Factors associated with the encroachment of bush into semi-arid savanna grazing lands in southern Africa.

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I hereby declare that the results presented here are my own work. These have not been submitted in full, or any part, to another university for degree purposes.

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Abstract

A study was carried out in the semi-arid and arid savanna regions of South Africa to determine which environmental factors are associated with the process of bush encroachment.

It was found, using discriminant analysis, that no single variable, or group of variables, was responsible for separating the degrees of woody density. Some soil textural factors showed associations with increased woody density. The highest woody densities were recorded on deep, sandy soils with a low annual rainfall.

Several site variables change as a result of a change in the bush-grass community. The most prominent of t ese is a change in the distribution pattern of some soil cations (calcium, magnesium and sodium), which expands the two layered, water linked hypothesis of Walter (1971) on savanna dynamics, to include the leaching of nutrients.

Bush clearing is not feasible in the arid regions on sandy soils, where the competitive effect of trees on grasses is strong, but the reverse is weak. On fine textured soils, however, the competition between these components is great in both directions, and control of woody thickening may be economically feasible.

Acknowledgements.

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Everything should be made as simple
as possible,
but not simpler.

(Albert Einstein, 1952)

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1. Introduction

Approximately 33% of South Africa is covered by bush, scrub or savanna (some 53 million hectares). It has been estimated that at least 18 million hectares of this bushveld have already been damaged by the abnormal coppicing of bush, or are endangered by bush encroachment (Van der Schijff, 1957). According to Mostert, et al.,(1971), Donaldson (1967a, 1967b) and Walter (1971) bush encroachment has become a serious problem during the past thirty years in the Vryburg-Mafekeng area, the Molopo area, northwestern and northern Transvaal, Botswana, South West Africa (Namibia), Zimbabwe, northern Natal, Zululand, Swaziland, Mozambique, and the Eastern Cape. Millions of hectares of valuable pasture have been encroached by woody plants to such an extent that the *carrying capacity* of the veld (rough grazing lands) has been considerably reduced, not only because of reduction in grass cover and quality, but also because large areas have become impenetrable to stock (Mostert, et al., 1971). Because of the absence of a dense grass cover under the bush component, soil losses due to water and wind erosion are also greater (Walter, 1971) It is estimated that in some areas at least 50% of the natural pasture has been invaded by woody elements (Donaldson, 1973).

With an increase in the density of woody plants there is a reduction of the total land area available for grazing, and in areas with a moderate infestation of woody species the quality and quantity of available grazing deteriorates.
Unless the stocking rate of the area is altered to compensate for this decrease in grazing the parts of the farm not infested with woody species will be severely overgrazed, which may lead to a further increase in the woody species.

Savanna vegetation, as defined by Walter (1971), refers to the natural homogeneous zonal vegetation of the tropical summer rainfall zone, show[illegible]losed grass cover and scattered, individual woo[illegible]s, either trees or shrubs. This climatologically conditioned savanna probably occurs in Africa only in areas with rainfall below 700mm per annum.
Natural savanna is therefore understood to mean a homogeneous plant community in which individual woody plants grow more or less widely apart on a grass dominated background (Walter, ibid.).

The term "bush encroachment" is frequently a misnomer, implying a problem which is not the one with which agriculturalists are concerned. It implies that woody species are invading areas that have always had either a low density of, or have been devoid of, trees and shrubs. Most often this is not the case.

Woody species are present in most savanna regions, and their spread is suppressed by fire and wood chopping. The term "woody thickening" is more suitable in that it implies that woody species were present in the area and that as a result of a change in the management, these species have increased in density and vigour.

Bush encroachment has been studied in most of the savanna regions of the world, but much of this research has been orientated towards the eradication and control of woody species (Donaldson, 1967a; Walter, 1971; Mostert, et al., 1971).
The prime objective of this study was an attempt to contribute towards an understanding of the factors associated with bush encroachment, and how these factors interact. One aim was to produce a predictive model of bush encroachment in South Africa. This information may be used to identify those areas in South Africa which are sensitive to change and potentially liable to become encroached. To achieve this the relationships between woody density and each of a set of environmental factors must be established.

2. Literature Review.

2.1 Bush encroachment - the world position.

According to Donaldson (1967) the invasion of bushy shrubs and trees is one of the most difficult and troublesome problems with which the cattle rancher has to deal. The value of grazing land may be completely destroyed by encroaching woody plants, and their eradication may cost more than the land is worth. Millions of hectares of formerly and potentially good grazing of the earth's surface, particularly in Africa, the Americas, and Australia, are infested with worthless bushes and trees.

In the United States of America, upwards of 500,000 square miles of land are dominated by bush. In the state of Texas alone, 55 million acres are infested with mesquite (Prosopis juliflora), 18 million acres with Juniper woodland, 20 million acres with scrub oak, and 6 million acres with huisache (Donaldson 1967a). According to Herbel (1979) the density of brush on rangeland in the southwestern United States has increased rapidly since 1900.
A survey by the United States Soil Conservation Service found that 80% of Texas grasslands were infested with one or more low value woody plants. It is reported the 22 million hectares were covered with dense stands of brush requiring control measures before any other range improvements could be made.

Yet, in spite of efforts to control brush by chemical and mechanical methods, its density is increasing. The survey showed that the area of mesquite alone has increased by 500,000 hectares during the period 1938 - 1963.

A similar situation exists in the savanna regions of South America and Australia. In Queensland (Australia) more than 13 million acres of land are covered with brigalow scrub (Wilson and Graetz, 1979).

2.2. Southern Africa.

In South Africa, where approximately 33% of the total surface area is covered by bush, scrub, or savanna (some 53 million hectares in total), it is estimated that at least 18 million hectares of bushveld are already damaged by the abnormal coppicing of bush or are endangered by bush encroachment (Van der Schijff, 1957).

It is estimated that in the Molopo region over one million hectares of veld have been infested by *Acacia mellifera* (Donaldson, 1967a). It can be concluded from these estimates that the carrying capacity of the veld has been reduced by as much as 50% or more, and that millions of rands worth of animal products are lost annually as a direct result of bush encroachment.

A similar situation exists in the Eastern Cape where estimates by Venter (1980) show that approximately 50% of this region consists of some form of woody community.

The arid grassveld and bushveld areas of this region do not allow for intensification of farming, and are therefore ideal as natural pasture for cattle ranching. Venter (loc cit.) gives the following breakdown of the degrees of bush encroachment in this region :

(i) 7% of the surface area of the Eastern Cape region is heavily encroached by bush (i.e. bush densities of greater than 1500 bushes/hectare).

(ii) 13% is lightly encroached.

(iii) 23% of this region is an area of potential encroachment.

The same situation exists over large portions of Zimbabwe, where according to West (1958) and Rattray (1957) the climax vegetation over nearly the whole country is woodland or shrubland. Barnes (1972) states that by shifting the dynamic balance which existed in the past between the vegetation and various factors, the equilibrium has been changed and a new condition has arisen, i.e. the movement of certain regions towards a thicket type of vegetation.

2.3 Causes of bush encroachment.

At the turn of the century many travellers in the bushveld areas of southern Africa noted the open nature of the vegetation (Sykes, 1897; Decle, 1900) which is contrary to the belief of Rattray (1957) and West (1958)

who suggest that the climatic climax vegetation of these areas is a woodland of deciduous trees and shrubs with an understorey of grasses and, to a lesser extent, herbs.
Strang (1973) remarked that early pioneers commented on the wide expanses of grassland occurring south of Harare (formerly Salisbury) where the present vegetation is woodland. It is thought by West (1947) and Strang (1973) that this situation was brought about by conditions favouring frequent, intense fires. The result of an era of burning, clearing and felling deceived the first white settlers as to the true nature of the vegetation and encouraged the development of cattle ranching.

The introduction of domestic livestock into Africa has resulted in serious and extensive damage to many tracts of land (Brown, 1968). There are several reasons for this. Cattle utilize the herbaceous vegetation to a greater extent than necessary, since they are able to put on weight by laying down fat, and therefore continue to feed even when their immediate needs are satisfied (Kelly, 1973). In contrast, most wild herbivores are incapable of laying down extensive fat reserves and evidence suggests that they may be physiologically geared to a maintenance level of production so that when these requirements have been satisfied they cease to feed (Ledger, 1963). Because of encroachment, much of the grazing area is producing less than its potential, and all of it is threatened. The value of browse to cattle appears to be less than that of the grass which is displaced by trees and shrubs (Strang, 1973).

Various factors have been mentioned as possible causes of bush encroachment. Aucamp (1976) is of the opinion that the absence of browsers in the animal production systems has been the chief cause of bush encroachment, especially in the Valley Bushveld and Thornveld (Acocks, 1953) of the Eastern Cape. Defoliation by indigenous game was in earlier times spread over the grass and bush layers, and under these conditions the balance between the two components was maintained. This ideal balance has been disturbed by replacing the grass and shrub feeding game with cattle and sheep, which are both primarily grazers. Aucamp (ibid.) maintains that if bush encroachment is to be prevented, the browser must be brought back into the animal production systems, and he suggests the goat as a good domestic browser.

In Zimbabwe, Kelly and Walker (1976) suggest that in former times the unrestricted movement of game in response to changing conditions of water availability and herbage quality would have resulted in relatively light overall utilization of veld and periods of rest for defoliated grasses to maintain their vigour. However, with the rising numbers of cattle and the reduction in the frequency and intensity of fires, presistent heavy grazing has weakened the perennial grasses, hastening the establishment and encroachment of woody species (Kennan, 1966).

Working in the northwestern Cape, Donaldson (1967a) came to the conclusion that no single factor can be responsible as a cause for bush encroachment. It is suggested that the periodic occurrence of veld fires maintained the balance between the grass and woody species. The problem of bush encroachment as it exists today has been brought about by ringfencing, paddocking, the confinement of relatively large numbers of animals to small areas, and the exclusion of veld fires (Donaldson, 1967a; Strang, 1973; West, 1972; Barnes, 1972 and many others).
Farmers often blame the discontinuation of veld fires for the encroachment of bush. Walter.(1971), however, maintains that closer investigation has shown that invasive scrub is not generally caused by discontinuation of veld fires, but that it is usually associated with large numbers of grazing animals which reduce the perennial grasses in semi-arid regions by over-grazing.

Population growth also has much to do with the problem. Farms are gradually becoming smaller and overstocking is more widespread. If sound grazing management at the correct stocking rate is not applied under such conditions, the quality of the pasture declines, and the spread of woody elements is encouraged (Walter, 1971). According to Walter (ibid.) thicket formation poses a greater threat to the thinly populated areas (farming areas) than to areas occupied by the indigenous peoples.

