDOR<92.55 10   2119.0 30.100 *
              189) RFDOR>92.55 6    133.3  7.667 *
             95) THICK.A>0.143 37   9603.0 35.490
              190) BULKMAS<57.41 15   3072.0 45.000
                380) DAYYR<37.9 5   1090.0 58.000 *
                381) DAYYR>37.9 10    714.5 38.500 *
              191) BULKMAS>57.41 22   4248.0 29.000
                382) DAYGRO<34.5 9    788.9 16.890 *
                383) DAYGRO>34.5 13   1225.0 37.380 *
    3) DAYYR.2>61.3 50  34960.0 60.960
      6) CLAY<29.5 6    193.5 11.500 *
      7) CLAY>29.5 44  18090.0 67.700
       14) MIXMAS.1<191.25 38   8001.0 72.660
         28) SSKEW<-0.32055 7    877.7 56.430 *
         29) SSKEW>-0.32055 31   4863.0 76.320
           58) CONCMAS.1<89.23 24   1958.0 81.000 *
           59) CONCMAS.1>89.23 7    579.4 60.290 *
       15) MIXMAS.1>191.25 6   3249.0 36.330 *
```

FIGURE 4.23: DECREASERS ON GRANITE, INCLUDING ET VARIABLES

```
Regression tree:
Variables actually used in tree construction:
 [1] "ETGRO"       "KSZGRO"      "RFYR.3"
 [4] "PH.A"        "MIXMAS.2"    "KSZGRO.1"
 [7] "BURN.INTER"  "RFGRO.2"     "RFYR.2"
[10] "ETDOR"       "AVGKSGRO.3"  "DAYYR"
[13] "CLAY"        "BULKMAS.1"   "KS1GRO"
[16] "EFF.DPTH"    "BULKMAS.2"   "BSFI"
[19] "CFVAR"       "MIXMAS.3"    "WDYCANO"
[22] "SSKEW"       "AVGKSGRO"    "DIST.H2O"
[25] "AVGKSGRO.1"  "DAYGRO.2"    "KS1GRO.3"
Number of terminal nodes:  31
Residual mean deviance:  61.14 = 16570 / 271
Distribution of residuals:
Min.    1st Qu.        Median  Mean           3rd Qu.        Max.
-21.43  -4.686         -0.5    -5e-017        5.261          19.57

node), split, n, deviance, yval, * denotes terminal node

  1) root 302 105300.00 28.020
    2) ETGRO<200.2 131  20470.00 15.630
      4) KSZGRO<0.5 60  11210.00 22.500
        8) RFYR.3<612.3 50   7615.00 19.780
         16) PH.A<5.155 15   1206.00 11.800
           32) MIXMAS.2<56.25 8    490.90 17.880 *
           33) MIXMAS.2>56.25 7     82.86  4.857 *
         17) PH.A>5.155 35   5044.00 23.200
           34) KSZGRO.1<2 25   3433.00 26.720
             68) BURN.INTER<2.68 10   1030.00 35.400 *
             69) BURN.INTER>2.68 15   1147.00 20.930
              138) RFGRO.2<331.15 7     87.43 26.710 *
              139) RFGRO.2>331.15 8    620.90 15.880 *
           35) KSZGRO.1>2 10    526.40 14.400 *
        9) RFYR.3>612.3 10   1377.00 36.100
         18) RFYR.2<598.45 5    494.00 44.000 *
         19) RFYR.2>598.45 5    258.80 28.200 *
      5) KSZGRO>0.5 71   4042.00  9.831
       10) ETDOR<90.85 66   2746.00  8.803
         20) AVGKSGRO.3<0.455 57   1626.00  7.719
           40) DAYYR<52.4 46    960.90  6.739 *
           41) DAYYR>52.4 11    435.60 11.820 *
         21) AVGKSGRO.3>0.455 9    630.00 15.670 *
       11) ETDOR>90.85 5    305.20 23.400 *
    3) ETGRO>200.2 171  49400.00 37.500
      6) CLAY<29.5 145  31170.00 34.920
```