A farm is usually occupied by one family and a few farm hands and utilization of wood by the household is very limited. The situation is quite different among the indigenous peoples, who live in large numbers around watering places and who need much wood for cooking purposes. Invasive scrub is absent in such areas (Walter, ibid.). Instead a bare desert-like area develops through severe overgrazing which leads to soil erosion. From an economic point of view, this development is even worse than encroachment.

Mostert, et al. (1971) conclude that the grass-tree balance was maintained in the past by various factors. Two of the most important ones are (i) the presence of browsers and the overall utilization of the vegetation, and (ii) veld burning. A third general factor which is often overlooked is the role of man as a woodgatherer (Strang, 1973).

[illegible].4 Grass and trees as competitors.

It is generally accepted that the suppressive effect of woody species on grass yields is brought about largely through the competition for soil moisture (Donaldson and Kelk, 1970; Walker, 1974; Walker et al., 1981). There is a high mortality of grasses under bush during severe droughts (Donaldson, 1967a) and comparatively high resistance of trees and shrubs to drought damage at these times (Van Wyk, et al., 1969).

Walter (1971) proposed that a two-layered soil structure operates functionally in a savanna. This is based on differential usage of water by the woody and grass components. In contrast to the grasses, the shrubs have a more extensive root system, i.e. they extend laterally very far, and to a certain extent they also extend vertically to some depth. Stony soils, in which only small amounts of fine soil are held among the rocks, are therefore very favourable to woody plants (Walter, ibid.). By contrast, on fine textured soils an extensive root system is at a disadvantage, compared with a compact root system, in competition for small quantities of residual water. In such conditions shrubs can only maintain a foothold among grasses where more water is left in the soil during the dry period than is used up by the grasses (Walter, ibid.). When these aspects are considered, the distribution of woody plants and grasses in the semi-arid regions becomes quite understandable. It depends largely on climate and soils.

Walter (ibid.) summarises the status of semi-arid savannas with respect to climate and soils as follows :

A. Soils stony : woody plants dominate over grasses.

B. Soils of finer texture :

(i) Low precipitation (100-250mm) : pure grassland, woody plants absent.

(ii) Precipitation higher (250-500mm) : savanna, grasses dominate but woody plants are also present.

(iii) Precipitation high (above 500mm) : woodland, grasslands less dominant.

Because wateris a limiting factor in semi-arid savannas (Walker, 1974) the two components of this system, i.e. grasses and woody species, compete strongly with each other, so that one is present to the exclusion of the other (Walter, 1971).
Knoop (1983) found that woody seedling germination and growth is severely suppressed by the herbaceous layer. The seedlings experience the indirect competition for water, and, in addition, there is likely to be direct competition for water and possibly for space and nutrients in the topsoil. Above-ground competition for light and carbon dioxide may also be important in view of the density of the grass sward. Walker, et al. (1981) produced a model of this hypothesis which defines many of the assumptions made in the original one and allows computer simulations based in the model to be made (Walker and Noy-meir, 1982). Knoop (ibid.) concludes that only under certain combinations of rainfall and soil textures can the model originally proposed by Walter (1971) be usefully applied. However, the principle of the two layer hypothesis (Walker and Noy-meir, 1982) appears to be generally applicable to savannas.

2.5 Bush clearing.

With scrub invasion the question arises, whether or not this change can be considered permanent. Walter (1971) maintains that regeneration of woody plants does not take place in the dense thickets, probably because of the high light requirements of the seedlings. When the shrubs attain their age limit, after a few decades, and begin to die out, a grass cover has already been established which can then close up rapidly. Of course, a farmer does not want to wait so long and wishes to eliminate the scrub rapidly.

Numerous authors have recorded greater herbaceous productivity after thinning or removal of woody plants (Ward and Cleghorn, 1964; Barnes, 1973). In Australia, Wilson and Graetz (1979), and Walker, et al. (1981) found that herbage growth may be increased threefold by the removal of trees and shrubs that are inedible to cattle and sheep. They concluded that a density of six trees or 360 shrubs per hectare is the upper limit before herbage growth is limited.

There are several methods available for bush clearing and control, ranging from mechanical removal to the application of arboricides (Donaldson, 1967a). In the western United States large areas dominated by sagebrush have been returned to climax composition by application of the hormonal herbicide 2,4 - D (Donaldson 1967a). This resulted in a marked increase in herbage production on both arid and mesic sites. Similar results were obtained in Arizona by Clary and Jameson (1981), who found that the greatest increase in herbage production wason sites with a high annual precipitation.

However, the costs of bush control or removal are often greater than the cost of the land (Donaldson, ibid.) The reintroduction of browsers may provide a more feasible alternative. Trollope (1980) and Aucamp (1976) have shown that the grass-bush balance may be maintained in an open state by using domestic goats as a biological control measure.

Game ranching has been proposed as an alternative form of land-use in savanna regions, but in the past landowners have generally assumed that indigenous herbivores compete with livestock for food (Kelly, 1973). However, according to Strang (1973) it seems more logical to use animals which are adapted to the environment, than to impose an introduced grazing herd on country which is not naturally grassland.
Walker (1976, 1979a)shows that high production from indigenous herbivores is not feasible, and that the breeding and domestication of a new browser may provide a better alternative for the utilization of the woody component in the savanna areas (Walker, 1980b).

2.6 Infiltration.

According to Walter (1971), grass and woody plants occupy two levels in the soil. An upper layer where the grass and tree roots compete actively for resources, the grass being the superior competitor in this layer, and a deeper subsoil region where the woody roots have sole access to these resources.

The amount of water in these layers depends on how much of the incoming precipitation enters the soil. Therefore, because semi-arid savannas are water limited systems (Walker, 1974), any reduction of the water input into the soil is critical.

Infiltration concerns the movement of water into the soil (Chow, 1964). By some, it has been considered as a surface phenomenon, governed entirely by the surface conditions, particularly the non-capillary porosity of the soil surface. Others have used infiltration to describe the movement of water into the soil as governed by the permeability of the entire profile (Chow, 1964).

When turbid water is applied to the soil, non-capillary pores are quickly choked and infiltration rate is sharply reduced. The same result is obtained when raindrops strike the unprotected soil, detaching the soil particles which block the pores (Laws, 1941).

From the foregoing, it is obvious that infiltration is strongly influenced by soil texture and structure, which govern non-capillary porosity, soil wetness, and the amount of protection of the soil surface from rainfall impact offered by vegetation.

Walker (1974) states that the rate of water infiltration into the soil is a function of two factors, viz. the percentage of the ground covered by litter, and the basal cover of caespitose, perennial grasses.
Kelly and Walker (1976) and Walker (1974) have found that on sandy loam soils the ratio of infiltration under a litter cover and on bare surfaces, as measured with a double-ring infiltrometer, is of the order 9 : 1. This is confirmed by Duley and Kelly (1939), who found that the infiltration rate on native sod with a good cover was several times that of bare ground.

Duley and Domingo (1949) found that total cover, including live grass and associated litter, was more important than the kind of grass or the type of soil in inducing a high water intake. Dyksterhuis and Schmutz (1947) noted that natural mulch was a primary factor in determining the amount of infiltration of water into rangeland. Rauzi (1960) found that the water intake increased with the increase in the amount of natural mulch and standing vegetation. Meeuwig (1965) states that infiltration capacity is influenced primarily by soil bulk density on non-capillary porosity, and secondarily by the amount of protective cover afforded by plants, litter and stone. Soil stability is influenced primarily by the density of protective cover, and secondarily, by soil bulk density.

According to Singer and Blackard (1978) cover shape and distribution of intercover space appears to be important in affecting sediment loss. Runoff volume is significantly reduced by high cover levels which protect the soil from sealing and maintain a high infiltration rate.

Both Tomanek (1948) and Hopkins (1954) showed that a relationship exists between the amount of natural mulch and the moisture content of rangeland soils. However, according to Crosby, et al. (1980) the influence of surface mulch on soil loss is much greater that it is on runoff. Rhodesian experiments (Hudson, 1961) where field plots were protected by gauze showed that after nine years the soil loss from the unprotected plot was 127 times greater than that from the protected plot, while runoff from the unprotected plot was 13 times greater.

Wischmeir and Smith (1978) identified three main subfactors of the cover-management factor (c) in the Universal Soil Loss Equation, viz : surface cover, canopy cover, and below surface effects. Dissmeyer and Foster (1981) demonstrated that these factors were not sufficient in estimating total soil loss from a site, and suggest that the cover-management factor should consist of nine sub-factors, viz : amount of bare soil, canopy, soil reconsolidation, high organic content, fine roots, residual binding effect, on-site storage, steps, and contour tillage.

Land use, past and present, plays an important role in the determination of infiltration loss and soil loss. Aina (1979) found that continuous long term arable cultivation resulted in rapid deterioration of the physical properties of the soil, whereas fallowing improved soil physical properties and resulted in nutrient accumulation. Alderfer and Robinson (1947) found runoff losses to vary from 0 to 2 percent in ungrazed range and from 33 to 80 percent on heavily grazed range. However, Johnson (1962) showed that even after ten years of very heavy grazing soil erosion by water is not a critical factor in management. The water intake rates increase with increasing amounts of standing vegetation and mulch.

Rauzi and Hanson (1966) demonstrated that water intake rates on differentially grazed watersheds are nearly linear with heavily grazed watersheds having the lowest, and lightly grazed watersheds the highest rates. Annual runoff was greatest from the heavily grazed sites and least from the lightly grazed sites. McGinty, et al. (1978) showed that terminal infiltration rates for a pasture in a rotation grazing system and a long term exclosure were very similar, whereas a heavily, continuously grazed pasture exhibited less than one half of the terminal infiltration rate of the rotation pasture and exclosure. Wood, et al. (1978) found similar trends in Texas and state that in some ecosystems a grazing system may not increase plant production more than a light or moderately stocked, continuous grazing system. However, where increased plant production can be accomplished by implementing a grazing system, increased infiltration and decreased sediment production can be expected.

Glover, et al. (1961) found that the depth of rainwater penetration is approximately equal to the height of the plant plus the normal penetration of the shower into bare soil. It is considered by these authors that in the overgrazed dry grassland parts of Kenya, stemflow and rainwater penetration around trees may now be playing a part in changing the character of the local vegetation. It is also suggested that leaf catchment and stemflow systems may be involved in the maintenance of grassland vegetation patterns.

Walker (1974) states that the low rate of infiltration on bare areas in southeastern Zimbabwe is due mostly to the presence of a soil cap, and the effect of this cap is frequently intensified by the development of an algal crust, mainly composed of blue-green algae (Cyanobacteria) (Dulieu, et al. 1977). During dry periods this crust forms a hydrophobic, impermeable surface, and observations in the laboratory have shown that it takes up to two hours, or longer, for the surface to soften and absorb water. This is considerably longer than the duration of an average rainstorm.

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According to Chow (1964) a further cause of reduced infiltration is the presence of a layer of small vesicles near the surface of the soil, which effectively prevent water percolating through. In the vegetated areas, water infiltration through the base of a grass tuft is very rapid, and the perennial caespitose tufts funnel water into their own rhizospheres (Glover, et al. 1961).

3 Materials and Methods.

3.1 Additional objectives.

In addition to the prime objective of the study, several key questions arise from the literature. Savannas are water limited systems (Walker, 1974) and the most important input of water into the soil is through infiltration. Therefore, any factors which influence the rate of water infiltration into the soil need to be considered. From the literature review, several site variables influence infiltration rate (Kelly and Walker, 1976 ; Dissmeyer and Foster, 1981). It was considered important to measure these factors and determine how they influence infiltration rate, and how these factors change with different degrees of woody density under different environmental conditions. Since nutrients are probably associated with the movement of water through the soil, the distribution of certain nutrients in relation to changes in the bush-grass balance need to be determined.

Also, several hypotheses on the establishment of woody seedlings in South African savannas have been postulated (Walter, 1971; Mostert, <u>et al</u>., 1971: Donaldson, 1974). A question which arises is : what are the general conditions associated with the successful establishment of woody plants?

3.2 Site selection.

The aim was to select as many sites as possible, representing areas that have a high woody density and those that don't. It was, therefore, important to cover as many combinations of soil type, rainfall, and past management history as possible, in order to give a significant overview.

The sites chosen were, therefore, in areas that had experienced, or were experiencing, an increase in woody elements, and also areas that have had a long history of heavy grazing pressure without an increase in the woody component.

All the areas selected fall into the broad vegetation type of Bushveld as defined by Acocks (1953) (fig. 1), and as many of the variations of this vegetation type as possible were sampled. Sites were not only situated in cattle ranching situations, but also on game ranches, with mixed indigenous herbivores and cattle, on private farms with cattle and domestic browsers, and on game reserves. This served to give a generalized overview of the phenomenon of increased woody density.
The sites, which were spread over all four provinces of the Republic of South Africa, were located as follows (fig. 2) :

1. Transvaal.
   Messina Agricultural Research Station
   Mara Agricultural Research Station.
   Towoomba Agricultural Research Station

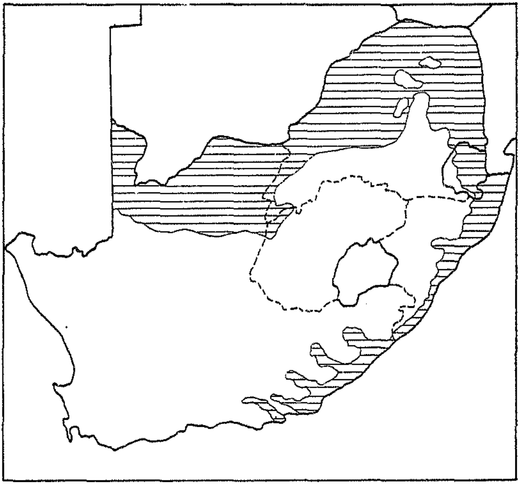

Fig. 1. Map of South Africa showing the extent of the Bushveld vegetation type (shaded area) (after Acocks, 1953).

Klaserie Private Nature Reserve
Cattle ranches in the Thabazimbi
and Zeerust districts.

2. Natal
Umfolozi Game Reserve
Hluhluwe Game Reserve

3. Northwestern Cape
Private farms in the Molopo region
around the towns of Tosca and Bray.

4. Eastern Cape
Adelaide Experimental Station
Private farms in the Adelaide, Bedford
and Fort Beaufort districts.
Alice Experimental Farm of the
University of Fort Hare.

3.3. Field Methods.

Once the areas had been visited and identified, representative sites of 400m² were laid out and each site characterized according to its vegetative, physical, climatological, and past management attributes.

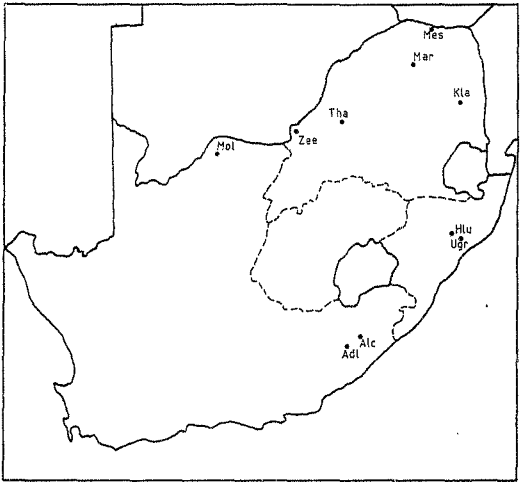

Fig. 2. Map of South Africa showing the position of the study regions. (legend overleaf)

Mes	Messina Agricultural Research Station
Mar	Mara Agricultural Research Station
Kla	Klaserie Private Nature Reserve
Tha	Thabazimbi district
Zee	Zeerust district
Mol	Molopo region
Hlu	Hluhluwe Game Reserve
Ugr	Umfolozi Game Reserve
Alc	Alice Experimental Farm
Adl	Adelaide district

Fig. 2 (cont.) Key to abbreviations used for all maps, figures and tables.

Mes	Messina Agricultural Research Station
Mar	Mara Agricultural Research Station
Kla	Klaserie Private Nature Reserve
Tha	Thabazimbi district
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Fig. 2 (cont.) Key to abbreviations used for all maps, figures and tables.

3.3.1 The Vegetation.

The vegetation was measured to give an overall impression of the present status of the sites, and also to determine the relationships between the various components. For the purpose of this study the vegetation was sub-divided into two components.

3.3.1.1. Grass.

Grass and herb basal areas were measured using a ten point frame (Levy and Madden, 1933). Eight hundred points were set out on transects within each plot. From these data the percentage rooted grass basal area (live and dead) and the herb basal area were calculated.

Grass height was determined from 16 sample points within each site and the mean calculated to give a single value for the whole stand.

It was considered unnecessary to obtain an accurate measure of the species composition of the grasses occurring on each site because of the variation in species composition within and between the areas visited. However, a ranking scheme was used to record the dominant grass species within each site.

3.3.1.2 Woody Species.

Two procedures were used to measure this component.

3.3.1.2.1 Initial Procedure.

The amounts of the woody component are central to this study and provide a measure for the degree of bush encroachment. An accurate measure of the characteristics of the woody component was therefore desirable.

Woody basal area was determined by measuring the basal circumference of each woody plant, at the soil surface, within a site. These values were transformed to area values, using the equation for the area of a circle, and summed to give the total woody basal area for the site. These data were expressed as the percentage of the site that was covered by woody basal area.
A similar procedure was used to obtain woody density, expressed as the number of woody individuals per hectare. No attempt was made to separate the woody size classes. Woody canopy dimensions were determined assuming that the area of an ellipse approximates an average woody canopy in horizontal section. To determine the area, the maximum canopy spread and an orthogonal minor canopy spread was measured for each woody plant within a site, and the summed woody canopy area expressed as a percentage of the surface area of the site.

3.3.1.2.2 Ranking scheme.

The physical measurement of each woody plant was found to be very time consuming, and a ranking scheme was

developed from existing data to enable a more rapid measurement of each site. The woody species were ranked into ten size classes and by using the midpoint of each class, the predicted values were within 9% of the original data for basal area, woody density, and canopy area.
Using this ranking scheme, the number of sites measured could be greatly increased, still maintaining a reasonable level of accuracy.

3.3.2 Soils

3.3.2.1 Soil surface characteristics.

With an increase in woody density there are often related changes in the soil surface characteristics (Barnes, 1973). These characteristics were measured using a ten point frame. Eighty of these frames were set out in each site, giving a total of 800 points. The following soil surface characteristics were recorded at each sampling point :

(i) Bare disturbed soil (hoof imprints, termite activity)
(ii) Bare undisturbed soil
(iii) Clay capping (surface sealing)
(iv) Algal capping (microfloral crusts)
(v) Litter (total vegetative litter)
(vi) Stones (particles less than 2.5cm in diameter)

(vii) Rocks (particles greater than 2.5cm in diameter)

(viii) Dung

The number of strikes for each variable were recorded and expressed as a proportion of the total number of points, giving a percentage of the surface area covered by each factor in each site.

3.3.2.2 Soil samples.

The soil was sampled at four points within each site. Samples were taken from the topsoil (i.e. 150mm below the soil surface), immediately below the grass roots (300 - 400mm below the soil surface), and from the subsoil (at bedrock, or as deep as possible with the instruments available).
Soil depth was determined at each of the sampling points, using a screw type auger, and averaged to give a single value of soil depth for each site.

3.3.3 Management history.

Past and present management history was obtained from individual landowners and the governing bodies under whose jurisdiction the management of the areas fell. These data were often unreliable and difficult to obtain because of the lack of records from many of the farms in the remote areas. In those areas where records do exist, data concerning grazing management, fire management, and bush control were collected.

3.3.4 Climatological data.

This information was obtained from meteorological stations in each region. Annual rainfall and seasonal distribution records were used.

3.3.5 Infiltration

3.3.5.1 Rainfall simulation.

High intensity thunderstorms account for most of the runoff and sediment production from rangelands in semi-arid and arid rangelands. Infiltration and sediment production experiments based on sporadic storm events are very seldom economically feasible. An alternate to natural precipitation is simulated rainfall applied to small plots (Blackburn, *et al.*, 1974). Rainfall simulation, the technique of applying water to plots in a manner similar to natural rainfall, is a tool that has been used for many years in studies of erosion, infiltration and runoff.

In the United States, simulation work began in the early 1930s, continued through the 1940s, and accelerated in the early and mid-1950s. Following this surge, simulation experienced rather modest growth until about ten years ago. There has been increasing interest during the last decade as evidenced by the number of people who are building and using simulators of either new designs or modifications and improvements of existing designs (Gifford, 1978).

Limitations and advantages of rainfall simulators have been discussed by Mech (1965) and Meyer (1965). However, as noted by Bubenzer (1979) rainfall simulators as a research tool have long since proved their value, and according to Gifford (1978), it appears that rainfall simulators are here to stay.
Bertrand and Parr (1961) indicate that the principle inadequacy of present day infiltrometers appears to be the absence of a widely acceptable method for determining soil infiltration rates. This fact is true even today. Gifford (ibid.) indicates that infiltrometers may be considered in two general groups : (i) Rainfall simulators, with the water applied in the form and at the rate comparable with natural rainfall, and (ii) Flooding type, with the water applied in a thin sheet upon an enclosed area and usually in a manner to obtain a constant hydraulic head.