```
     12) ETGRO<277.5 78  15010.00 28.970
       24) BULKMAS.1<183.535 73  11550.00 27.320
         48) KS1GRO<56.5 15   2968.00 37.000
           96) EFF.DPTH<0.65 10   1001.00 31.100 *
           97) EFF.DPTH>0.65 5    922.80 48.800 *
         49) KS1GRO>56.5 58   6809.00 24.810
           98) PH.A<5.595 38   3383.00 21.080
            196) BULKMAS.2<69.17 23   1770.00 25.000
              392) BSFI<2.30925 16    747.00 21.250 *
              393) BSFI>2.30925 7    283.70 33.570 *
            197) BULKMAS.2>69.17 15    716.90 15.070 *
           99) PH.A>5.595 20   1892.00 31.900
            198) CFVAR<31.9822 5    290.80 43.200 *
            199) CFVAR>31.9822 15    749.70 28.130 *
       25) BULKMAS.1>183.535 5    324.80 53.200 *
     13) ETGRO>277.5 67  10200.00 41.840
       26) MIXMAS.3<162 56   6943.00 39.210
         52) WDYCANO<196.56 49   5029.00 37.330
          104) SSKEW<-0.2247 13   1447.00 45.380
            208) AVGKSGRO<0.405 5    209.20 53.600 *
            209) AVGKSGRO>0.405 8    689.50 40.250 *
          105) SSKEW>-0.2247 36   2433.00 34.420
            210) DIST.H2O<2.059 8    370.90 42.880 *
            211) DIST.H2O>2.059 28   1326.00 32.000
              422) RFYR.3<579.5 7    203.40 25.710 *
              423) RFYR.3>579.5 21    753.80 34.100 *
         53) WDYCANO>196.56 7    517.70 52.430 *
       27) MIXMAS.3>162 11    915.60 55.180 *
    7) CLAY>29.5 26  11850.00 51.920
     14) AVGKSGRO.1<0.445 14   2927.00 36.290
       28) DAYGRO.2<36 7    420.90 26.140 *
       29) DAYGRO.2>36 7   1066.00 46.430 *
     15) AVGKSGRO.1>0.445 12   1506.00 70.170
       30) KS1GRO.3<65.5 7    223.40 62.290 *
       31) KS1GRO.3>65.5 5    238.80 81.200 *
```

FIGURE 4.24: DECREASERS ON GRANITE, EXCLUDING ET VARIABLES

```
Regression tree:
Variables actually used in tree construction:
 [1] "DAYGRO.1"    "RFDOR"       "BULKMAS.1"
 [4] "BURN.INTER"  "MIXMAS.1"    "DAYGRO.2"
 [7] "SSKEW"       "CONCMAS.3"   "EFF.DPTH"
[10] "BULKMAS"     "DAYYR"       "MIXMAS.2"
[13] "DAYDOR"      "CLAY"        "RFYR"
[16] "DIST.H2O"    "BULKMAS.2"   "WDYCANO"
[19] "CCFI"        "RFGRO"       "RFYR.2"
[22] "DAYGRO.3"    "CONCMAS"     "SILT"
Number of terminal nodes:  35
Residual mean deviance:  81.19 = 21680 / 267
Distribution of residuals:
Min.    1st Qu.        Median         Mean           3rd Qu.        Max.
-21.6   -5.792         0.002463       3.059e-016     5.753          26.6