Double-ring infiltrometers (Swartzendruber and Olson, 1961) are the commonly used instruments of the flooding type of infiltrometer. Rainfall simulators cover a wide range of designs and essentially fall into two categories : (i) spray type simulators, which include designs such as the Rocky Mountain infiltrometer (Dortignac and Love, 1960), where water is sprayed upwards through a nozzle to obtain terminal velocity of the simulated raindrops, the Purdue rainfall simulator (Bertrand and Parr, 1961) where water is spray'd downwards from an elevated nozzle, to very sophisticated designs with rotating booms covering large areas on the ground (Gifford, 1978), and (ii) modular, drip type simulators (Meeuwig, 1970; Malekuti and Gifford, 1978; Gifford, 1980) which are portable and utilize a drop forming module to simulate rainfall. This type of simulator has been shown to give reliable estimates of infiltration rapidly on small plots (Blackburn, et al., 1974), which allow a larger sample size over a shorter time period.

3.3.5.2 The Infiltrometer.

The infiltrometer used was a drip type rainfall simulator designed for use on rangeland in the south-eastern United States of America. It is a modular type infiltrometer originally designed by Meeuwig (1970) and later modified according to Malekuti and Gifford (1978), and has been used extensively for hydrologic studies (Gifford, pers comm.). This type of simulator was selected because it is very portable, uses relatively small amounts of water, and is simple to use by one operator (plate 1.).

The infiltrometer (fig. 3) will deliver simulated rainfall at intensities ranging from about 3 to 25cm.hr^{-1} over a plot size of 3413cm^2. Raindrop size is approximately 2.5mm in diameter, which approximates the mean drop size found in a typical rain storm (Laws, 1941; Bubenzer, 1979).

The drops fall from a height of 1.6m and reach a velocity about 30% of terminal velocity (Laws, 1941).

The infiltrometer consists of the following components (fig. 3) :

1. Water chamber : 60.9 by 60.9cm plexiglass box.
2. Flow meter : regulates the flow from the reservoir to the water chamber, and therefore the rate of rainfall.
3. Reservoir : 25 litre polyethylene container connected to the flow meter by flexible plastic tube.
4. Drop formers : 517 stainless steel tubes with a 0.476mm inner diameter and a 0.635mm outer diameter. The tubes project 3.2mm above and 9.5mm below the plexiglass base of the chamber.

There are no plot frames on the ground, only a trough on the downslope edge of the plot for delivering plot runoff to a bucket. Because the entire plot is sprinkled infiltration rates are somewhat exaggerated due to lateral movement (Gifford, 1978). The simulator is, however, portable and is well suited to steep slopes and to rocky soils, and only requires about 25 litres of water per 30 minutes at a rate of 7.5cm.hr^{-1}.

The design of Malekuti and Gifford (1978) used a rotating mechanism to give a randomized drop pattern on

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1. Water chamber : 60.9 by 60.9cm plexiglass box.
2. Flow meter : regulates the flow from the reservoir to the water chamber, and therefore the rate of rainfall.
3. Reservoir : 25 litre polyethylene container connected to the flow meter by flexible plastic tube.
4. Drop formers : 5:7 stainless steel tubes with a 0.4.3mm inner diameter and a 0.635mm outer diameter. The tubes project 3.2mm above and 9.5mm below the plexiglass base of the chamber.

There are no plot frames on the ground, only a trough on the downslope edge of the plot for delivering plot runoff to a bucket. Because the entire plot is sprinkled infiltration rates are somewhat exaggerated due to lateral movement (Gifford, 1978). The simulator is, however, portable and is well suited to steep slopes and to rocky soils, and only requires about 25 litres of water per 30 minutes at a rate of $7.5 cm.hr^{-1}$.

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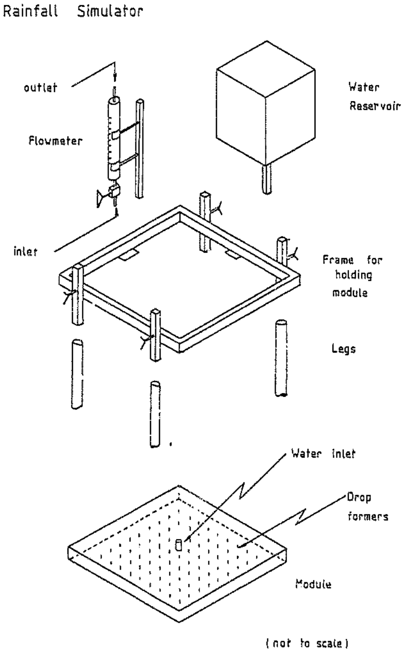

Fig.3 An exploded view of the modified rainfall simulator.

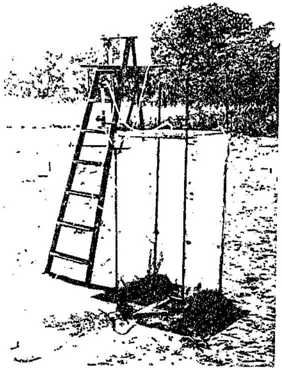

Plate 1. Rainfall simulator operating under field conditions.

the plot. However, for this study it reduced the portability of the instrument, and since under field conditions any slight air movement gave a satisfactory drop pattern on the plot surface, this mechanism was removed.

3.3.5.3 Determination of infiltration rate.

The rate of infiltration is determined as the difference between the amount of water applied and the amount of runoff collected. Runoff was collected at five minute intervals for 30 minutes, to construct an ltration curve for each site. For this reason a 'dry run' was carried out rather than pre-wetting the soil profile. Terminal infiltration was obtained from the infiltration rate readings after 30 mins., or when the amount of runoff remained constant. The infiltration rates were expressed as litres of water infiltrating per unit of time per unit area (that is $l.min^{-1}.m^2$).

3.4 Laboratory methods.

3.4.1 Soil sample analysis.

3.4.1.1 Soil sample preparation.

The soil samples from the field were analysed on return from a collecting trip. These were sieved through a 2mm soil sieve and oven dried for 48 hours at 85°C.

3.4.1.2 Soil pH.

A 1 : 2 suspension by weight of soil and 1M KCl was made up and the pH determined using a glass electrode electronic pH meter.

3.4.1.3 Electrical conductivity.

A 1 : 1 suspension by weight of soil and deionized water was prepared from each sample, allowed to stand, and the conductivity determined using a cell type conduct[illegible]ter. Soil conductivity gives an indica[illegible]the nutrient status of the soil suspensio (Buckman and Brady, 1969).

3.4.1.4 Soil texture.

The textural components of the soil were separated using the hydrometer method of Bouyoucos (1951). This method relies on differential rates of sedimentation of soil particles in an aqueous solution.
A sample of soil (50 - 100g) was suspended in deionized water with 1ml sodium hexametaphosphate (to disperse the clay aggregates), dispersed in a soil blender for five minutes, and made up to 1000ml with deionized water. After being shaken by hand, the specific gravity of the suspension was determined at 40 seconds and 120 minutes using a soil hydrometer. The percentages of sand, silt, and clay were calculated from these values (Bouyoucos, ibid.).

3.4.1.5 Soil cations.

The soils were analysed for their cation content. The cations measured were calcium, magnesium, potassium, and sodium. These were extracted from the soil samples using a 1:10 suspension, by weight, of oven dried soil and 1N ammonium acetate, shaken for half an hour and filtered. A small volume of strontium chloride was added to each sample to compensate for the masking effect caused by phosphorus in the soil. Following dilution, the amount of each cation in the soil suspension was measured using an atomic absorption spectrophotometer, and the concentrations determined using standard curves for the individual cations (this method was obtained from : Methods of Soil Analysis, Fertilizer Society of South Africa).

3.5 Data analysis.

3.5.1 Raw data transformation.

From the field data, woody basal area, woody canopy area, and woody density were calculated using the midpoint of each size class. The sites were grouped into a priori groups according to the woody density. This grouping was done within each region sampled. Within each region the sites are grouped into three sub-groups. The symbols used to denote the grouping are as follows :

1 = Open sites 0 - 500 bushes/hectare

2 = Slightly woody sites 500-2500 bushes/hectare

3 = Very woody sites above 2500 bushes/hectare

The grouping is arbitrary, but was found to be most convenient for the type of analysis used, providing an even spread of stands across the woody density classes.

3.5.2 Comparison of site factors with woody density.

A correlation matrix (r values) for all the measured site factors was determined for each region using the SAS computer package (Barr, et al., 1976). In addition all the site variables were compared to woody density using a plotting facility of the same computer package.

3.5.3 Discriminant analysis.

A multivariate technique was used to predict which variables (site factors) play an important role in the separation of groups according to the density of their woody component.
One such technique is discriminant analysis (Cooley and Lohnes, 1971; Cacoullos, 1973). The objective is to distinguish statistically between two or more groups of sites. To distinguish between groups, a collection of discriminating variables is selected that measure the characteristics on which the groups are expected to differ.

The primary data will therefore consist of k groups containing n_1, n_2, ..., n_k individuals respectively. Each of tha individuals will have been defined in terms of p variables which need not have been measured in the same units.

Discriminant analysis tries to analyse the problem by forming one or more linear combinations of the discriminating variables. These discriminant functions are of the form,

$$D_i = d_{i1}Z_1 + d_{i2}Z_2 + \ldots\ldots\ldots + d_{ip}Z_p$$

where D_i is the score on the discriminant function i, the d's are the weighting coefficients, and the Z's are the standardised values (Nie, et al., 1975) of the p variables used in the analysis. The mathematical derivation of the coefficients have been described by Cooley and Lohnes (1971) and Tatsuoka (1971). In general terms, it involves solving the eigenvector problem of the product matrix $W^{-1}B$, where B and W are, respectively, the between- and within-groups sums of squares and cross products matrices of the standardized variables (Davies, 1971).

The functions are formed in such a way as to maximise the separation of groups. Once the discriminant functions have been derived, one is able to pursue the two research objectives of this procedure, namely analysis and classification.

3.5.3.1 Analysis.

The analysis aspects of discriminant analysis provide several tools for the interpretation of data. Among these are statistical tests for measuring the success with which the discriminating variables actually discriminate when combined into discriminant functions. Since the discriminant functions can be thought of as axes in geometrical space, they can be used to study the spatial relationships among the groups. More importantly, the weighting coefficients can be interpreted much as in factor analysis or multiple regression. In this respect they serve to indentify the variables which contribute most to the differentiation along the respective dimensions.

3.5.3.2 Classification.

The use of discriminant analysis as a classification technique comes after the initial computation. Once a set of variables is found which provides satisfactory discrimination for sites with a known group membership, a set of classification functions can be derived which will permit the classification of new sites with unknown group membership.

Most classification equations are derived from the pooled within-groups covariance matrix and the centroids for the discriminating variables (Nie, et al., 1975).

The resulting classification coefficients are multiplied by the raw variable values, summed together, and added onto a constant. The equation for one group would appear as :

$$C_i = C_{i1}V_1 + C_{i2}V_2 + \ldots\ldots + C_{ip}V_p + C_{io}$$

where C_i is the classification value for group i, the C_{ij}'s are the classification coefficients with C_{io} being the constant, and the V's are the raw scores on the discriminating variables. There is always a separate equation for each group.

3.5.2.3 Computer packages.

The analyses were carried out using the discriminant analysis sub-programme of the Statistical Package for the Social Sciences (SPSS) adapted for use on an IBM 360/370 system. Some additional analyses were carried out using the Biomedical package (BMDP) which utilizes a similar algorithm to the SPSS analysis. (The algorithm and statistical procedures may be found in SPSS Update Manual, Release 8.0 - Algorithms for SPSS, McGraw-Hill, New York).

3.5.3.1 Interpretation of results.

In the sub-programme discriminant (SPSS) the standardized variables of the discriminant functions are always used. The value of the discriminant function is computed by multiplying each discriminating variable by its corresponding coefficient and adding together these products. There will be a separate value for each site in each function. The variables have been derived in such a way that they are in the standard form (Klecka, 1975). This means that over all the sites in the analysis, the value on one function will have a mean of zero and a standard deviation of one. Thus any single value represents the number of standard deviations that site is away from the mean for all cases on the discriminant function. By averaging the values for the sites within a particular group (degree of woody density), the group mean on the respective function is calculated. For a single group the means on all the functions are referred to as the group centroid, which is the most typical location of a site from that group in the discriminant function space.

The standardized discriminant function coefficients (standardized with respect to the measured variables) are of great importance. When the sign is ignored, each coefficient represents the relative contribution of its associated variable to that function. The sign merely denotes whether the variable is making a positive or negative contribution (Nie, et al., 1975). The interpretation is analogous to the interpretation of beta weights in multiple regression.

It is important to note that unstandardized coefficients do not reflect the relative importance of the variables, since they have not been adjusted for the measurement scales and variation in the original variables.

3.5.3.5 Rotation of discriminant axes.

The discriminant functions are derived in such a way that the first function separates the groups as much as possible. The second function separates them as much as possible in an orthogonal direction, given the first function. The end result is that the groups are as separate as possible given the original variables. As in factor analysis it may be useful to rotate the axes (discriminant functions) while holding constant the relative locations of the sites and the group centroids. This is done by Varimax solution available in the sub-programme discriminant (SPSS). It has the advantage of improving the interpretability of the new axes since the main variables contributing to each axis are highlighted. Such a rotation has no effect on the group separation and the relative location of new sites. It is however, important to note that although rotation of the discriminant axes have suggested in the statistical literature (Cooley and Lohnes, 1971), little, if any, treatment has been given to the consequences of such a rotation. Klecka (1975) therefore suggests that users should treat this feature as experimental and employ it only after acquiring a thorough understanding of the technique.

3.5.3.6 Selection methods.

In the discriminant analysis procedure of SPSS and BMDP, two methods of variable selection are available.

3.5.3.6.1 Direct method.

All the independent variables are entered into the analysis concurrently. The discriminant functions are created directly from the entire set of independent variables, regardless of the discriminating power of the independent variables.
The direct method is appropriate when, for theoretical reasons, the researcher wishes to have all the independent variables entered in the analysis, and is not interested in results based on subsets of the independent variables.

3.5.3.6.2 Stepwise methods.

The alternative to the direct method is to use a stepwise selection method. Independent variables will be selected for entry into the analysis on the basis of their discriminating power.
In many instances, the full set of independent variables may not be very useful in discriminating among the groups. By sequentially selecting the 'next best' discriminator at each step, a reduced set of variables will be found which is almost as good as, and sometimes better than, the full set (Klecka, 1975).

The use of a stepwise procedure results in an optimal set of variables being selected. The result is only optimal (rather than maximal) because not every possible subset is considered. The assumption is that the stepwise procedure is an efficient way of approximately locating the best set of discriminating variables. A maximal solution would require testing every possible subset to determine which would produce the very best result. This can be done using a jack-knife technique, but usually there are too many variations for this to be performed in a reasonable amount of time.

For the purpose of this study, where all the variables were considered to have equal importance initially, a direct analysis procedure was used throughout.

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4. Results and Discussion

4.1 Functional classes of variables.

Some thirty variables were measured to characterise each site (table 1). Although all are in some way associated with the status of the bush-grass community, some variables may be inherent to the site (i.e. the variables do not change with different combinations of the grass and woody components), whereas the remaining variables change as a result of a change in the combination of the woody and grass components.

The main list of variables were separated into two functional subgroups. For convenience, the variables that do not change as a result of increased woody density will be termed 'causal variables' and those which change as a result of increased woody density will be termed 'consequential variables' (table 1).

4.2 Infiltration rates.

The rate of water infiltration into the soil was calculated as the difference between the amount of water applied and the runoff collected. Runoff was collected over a 50cm by 50cm plot receiving a constant rainfall intensity of 800mm.$hour^{-1}$.
To obtain an infiltration curve for each simulated rainfall, cumulative runoff was collected and measured

Variable	Type
Grass basal area Herb basal area Mean grass height	Grass component
Woody basal area Woody density Woody canopy area	Woody component
Rocks Stones Topsoil sand content Subsoil sand content Topsoil clay content Subsoil clay content Topsoil silt content Subsoil silt content Soil depth	Causal variables
Litter Algal capping Clay capping Bare undisturbed ground Bare disturbed ground Dung Topsoil conductivity Subsoil conductivity Topsoil pH Subsoil pH Topsoil:subsoil calcium Topsoil:subsoil magnesium Topsoil:subsoil potassium Topsoil:subsoil sodium Infiltration rate	Consequential varaibles

Table 1. Functional classes of the measured variables.

at 5, 10, 15 and 30 minutes after commencement of the simulated rainstorm.

The infiltrometer used (Malekuti and Gifford, 1978) did not, however, produce many significant results. Runoff was only obtained from a few sites (table 2) although the instrument was used on over one hundred sites.

The only sta'istically significant results obtained from the use of this instrument were, not surprisingly, that under simulated rainfall conditions soils with a heavy texture (i.e. a high clay content) showed a lower infiltration rate after 30 minutes than soils with a coarse texture (fig. 4). It is of interest that the infiltration rate curves were similar for most sites, but the points of inflection and the rates of infiltration after 30 minutes varied from site to site. In coarse textured soil (sands), the applied rainfall is absorbed very rapidly into the soil profile and very little runoff occurs. On ine textured soils, however, the opposite effect was observed. Runoff decreases fairly quickly, probably due to some surface sealing, and the infiltration rate after 30 minutes is approximately one half that for coarse textured soils.

Unfortunately, the numbe on which runoff occurred was very small an ,nificant relationships were derived between the site variables and infiltration rates, with the exception of the soil textural characteristics.

Site	Infiltration rate ($l.min^{-1}m^{-2}$)				Soil type
	5 min.	10 min.	15 min.	30 min.	
Kla 1	0.56	0.56	0.20	0.18	Fine textured soils
Kla 2	0.56	0.53	0.20	0.16	
Kla 3	0.56	0.54	0.23	0.22	
Kla 4	0.56	0.56	0.55	0.45	
Ugr 1	0.50	0.48	0.42	0.30	
Ugr 3	0.56	0.53	0.48	0.35	
Ugr 4	0.56	0.50	0.53	0.23	
Ugr 5	0.56	0.55	0.49	0.28	
Ugr 6	0.56	0.50	0.51	0.41	
Ugr 9	0.54	0.52	0.48	0.23	
Ugr 10	0.54	0.48	0.41	0.25	
Ugr 11	0.56	0.52	0.51	0.43	
Ugr 12	0.54	0.48	0.43	0.25	
Ugr 13	0.56	0.52	0.50	0.29	
Mar 13	0.56	0.51	0.43	0.38	Coarse textured soils
Mar 14	0.56	0.51	0.49	0.40	
Mar 15	0.56	0.55	0.50	0.47	
Mar 16	0.56	0.51	0.49	0.47	
Mar 17	0.56	0.56	0.51	0.51	
Mar 19	0.56	0.55	0.52	0.51	
Mar 20	0.56	0.55	0.51	0.50	
Mar 31	0.56	0.55	0.51	0.51	
Mar 32	0.54	0.53	0.47	0.47	
Mar 33	0.56	0.55	[illegible]	0.47	
Mar 34	0.56	0.52	0.47	0.46	

Table 2. Infiltration rates on sites where runoff occurred.

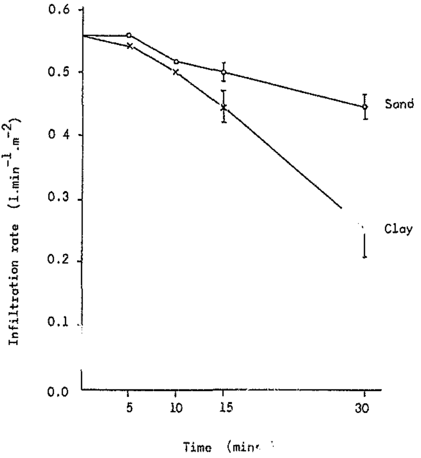


Fig. 4. Infiltration rates of so... ..th different textures.

A major drawback of the rainfall simulator is the low kinetic energy attained by the simulated raindrops. Laws (1941) showed that raindrops of 2.5mm in diameter attain only 30% of their terminal velocity when they fall from 1.5m in still air. To achieve 95% terminal velocity, and therefore 95% of maximum kinetic energy, the drops have to fall from a height of 7.5m. To use a modular rainfall simulator which is raised to this height above the soil surface, is not a feasible or practical solution under field conditions. However, Gifford (pers comm.) feels that the reduced kinetic energy obtained using this type of simulator should not be a critical factor, in that the objective of measuring infiltration was to obtain a comparative measure of the infiltration rate between sites, and not absolute rates of infiltration.
However, on the majority of sites measured, no runoff was collected after a 30 minute run, indicating that all the water applied infiltrated into the soil over this time period. This is, however, not the case under natural rainfall conditions as signs of surface flow of water were observed on almost all the sites.

This type of simulator does not seem to be suitable for use on South African soils, especially on coarse textured soils. Better results may be obtained if the soils are pre-wet to field capacity before the infiltration rates are determined to reduce the exaggerated infiltration rates caused by lateral infiltration. This may, however, change the soil surface characteristics, and the time period for terminal infiltration to be reached will not be determined. Another type of simulator may be used which can produce higher kinetic energies. These are usually of a spray type (Gifford, 1980) and are not very portable, using large amounts of water during a simulated rainfall.

4.3 Past management practices.

All of the sites measured occur in bushveld as defined by Acocks (1953). This vegetation consists of various combinations of herbaceous and woody components, and is used extensively for grazing, especially by cattle ranchers. Some game ranching is also carried out in these areas.