node), split, n, deviance, yval, * denotes terminal node

  1) root 302 105300.0 28.020
    2) DAYGRO.1<30.5 124  23540.0 18.820
      4) RFDOR<32.25 22   2903.0 31.550
        8) BULKMAS.1<44.4775 10    614.1 24.300 *
        9) BULKMAS.1>44.4775 12   1327.0 37.580
         18) BURN.INTER<4.095 6    588.8 44.170 *
         19) BURN.INTER>4.095 6    218.0 31.000 *
      5) RFDOR>32.25 102  16310.0 16.080
       10) MIXMAS.1<50.75 52   9829.0 20.580
         20) DAYGRO.2<39 47   6743.0 18.570
           40) SSKEW<0.18135 22   2853.0 25.140
             80) CONCMAS.3<4.69 6    825.5 35.500 *
             81) CONCMAS.3>4.69 16   1141.0 21.250
              162) EFF.DPTH<0.34 11    346.5 24.360 *
              163) EFF.DPTH>0.34 5    453.2 14.400 *
           41) SSKEW>0.18135 25   2110.0 12.800
             82) SSKEW<0.66205 12    473.7  7.833 *
             83) SSKEW>0.66205 13   1067.0 17.380
              166) BULKMAS<23.135 5     65.2  9.600 *
              167) BULKMAS>23.135 8    509.5 22.250 *
```

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       21) DAYGRO.2>39 5   1125.0 39.400 *
     11) MIXMAS.1>50.75 50   4330.0 11.400
       22) DAYYR<52.3 42   1930.0  9.167
         44) MIXMAS.2<54 13    798.8 13.690 *
         45) MIXMAS.2>54 29    745.4  7.138 *
       23) DAYYR>52.3 8   1091.0 23.120 *
  3) DAYGRO.1>30.5 178  64030.0 34.420
    6) DAYDOR<17.5 123  43400.0 39.240
     12) CLAY<29.5 105  28110.0 35.700
       24) RFYR<612.15 85  17900.0 38.940
         48) DIST.H2O<2.246 25   6308.0 47.600
           96) BULKMAS<24.69 5   1593.0 27.600 *
           97) BULKMAS>24.69 20   2215.0 52.600
            194) RFYR<466.4 7    255.4 61.290 *
            195) RFYR>466.4 13   1147.0 47.920
              390) BULKMAS.2<47.47 5    145.2 54.400 *
              391) BULKMAS.2>47.47 8    660.9 43.880 *
         49) DIST.H2O>2.246 60   8935.0 35.330
           98) WDYCANO<196.56 55   6894.0 33.820
            196) CCFI<1.15955 21   2059.0 39.860
              392) CCFI<1.005 7    310.9 30.860 *
              393) CCFI>1.005 14    897.2 44.360 *
            197) CCFI>1.15955 34   3597.0 30.090
              394) MIXMAS.1<11.25 10   1018.0 38.200 *
              395) MIXMAS.1>11.25 24   1647.0 26.710
                790) CONCMAS.3<37.43 19    773.2 29.210 *
                791) CONCMAS.3>37.43 5    302.8 17.200 *
           99) WDYCANO>196.56 5    526.0 52.000 *
       25) RFYR>612.15 20   5539.0 21.950
         50) RFGRO<674.05 15   1080.0 14.400
          100) RFYR.2<468.55 9    476.0 19.000 *
          101) RFYR.2>468.55 6    127.5  7.500 *
         51) RFGRO>674.05 5   1039.0 44.600 *
     13) CLAY>29.5 18   6306.0 59.890
       26) DAYGRO.2<29.5 7   1537.0 43.710 *
       27) DAYGRO.2>29.5 11   1772.0 70.180
         54) MIXMAS.1<40.5 5    448.8 79.800 *
         55) MIXMAS.1>40.5 6    474.8 62.170 *
    7) DAYDOR>17.5 55  11360.0 23.640
     14) DAYGRO.3<33 14    937.4 11.570 *
     15) DAYGRO.3>33 41   7692.0 27.760
       30) CONCMAS<22.99 15   1578.0 36.400
         60) BULKMAS.2<45.84 10    788.1 31.700 *
         61) BULKMAS.2>45.84 5    126.8 45.800 *
       31) CONCMAS>22.99 26   4347.0 22.770
         62) BULKMAS<59.8725 20   2082.0 18.000
          124) SILT<7.5 9    683.6 25.780 *
          125) SILT>7.5 11    408.5 11.640 *
         63) BULKMAS>59.8725 6    293.3 38.670 *
```