4.3.1 Grazing management.

The sites can be categorized into two broad management practices :

i) On privately owned farms and the agricultural research stations the vegetation is used almost exclusively for cattle ranching. Some indigenous game is present in some areas, but usually in relatively small numbers. The grazing intensity is determined by the landowner or from advice from the extension service of the Department of Agriculture, and stocking rates vary from area to area.
The areas under cattle ranching mostly utilize a

rotational grazing system, usually with additional watering points in each paddock. In some of the more arid areas, especially the Molopo district and the Messina region, below average rainfall for the past five years has led to severe overgrazing of the herbaceous component, and on many farms in the Molopo region very little, if any, grazing is left. Consequently, some of these farmers have had to sell off much of their livestock and the farming area is becoming severely de-populated.

(ii) The game reserves are stocked with herbivores with mixed feeding preferences. This means that unlike cattle ranches, under game reserve conditions both the woody and the herbaceous component is utilized by the animals. Because the numbers of the indigenous herbivores are difficult to monitor, and the animals are free ranging and tend to congregate on highly palatable areas, many of the game reserves are overstocked and the degradation of the herbaceous component is apparent in many cases.

4.3.2 Fire

Fire is not generally utilized as a management tool in agricultural areas, especially in the semi-arid savanna regions. In many cases the herbaceous component is low and there is no build up of moribund grass, and therefore no need for a burning policy. However, some landowners believe they can reduce the woody component of the veld by periodic burning. Because of the reduced herbaceous component in these areas, there is not a sufficient fuel load to create an intense fire to kill the woody plants. Accidental fires do, however, occur periodically, but are usually low intensity, ground fires because of the low fuel load.

In the game reserves fire is regarded as a useful management tool, and most of these areas have a fairly flexible fire policy. The purpose is generally to reduce the amounts of moribund grass which builds up as a result of the selective grazing habits of the free ranging animals.

Trollope (1980) has shown that fire, combined with a follow-up treatment with domestic browsers (goats) can be used to maintain the vegetation in a particular state in the eastern Cape. In this area there is a sufficient fuel load, in the form of a good grass cover, to maintain an intense fire to kill the woody plants. With a follow-up treatment with goats, which browse on the re-growth of the woody plants, Trollope (ibid.) has been able to maintain an open grassland type of vegetation for several years.

4.3.3 Bush eradication.

On only one of the farms visited, in the Zeerust district, was any concerted effort made to eradicate the woody component of the savanna vegetation to obtain a higher grass yield. In this area a foliar spray of TORDON 255 was applied by helicopter with an estimated kill rate of 80% of all woody plants. Unfortunately, no measurements were made before or after the arboricide was applied, and the only information available is in the form of observations by the landowner, who, in the short term, believes that the grass production on his farm has increased.

4.4. Results.

The analysis of the data as one large matrix would be of little use because of the large differences in rainfall and soil type that occur between the regions. An initial attempt was made to analyse these data as one matrix to determine whether any variables were associated with increasing woody density. However, no significant correlations or associations between woodiness and the site variables were found. For this reason the data were analysed and discussed regionally, i.e. within a broad climatic and vegetation variation of the bushveld.

4.4.1 Regional analyses.

4.4.1.1 Messina and Klaserie.

4.4.1.1.1 Description.

These areas fall into the broad category of mopaneveld and lowveld as described by Acocks (1953). As the name suggests, the dominant woody species is Colophospermum mopane interspersed with evergreen shrubs, mainly Euclea spp. and others. There are also some areas of mixed bushveld dominated by Sclerocarya caffra, Combretum apiculatum, and Acacia spp. The grass cover is sparse in mopane areas, increasing in basal area and palatability in the mixed bushveld areas. The woody density is generally high especially in the scrub mopane variation where the mean height of the woody plant is 2 - 3m
The soils are sandy (ab[illegible] and) with isolated deposits of calcium carb[illegible] in the Messina area. The rainfall is low, ranging from 300mm per annum in the western region to about 450mm per annum in the east, with most of the rain falling in high intensity thunderstorms in the early and late summer.

4.4.1.1.2 Interrelationships of site variables and woody density.

All the measured variables were plotted against woody density, and a correlation matrix was derived using the SAS computer package (Append[illegible] 2). Only the significant relations are presented here.

With an increase in woody density there is an increase in woody basal area (fig. 5). In these sites the most common woody species is Colophospermum mopane. Under a high woody density there is not a great deal of coppicing and most of the woody plants are in the 2 - 4 m size class, giving a high woody basal area. Also, under low woody densities, most of the trees are from a mixed bushveld vegetation type, and although the number of stems pe hectare is lower, many of the woody plants are trees with a large basal circumference.

Topsoil pH and subsoil conductivity both increase with increasing woody density (figs. 6 and 7, respectively). The latter implies that under sites with a high woody density nutrients are being leached into the subsoil. However, many of the stands with a high woody density, especially in the Messina area, occur on sites with calcium carbonate deposits which account for an increased topsoil pH (i.e. more basic) of these sites.

Woody density and subsoil sand content are positively correlated (fig. 8) but topsoil silt content decreases with increasing woody density (fig. 9). The water holding capacity of the topsoil therefore decreases with increased woody density.

4.4.1.1.3 Discriminant analysis.

The first discriminant function accounted for 56% of the variance, and indicates a trend from a grass

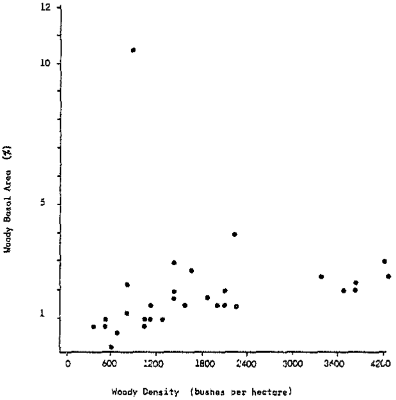


Fig. 5 The relationship between woody density and woody basal area in the Messina sites.

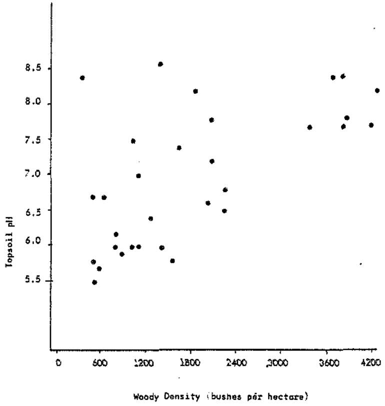


Fig. 6 The relationship between woody density and topsoil pH in the Messina sites.

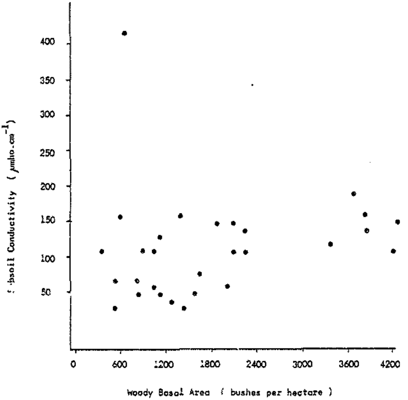


Fig. 7 The relationship between woody density and subsoil conductivity.

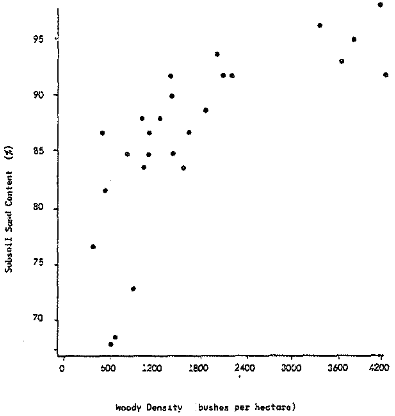


Fig. 8 The relationship between woody density and subsoil sand content in the Messina sites.

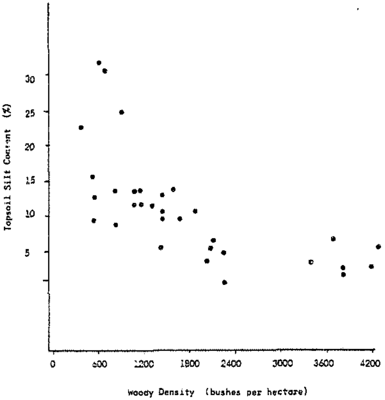


Fig. 9 The relationship between woody density and topsoil silt content in the Messina sites.

dominated vegetation type to a dense, woody dominated type. The all-groups scatterplot (fig. 10) includes the second discriminant function which accounted for the re ring 44% of the variance. The spatial orientation of these groups shows that they are fairly discrete with little overlap between groups on these axes.

The variables which are most strongly associated with this discrimination are litter, bare undisturbed soil, and topsoil conductivity (table 3). The numeric value of the canonical coefficients gives an indication of the importance of the variable to the derived discriminant function, with the sign denoting whether the variables are positively or negatively associated with the discrimination.

The variables with the highest numerical coefficients from this region imply that with an increase in woody density there is an increase in litter, which is derived from dropped leaves. Associated with this, there is an increase in the amount of bare soil with increasing woody density. This is accounted for by the dramatic decrease in grass basal area, from about 6.5% in open sites to virtually zero in sites with a high woody density.

The association between increasing woody density and decreasing topsoil conductivity indicates a lower

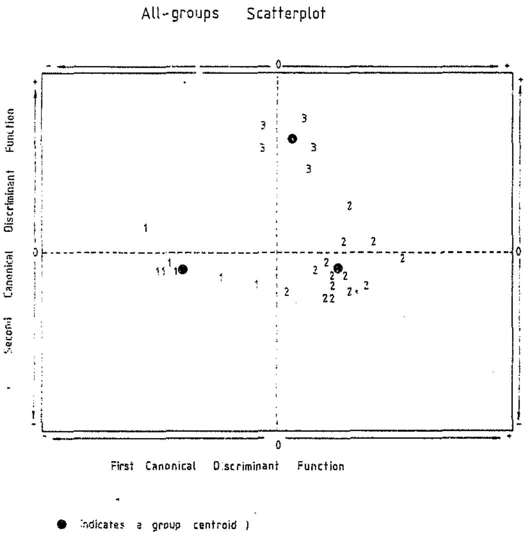


Fig. 10. The spatial orientation of the Messina and Klaserie sites in discriminant function space.