4. TREE REGRESSIONS FOR MANAGEMENT PUROSES

FIGURE 4.25: PRODUCTION ON BASALT (RAINFALL AND COMPOSITION ONLY)

```
Regression tree:
Variables actually used in tree construction:
[1] "DAYYR"   "DAYGRO"  "PEREN"   "SSKEW"
[5] "RFDOR"   "RFGRO.2"
Number of terminal nodes:  9
Residual mean deviance:  9.256 = 583.2 / 63
Distribution of residuals:
Min.    1st Qu.       Median        Mean          3rd Qu.       Max.
-8.383  -0.89         -0.09881      -3.084e-017   0.8821        13.72

node), split, n, deviance, yval, * denotes terminal node

 1) root 72 2646.000  7.564
   2) DAYYR<58.45 54  266.400  5.000
     4) DAYGRO<30 38   49.140  4.071
       8) PEREN<22 7    1.769  2.914 *
       9) PEREN>22 31   35.890  4.332
        18) SSKEW<0.0476 10   14.630  4.990 *
        19) SSKEW>0.0476 21   14.870  4.019 *
     5) DAYGRO>30 16  106.600  7.206
```

```
      10) PEREN<71 5   11.870  4.760 *
      11) PEREN>71 11   51.240  8.318
        22) RFDOR<82.65 5    5.812  6.560 *
        23) RFDOR>82.65 6   17.090  9.783 *
  3) DAYYR>58.45 18  960.100 15.260
    6) DAYYR<69.85 12  331.100 12.390
      12) RFGRO.2<354.25 6   67.270  8.883 *
      13) RFGRO.2>354.25 6  116.100 15.900 *
    7) DAYYR>69.85 6  333.700 20.980 *
```

FIGURE 4.26: PRODUCTION ON GRANITE (RAINFALL AND COMPOSITION ONLY)

```
Regression tree:
Variables actually used in tree construction:
[1] "RFYR"     "RFGRO.1" "PEREN"    "RFYR.3"
[5] "CFVAR"    "RFYR.1"  "SKURT"
Number of terminal nodes:  9
Residual mean deviance:  4.958 = 361.9 / 73
Distribution of residuals:
Min.   1st Qu.        Median        Mean          3rd Qu.       Max.
-7.7   -0.9988        -0.1333       -1.408e-016   0.7922        8.1

node), split, n, deviance, yval, * denotes terminal node

 1) root 82 1434.000  6.889
   2) RFYR<489.1 39  124.700  4.149
     4) RFGRO.1<368.3 20   10.410  2.895 *
     5) RFGRO.1>368.3 19   49.780  5.468
      10) PEREN<75 14   21.370  4.857
        20) RFYR.3<606.75 6    3.813  5.633 *
        21) RFYR.3>606.75 8   11.240  4.275 *
      11) PEREN>75 5    8.528  7.180 *
   3) RFYR>489.1 43  751.100  9.374
     6) CFVAR<41.5197 34  358.000  8.362
      12) RFYR.1<499.9 5   46.990 14.220 *
      13) RFYR.1>499.9 29  109.900  7.352
        26) RFYR<573.85 13   13.470  6.146 *
        27) RFYR>573.85 16   62.130  8.331
          54) SKURT<-0.72935 7   16.210  7.029 *
          55) SKURT>-0.72935 9   24.800  9.344 *
     7) CFVAR>41.5197 9  226.500 13.200 *
```

FIGURE 4.27: STANDING CROP ON BASALT (RAINFALL, COMPOSITION AND BURN INTERVAL ONLY)

```
Regression tree:
Variables actually used in tree construction:
 [1] "DAYGRO"     "RFGRO"     "PEREN"
 [4] "DAYYR"      "DAYDOR"    "BARE"
 [7] "BURN.INTER" "DAYGRO.3"  "SSKEW"
[10] "RFYR"       "DAYGRO.1"  "RFDOR"
[13] "RFYR.2"     "RFYR.3"    "SKURT"
[16] "DAYYR.1"    "RFGRO.2"   "VAR"
[19] "RFGRO.3"    "FORBS"     "DAYYR.2"
Number of terminal nodes:  50
Residual mean deviance:  9.7 = 6257 / 645
Distribution of residuals:
Min.   1st Qu.        Median        Mean          3rd Qu.       Max.
-9.42  -1.776         -0.2586       1.981e-016    1.529         13.12

node), split, n, deviance, yval, * denotes terminal node

  1) root 695 26670.000  9.656
    2) DAYGRO<33.5 361  5223.000  6.312
      4) RFGRO<361 283  2770.000  5.594
        8) PEREN<89.5 254  1600.000  5.115
         16) DAYYR<36.85 119   475.100  4.145
           32) DAYDOR<6.5 17   128.900  6.000 *
           33) DAYDOR>6.5 102   277.900  3.836
             66) BARE<17.5 83   210.900  4.119 *
             67) BARE>17.5 19    31.340  2.600 *
         17) DAYYR>36.85 135   914.700  5.969
```

```
       34) BURN.INTER<4.445 62   230.900  4.911 *
       35) BURN.INTER>4.445 73   555.500  6.867
         70) PEREN<46 44   253.500  5.950 *
         71) PEREN>46 29   208.900  8.259 *
    9) PEREN>89.5 29   599.900  9.793
     18) DAYGRO.3<30.5 13   345.400 12.230
       36) SSKEW<-0.0814 6   232.100 14.850 *
       37) SSKEW>-0.0814 7    36.870  9.986 *
     19) DAYGRO.3>30.5 16   114.500  7.812 *
  5) RFGRO>361 78  1777.000  8.918
   10) BURN.INTER<7.62 45   630.700  7.009
     20) RFYR<488.5 25   229.300  5.676 *
     21) RFYR>488.5 20   301.400  8.675
       42) DAYGRO.1<25.5 14   134.000  7.464 *
       43) DAYGRO.1>25.5 6    98.960 11.500 *
   11) BURN.INTER>7.62 33   759.100 11.520
     22) RFDOR<180.65 26   467.400 13.010
       44) RFYR.2<211.95 7    49.120  9.743 *
       45) RFYR.2>211.95 19   316.200 14.210
         90) RFYR.3<517.45 13   129.500 13.080 *
         91) RFYR.3>517.45 6   133.700 16.670 *
     23) RFDOR>180.65 7    20.820  6.000 *
3) DAYGRO>33.5 334 13040.000 13.270
  6) DAYGRO<58.5 294  9531.000 12.300
   12) PEREN<76.5 108  3210.000  9.881
     24) RFYR<564.3 49  1015.000  7.704
       48) SSKEW<-1.08535 12   535.100 10.270
         96) DAYDOR<22.5 5   375.300 14.480 *
         97) DAYDOR>22.5 7     7.657  7.257 *
       49) SSKEW>-1.08535 37   375.800  6.873
         98) BURN.INTER<9.36 31   178.000  6.013 *
         99) BURN.INTER>9.36 6    56.390 11.320 *
     25) RFYR>564.3 59  1769.000 11.690
       50) SSKEW<-1.54335 5    96.550  3.620 *
       51) SSKEW>-1.54335 54  1317.000 12.440
        102) BURN.INTER<3.59 23   498.300 15.240
          204) SKURT<-0.3735 11   103.900 17.700 *
          205) SKURT>-0.3735 12   266.700 12.980
            410) PEREN<44 6    25.130 10.320 *
            411) PEREN>44 6   156.300 15.650 *
        103) BURN.INTER>3.59 31   504.100 10.360
          206) DAYYR.1<58.3 26   404.000 11.130
            412) PEREN<47 9    78.040  8.222 *
            413) PEREN>47 17   209.500 12.670 *
          207) DAYYR.1>58.3 5     3.812  6.340 *
   13) PEREN>76.5 186  5322.000 13.700
     26) SKURT<-0.61555 88  1743.000 11.560
       52) DAYYR<69.85 57   749.300 10.290
        104) RFGRO<336.85 6    15.470  6.517 *
        105) RFGRO>336.85 51   638.400 10.730
          210) PEREN<80 8    44.120  7.763 *
          211) PEREN>80 43   510.600 11.290
            422) RFGRO.2<446.75 35   303.800 10.770
              844) VAR<6.97545 20   190.700 11.710 *
              845) VAR>6.97545 15    71.960  9.520 *
            423) RFGRO.2>446.75 8   157.000 13.540 *
       53) DAYYR>69.85 31   733.500 13.890
        106) BARE<1.5 25   464.400 15.080
          212) RFGRO.3<362.9 12   195.400 12.450 *
          213) RFGRO.3>362.9 13   109.000 17.520 *
        107) BARE>1.5 6    85.030  8.917 *
     27) SKURT>-0.61555 98  2809.000 15.630
       54) DAYYR<52.25 51  1003.000 13.600
        108) RFGRO.3<316.5 23   256.300 11.420 *
        109) RFGRO.3>316.5 28   546.600 15.400
          218) PEREN<78.5 5    12.640 20.500 *
          219) PEREN>78.5 23   375.400 14.290
            438) FORBS<4 15   217.900 15.670 *
            439) FORBS>4 8    75.400 11.700 *
       55) DAYYR>52.25 47  1368.000 17.840
        110) DAYGRO.3<27.5 15   448.600 15.060
          220) PEREN<85 6   215.900 11.970 *
          221) PEREN>85 9   137.000 17.120 *
        111) DAYGRO.3>27.5 32   749.600 19.140
          222) DAYYR.2<42.45 5   184.000 24.520 *
          223) DAYYR.2>42.45 27   393.900 18.140
            446) RFYR.3<602.7 20   269.100 17.140
              892) RFYR<538.45 8    62.720 19.060 *
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```
                  893) RFYR>538.45 12   157.400 15.870 *
                447) RFYR.3>602.7 7    48.270 20.990 *
      7) DAYGRO>58.5 40  1202.000 20.400
       14) BURN.INTER<2.595 12   311.400 25.010
         28) FORBS<2.5 7   122.500 22.860 *
         29) FORBS>2.5 5   111.200 28.020 *
       15) BURN.INTER>2.595 28   526.500 18.430
         30) DAYYR<89 12    64.010 21.240 *
         31) DAYYR>89 16   296.300 16.320
           62) SKURT<-1.0188 6   107.700 19.670 *
           63) SKURT>-1.0188 10    80.990 14.310 *
```