Standardized canonical discriminant function coefficients

Variable	Function 1	Function 2
Litter	6.35561	0.59829
Open disturbed ground	3.68805	3.40248
Open undisturbed ground	6.77768	1.28226
Algal capping	1.97400	0.38815
Clay capping	-1.32117	-1.10027
Rocks	0.68878	-0.19134
Dung	-1.81111	-0.06345
Topsoil conductivity	-2.77884	-3.57952
Subsoil conductivity	0.76919	0.659777
Topsoil pH	2.48071	0.39976
Subsoil pH	0.94584	0.88541
Subsoil sand	-0.40659	0.37606
Topsoil clay	-0.27757	-0.41582
Subsoil clay	-1.20245	-1.77445
Topsoil silt	-0.55848	-0.62835
Soil depth	0.07433	0.01505

Table 3. Standardized discriminant function coefficients for the Messina and Klaserie sites.

nutrient status of the topsoil under trees than in grass dominated sites. This is accompanied by a positive association of subsoil conductivity with increasing woody density. Taken together, these results suggest that under grass dominated sites the nutrients are held in the topsoil by the herbaceous component and there is very little loss to the subsoil via leaching. In sites with a high woody density, there is a great reduction in the herbaceous component which allows downward leaching of the nutrients to the subsoil.

Other consequential variables that show associations with increasing woody density are positive associations of algal capping and pH, and negative associations of dung and clay capping. These associations mainly indicate the degradation of the soil surface with increasing woody density. An interesting feature is that clay capping (surface sealing) shows a negative association whereas algal capping (microfloral crust) shows a positive association with the discriminant function. The formation of an algal cap may be associated with litter, which is high under the woody component and decreases in the well grassed sites. Clay capping, on the other hand, is associated with the grass component. The tree canopy provides an interception surface to incoming precipitation, thus reducing the kinetic energy of the drops before they strike the surface. This reduces the possibility of surface sealing. In a separate analysis, clay capping

Variable	Correlation coefficients
Grass basal area - mean grass height	0.715
Grass basal area - open disturbed ground	0.943
Grass basal area - clay capping	0.740
Grass basal area - topsoil conductivity	0.702
litter - open undisturbed ground	-0.894
Open disturbed ground - clay capping	0.911
Open disturbed ground - woody basal area	0.735
Open disturbed ground - topsoil conduc.	0.718
Clay capping - woody basal area	0.879
Topsoil pH - subsoil pH	0.774
Subsoil sand - topsoil silt	0.800
Topsoil clay - subsoil clay	-0.976
Subsoil clay - woody density	0.712

Table 4. Significant correlations (r values with probabilities of less than 0.001) of variables from the Messina sites.

shows a positive correlation with grass basal area (table 4) which may support the above hypothesis. However, clay capping also shows positive correlations with woody basal area and open undisturbed ground (table 4) which are both associated with increasing woody density. Also, there is no real evidence for implying a causative relation between algal capping and litter, and between clay capping and grass basal area.

Of the causal variables (i.e. the physical features of the site) soil depth is most strongly (and positively) associated with increasing woody density, implying that sites with a high woody density occur on deep soils and *vice versa*. There is also a negative association of topsoil silt with increasing woody density. This may lend some support to the hypothesis proposed by Walter (1971). Well grassed sites have a higher topsoil silt content than sites with a high woody density, giving the topsoil in the former sites a higher water holding capacity. However, in an independent analysis, topsoil silt is positively correlated with topsoil sand. This implies that topsoil clay content, which is the third component of soil texture, must increase with increasing woody density. However, subsoil and topsoil clay content have a strong negative correlation with each other ($r = -0.976$) and subsoil clay shows a positive correlation with woody density ($r = 0.712$). This is, however, contradictory in that the correlations, which were derived independently from the discriminant analysis, show that topsoil clay content decreases with increasing woody density.

Rockiness shows a positive association with the discriminant function indicating that sites with a high woody density have a greater amount of rocks on the soil surface than sites with a good grass cover.

4.4.1.1.4 Woody species composition.

The woody species which showed the highest densities in this area, in order of common occurrence, are :

Colophospermum mopane

Dichrostachys cinerea

Acacia nigrescens

Combretum apiculatum

Terminalia prunioides

From the data collected it is not possible to state which of them are aggressive, but the sites with the highest woody densities had dense stands of either Colophospermum mopane or Dichrostachys cinerea. According to Acocks (1953) and Drummond and Coates Palgrave (1973) Colophospermum mopane is usually considered to be soil type dependent and increasing density usually only occurs through coppicing (i.e. not strictly an invader). Dichrostachys cinerea, on the other hand, has been shown to be an aggressive invader, usually in areas of disturbance.

4.4.1.2 Thabazimbi and Zeerust.

4.4.1.2.1 Description.

The sites from these areas are all situated on privately owned cattle ranches. The main aim in visiting this region was to locate fence-line contrast sites which have different combinations of grass and woody components on either side of a fence as a result of different management practices. However, several other sites were also measured. Only the latter were used in the analyses since those subjected to artificial clearing would obviously invalidate relationships between current measurements of woody density and soil factors.

The region falls into the broad vegetation type of sourish mixed bushveld (Acocks, 1953). Rainfall is variable, ranging from 400mm per annum in the west to about 500mm in the Thabazimbi area. The soils are generally deep and sandy in texture.

4.4.1.2.2 Interrelationships of site variables and woody density.

In an initial analysis where all the measured variables were correlated with each other, and were plotted against woody density (Appendix 2) only dung (fig. 11) and grass basal area (fig. 12) showed significant relationships with woody density. With an increase in woody density there is an increase in the amount of dung on the soil surface, indicating that the animals prefer these sites, probably as a refuge for shade. Grass basal area declines with an increase in trees, but some of the more palatable grass species (Panicum maximum) occur more frequently under tree canopies and this may account for an increase in dung on the soil surface of sites with a high tree density.

4.4.1.2.3 Discriminant analysis.

In these sites the two extremes of woody density (i.e. open and very woody sites) were used in the discriminant analysis, excluding those that had been bush-cleared, resulting in a single discriminant function being derived.
The frequency of the individuals in each group were plotted along this axis (fig. 13), where 1 denotes open sites and 2 denotes woody sites. The degrees of woody density are fairly distinct along the discriminant function, with a small amount of mixing, showing a trend from low to high woody density (fig. 13).

The variables which are strongly associated with this trend are litter, bare soil, algal capping, subsoil pH, subsoil sand, and topsoil pH, mostly consequential variables.

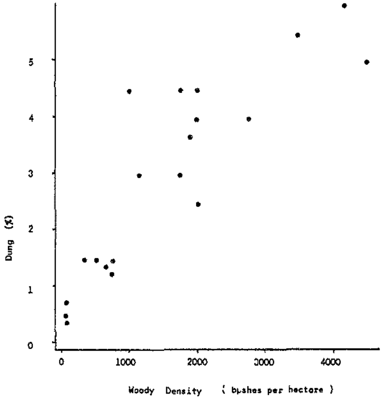


Fig. 11 The relationship between woody density and dung in the Thabazimbi and Zeerust sites.

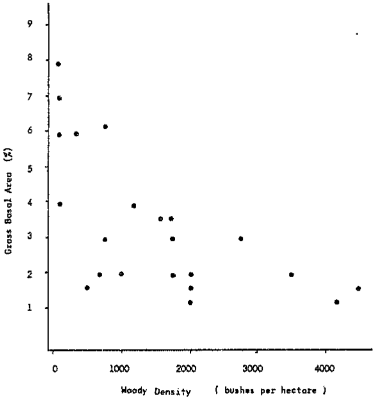


Fig. 12 The relationship between woody density and grass basal area in the Thabazimbi and Zeerust sites.

As in the Messina sites, litter and algal capping increase with increasing woody density. Litter is mainly derived from the woody species, since the herbaceous layer is well utilized throughout the year and very little litter accumulates. Algal capping and litter again seem to be associated with each other and the development of a microfloral crust may require the slightly increased moisture status of the topsoil under the layers of deposited litter, or under a tree canopy.
With increasing woody density there is a decrease in the amount of bare soil, probably as a result of an increase in litter under the woody plants. This is supported by a negative correlation between litter and bare soil (r = -0.70) (table 6). However, the sites were sampled in winter when the dominant woody species, Acacia erubescens, had shed its leaves.

Subsoil pH and subsoil sand content show a positive association with the discriminant function. This implies that under high woody densities, nutrients are being leached from the topsoil into the subsoil thus changing the acid-base status. Subsoil pH and subsoil clay are negatively correlated (r = -0.829) indicating, by deduction, a lower subsoil clay content in sites with a high woody density (table 6).

As in the Messina sites, which also occur on sandy soils, the sites from Thabazimbi and Zeerust also had the highest woody densities on deep soils.

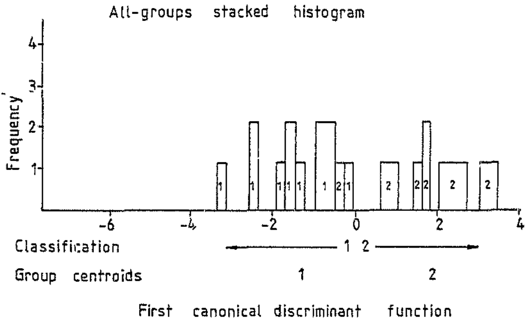


Fig. 13. The frequency and distribution of stands long the discriminant function for the Thabazimbi and Zeerust regions.

Standardized canonical discriminant function coefficients

Variable	Function 1
Litter	1.30624
Open disturbed ground	-1.05357
Open undisturbed ground	-0.99621
Algal capping	1.89830
Rocks	0.22137
Dung	-0.59872
Topsoil conductivity	0.69072
Subsoil conductivity	0.77364
Topsoil pH	-0.27819
Subsoil pH	1.21805
Subsoil sand	1.15577
Topsoil clay	-0.07964
Subsoil clay	-0.23114
Topsoil silt	0.72479
Soil depth	1.68018

Table 5. Standardized discriminant function coefficients for the Thabazimbi and Zeerust sites.

Variable	Correlation coefficients	Probability
Grass basal area - herb basal area	0.649	0.0008
Grass basal area - dung	-0.644	0.0009
Woody density - dung	0.885	0.0001
Litter - open disturbed ground	-0.700	0.0002
Dung - topsoil conductivity	0.848	0.0001
Open undisturbed ground - topsoil silt	-0.781	0.0001
Subsoil pH - subsoil clay	-0.829	0.0001

Table 6. Significant correlations (r values) of variables from the Thabazimbi and Zeerust sites.

4.4.1.2.4 Woody species composition.

The most common woody species differ slightly between the two areas. In the Thabazimbi area they are :

Acacia erubescens
A. tortilis
Grewia bicolor
G. flava
Rhus lancea

In the Zeerust area they are :

Acacia erubescens
Tarchonanthus camphoratus
Acacia mellifera
A. karroo

Acacia erubescens is, however, the most dominant woody species in both areas. Generally the western area is fairly encroached with woody densities reaching 4500 bushes per hectare. However, many of the high densities are found on sites which may have been disturbed in the past. On these *Acacia erubescens* and *A. mellifera* form dense thickets. According to farmers in the district, bush encroachment is only a serious problem in the region to the west of Zeerust. The remaining area is essentially a mixed bushveld, woody dominated, with thickets forming around sites of disturbance (e.g. watering and feeding troughs). In the Thabazimbi area, the farmers interviewed feel that bush encroachment is at present not a serious problem in the immediate district, but woody densities increase on sites to the west and northwest where soils are generally deeper and Acacia erubescens forms dense stands. Many of the high density sites in the Thabazimbi district are found on soils where cultivation may have taken place in the 1930s.