FIGURE 4.28: STANDING CROP ON GRANITE (RAINFALL, COMPOSITION AND BURN INTERVAL ONLY)

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Regression tree:
Variables actually used in tree construction:
 [1] "DAYYR"      "PEREN"      "RFGRO"
 [4] "RFYR.2"     "FORBS"      "SSKEW"
 [7] "RFDOR"      "CFVAR"      "BURN.INTER"
[10] "DAYYR.2"    "SKURT"      "RFYR.1"
[13] "DAYGRO.3"   "RFYR"       "DAYYR.3"
[16] "DAYYR.1"    "DAYGRO"     "RFYR.3"
[19] "DAYGRO.1"
Number of terminal nodes:  48
Residual mean deviance:  5.235 = 3513 / 671
Distribution of residuals:
Min.   1st Qu.       Median         Mean          3rd Qu.        Max.
-7.729 -1.245        -0.16          3.385e-016    1.167          9.678

node), split, n, deviance, yval, * denotes terminal node

   1) root 719 14580.000  7.640
     2) DAYYR<57.55 359  2822.000  5.196
       4) PEREN<47.5 154   582.400  3.695
         8) RFGRO<248.55 78    89.010  2.787 *
         9) RFGRO>248.55 76   363.000  4.628
          18) PEREN<22.5 22    26.140  3.050 *
          19) PEREN>22.5 54   259.800  5.270
            38) RFYR.2<610.3 49   184.700  4.986
              76) FORBS<47.5 40   138.700  4.605 *
              77) FORBS>47.5 9    14.460  6.678 *
            39) RFYR.2>610.3 5    32.230  8.060 *
       5) PEREN>47.5 205  1633.000  6.322
        10) SSKEW<0.39885 150  1217.000  6.999
          20) PEREN<70.5 84   452.500  6.167
            40) RFDOR<144.4 62   283.000  5.716
              80) FORBS<17.5 47   212.700  6.251
               160) CFVAR<37.2036 33   112.000  6.761 *
               161) CFVAR>37.2036 14    71.940  5.050 *
              81) FORBS>17.5 15    14.740  4.040 *
            41) RFDOR>144.4 22   121.500  7.436 *
          21) PEREN>70.5 66   632.600  8.059
            42) CFVAR<32.9995 17   243.900  9.882
              84) FORBS<4.5 10    53.740  8.200 *
              85) FORBS>4.5 7   121.500 12.290 *
            43) CFVAR>32.9995 49   312.500  7.427
              86) BURN.INTER<12.94 44   198.800  7.123
               172) DAYYR.2<58.95 35   104.800  6.620 *
               173) DAYYR.2>58.95 9    50.740  9.078 *
              87) BURN.INTER>12.94 5    73.900 10.100 *
        11) SSKEW>0.39885 55   159.200  4.476
          22) SKURT<-0.2945 31    74.050  5.410 *
          23) SKURT>-0.2945 24    23.290  3.271 *
     3) DAYYR>57.55 360  7476.000 10.080
       6) RFYR.1<365.8 40   269.300  5.685
        12) DAYYR<59.95 14    42.170  7.657 *
        13) DAYYR>59.95 26   143.300  4.623 *
       7) RFYR.1>365.8 320  6338.000 10.630
        14) RFGRO<371.85 68   939.000  7.615
          28) FORBS<8.5 27   316.800  9.889
            56) RFDOR<167.7 17   188.400  8.612
             112) BURN.INTER<1.555 6     3.348  6.483 *
             113) BURN.INTER>1.555 11   143.100  9.773 *
            57) RFDOR>167.7 10    53.520 12.060 *
```

```
  29) FORBS>8.5 41   390.600  6.117
    58) PEREN<18.5 9    11.390  3.189 *
    59) PEREN>18.5 32   280.400  6.941
     118) BURN.INTER<0.755 14    41.490  5.129 *
     119) BURN.INTER>0.755 18   157.100  8.350
       238) DAYGRO.3<31 5     4.028  5.320 *
       239) DAYGRO.3>31 13    89.560  9.515 *
15) RFGRO>371.85 252  4616.000 11.440
  30) RFYR<775.7 137  2035.000 10.450
    60) CFVAR<41.6844 112  1401.000  9.821
     120) DAYYR.3<55.85 39   229.800  7.995
       240) RFYR<571.8 12    11.940  5.883 *
       241) RFYR>571.8 27   140.500  8.933 *
     121) DAYYR.3>55.85 73   972.000 10.800
       242) DAYYR.1<69.7 33   364.500 12.120
         484) BURN.INTER<1.535 10    65.660  9.740 *
         485) BURN.INTER>1.535 23   217.700 13.150
           970) BURN.INTER<4.485 13    80.540 14.820 *
           971) BURN.INTER>4.485 10    53.680 10.980 *
       243) DAYYR.1>69.7 40   502.400  9.708
         486) FORBS<4.5 25   265.000 10.920
           972) PEREN<86.5 18   107.000  9.983 *
           973) PEREN>86.5 7   102.000 13.310 *
         487) FORBS>4.5 15   140.100  7.693 *
    61) CFVAR>41.6844 25   395.100 13.240
     122) RFGRO<455.2 20   271.300 12.280
       244) RFYR.2<608.25 14    78.660 10.550 *
       245) RFYR.2>608.25 6    52.130 16.330 *
     123) RFGRO>455.2 5    32.630 17.060 *
  31) RFYR>775.7 115  2283.000 12.630
    62) SSKEW<-0.4625 7    96.670 18.830 *
    63) SSKEW>-0.4625 108  1899.000 12.220
     126) DAYGRO<60 40   604.300 10.270
       252) DAYYR.2<71.15 31   329.600  9.584
         504) PEREN<30.5 7    14.910  5.986 *
         505) PEREN>30.5 24   197.600 10.630
          1010) RFYR.3<635.4 7    29.690 13.170 *
          1011) RFYR.3>635.4 17   104.200  9.588 *
       253) DAYYR.2>71.15 9   210.300 12.620 *
     127) DAYGRO>60 68  1052.000 13.380
       254) PEREN<89 60   809.600 12.850
         508) DAYGRO.1<37 21   183.800 14.830
          1016) SSKEW<-0.08005 16    76.360 13.750 *
          1017) SSKEW>-0.08005 5    29.310 18.280 *
         509) DAYGRO.1>37 39   499.300 11.780
          1018) DAYGRO.1<42.5 16   115.000 10.050 *
          1019) DAYGRO.1>42.5 23   302.700 12.990
            2038) PEREN<70.5 9    72.640 11.240 *
            2039) PEREN>70.5 14   184.900 14.110
              4078) SKURT<-1.15515 5    60.930 16.460 *
              4079) SKURT>-1.15515 9    81.170 12.810 *
       255) PEREN>89 8   101.800 17.310 *
```