4.4.1.3 Molopo region.

4.4.1.3.1 Description.

The thirty sites measured in this region occur in the vegetation type of Kalahari bur[illegible]d as described by Acocks (1953). Of prime interest were the areas dominated by Acacia mellifera. They occur to the northwest of Vryburg, near the towns of Tosca and Bray on the boundary between the Republic of South Africa and Botswana. The area is used extensively for cattle ranching, mostly on natural veld, although some farmers do supplement grazing from irrigated planted pastures.

The soil is deep and very sandy with deposits of calcium carbonate. The rainfall is low, about 350mm per annum, and very erratic, falling mainly in the summer. For the past five years severe drought has been a serious problem in the area, leading to large scale over-utilization of the veld.

4.4.1.3.2 Interrelationships of site variables and woody density.

Only grass basal area showed a significant relationship when correlated with woody density (fig. 14). With an increase in woody density there is a decrease in grass basal area. The reduction is severe in sites with a very high woody density (5000 - 7000 bushes per hectare) where grass basal area ranges from 0% to 0.5%.

4.4.1.3.3 Discriminant analysis.

Two discriminant functions were derived from these data, showing a trend from open and slightly woody sites to sites with a very high woody density. The geometrical representation of these functions (fig. 15) shows the three degrees of woody density to be separate with very little overlap between groups. The first canonical axis accounts for 60% of the variance between these groups.

The variable most strongly associated with the discriminant function are topsoil conductivity, subsoil sand and silt (table 7). Algal capping, litter, and bare ground show positive association with increasing woody density, as they did in the sites from the Messina Agricultural Station.

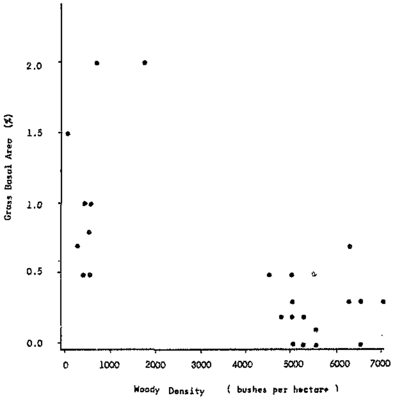


Fig. 14 The relationship between woody density and grass basal area in the Molopo sites.

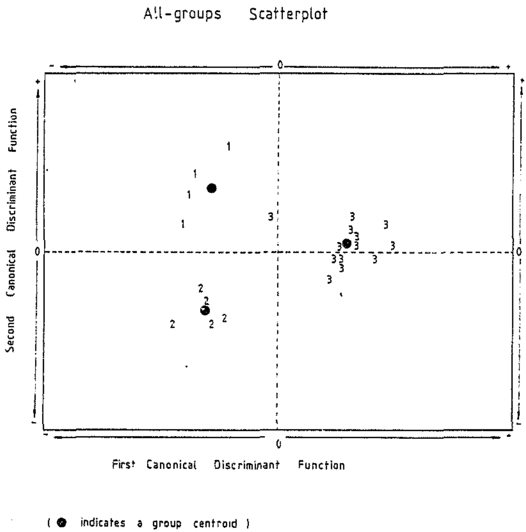


Fig. 15. The spatial orientation of the Molopo sites in discriminant function space.

Standardized canonical discriminant function coefficients

Variable	Function 1	Function 2
Algal capping	1.30523	0.17342
Rocks	1.71502	-0.59138
Open undisturbed ground	0.39425	0.51575
Topsoil conductivity	-2.39425	-0.00812
Subsoil conductivity	1.93014	-0.52287
Topsoil pH	1.53427	1.91360
Subsoil pH	-0.89472	0.44571
Topsoil sand	0.25010	-0.10057
Subsoil sand	2.11008	1.57622
Topsoil clay	1.53686	-1.10235
Subsoil clay	2.34576	-0.12539
Topsoil silt	0.34443	-0.44238
Subsoil silt	3.85190	1.04748
Topsoil:subsoil Magnesium	-0.58249	0.13266
" " Potassium	-0.80423	0.64321
" " Sodium	0.76055	-1.05629
Soil depth	-0.59268	0.81849

Table 7. Standardized discriminant function coefficients for sites in the Molopo region.

Variable	Correlation coefficients
Woody basal area - grass basal area	-0.701
Litter - open undisturbed ground	-0.920
Topsoil pH - subsoil pH	-0.995
Topsoil silt - topsoil sand	-0.859
Subsoil silt - subsoil sand	-0.878
Sodium - topsoil pH	0.886
Sodium - subsoil pH	-0.879
subsoil clay - subsoil silt	-0.787

Table 8. Significant correlations (r values with probabilities of less than 0.001) of variables from the Molopo sites.

Variable	Correlation coefficients
Woody basal area - grass basal area	-0.701
Litter - open undisturbed ground	-0.920
Topsoil pH - subsoil pH	-0.995
Topsoil silt - topsoil sand	-0.859
Subsoil silt - subsoil sand	-0.878
Sodium - topsoil pH	0.886
Sodium - subsoil pH	-0.879
subsoil clay - subsoil silt	-0.787

Table 8. Significant correlations (r values with probabilities of less than 0.001) of variables from the Molopo sites.

Soil conductivity also shows a strong association with the discriminant function. With an increase in woody density there is an increase in subsoil conductivity and a decrease in topsoil conductivity. Associated with this is a decrease in the topsoil to subsoil ratio of sodium and an increase in the topsoil pH. However, because of the extremely low actual values of sodium in the soil in comparison to those of the other measured cations, the correlations of sodium and soil pH may be of little significance. The changes in the conductivity and cation status of the soil indicate a movement of cations through the soil in areas with a high woody density. However, an increase in the topsoil pH does not support this leaching hypothesis. If the nutrients are being leached out of the topsoil they are usually replaced by hydrogen ions which lower the pH of the soil. Because of the localized deposits of calcium carbonate in these soils, woody species may prefer to grow in association with these deposits thus showing an increasing topsoil pH with increasing woody density (as found in the Messina sites). The only evidence supporting this idea is that increasing woody density is associated with surface rocks, and most of these are calcareous in composition.

The causal variables do show some association with the discriminant functions. With an increase in woody density there is an increase in the amounts of topsoil sand and silt. However, silt and sand have negative correlations for the topsoil and subsoil components (r = -0.859 and r = -0.878 respectively) (table 8).

4.4.1.3.4 Woody species composition.

The most common woody species occurring in this area are :

Acacia mellifera
Acacia hebeclada
Carissa bispinosa

with Acacia mellifera being very widespread and almost mono-dominant in most sites. Donaldson (1974) described this region as seriously encroached by blackthorn (Acacia mellifera). This situation appears to have deteriorated over the past few years, probably as an effect of drought, and exceptionally dense stands of this species occur over large regions. Acacia hebeclada often form dense patches of scrub thicket in the open spaces between the blackthorn trees, causing many of these stands of vegetation to be impenetrable to livestock and game.

4.4.1.4 Mara

4.4.1.4.1 Description.

Mara Agricultural Research Station lies just to the south of the Soutpansberg in the northern Transvaal, within Acocks' (1953) mixed bushveld. Rainfall is about 450mm per annum, with most of the rain falling in the mid-summer months (December to February). The research station has a wide variety of soil types giving rise to a distinct mosaic of vegetation. However, most of the soils fall into the loamy sand category, nerally of the Hutton and Glenrosa forms (Mcvicar, et al., 1977).

The research tion is grazed primarily by cattle, but some indigenous herbivores are still present and these tend to graze selectively since they are not confined by fencing within the farm. In general this area supports a much higher grass basal area and a lower woody density than the Thabazimbi or Messina sites. There is also a higher diversity of woody species, and these occur in local dense stands.

4.4.1.4.2 Interrelationships of site variables and woody density.

Gr rass basal area and woody basal area showed significant correlations. With an increase in woody density there is an increase in woody basal area (fig. 16) (r = 0.807, p = 0.0006) and a decrease in grass basal area (fig. 17) (r = -0.592, p = 0.0001).

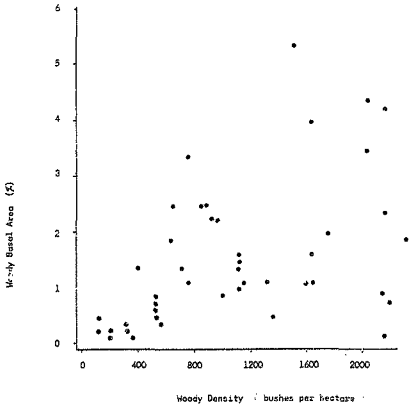


Fig. 16 The relationships between woody density and woody basal area in the Mara sites.

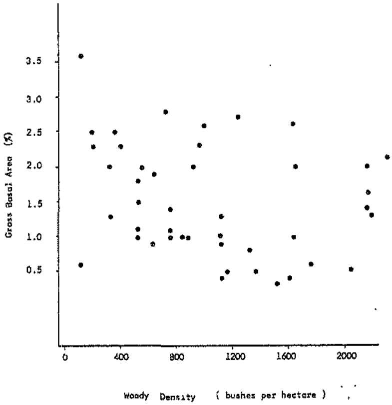


Fig. 17 The relationship between woody density and grass basal area in the Mara sites.

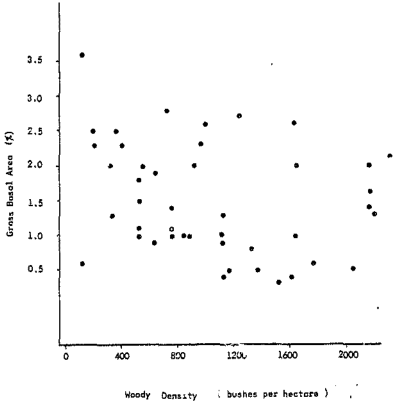


Fig. 17 The relationship between woody density and grass basal area in the Mara sites.

4.4.1.4.3 Discriminant analysis.

The first discriminant function accounted for 60% of the variance, showing a trend from sites with a high to those with a low woody density. However, the geometrical representation of the discriminant functions shows that the degrees of woody density do not form discrete groups. There is a large amount of overlap between them resulting in a continuum rather than a discrete grouping (fig. 18). This is a result of the high woody species diversity within this region, hence the name mixed bushveld.

Most of the variables which show an association with the discriminant function are consequences of increased woody density (table 9). Bare ground shows a negative association with the discriminant function. Despite the lower tree density in this region, there is still evidence of a litter build up under the trees, derived from the deciduous nature of the woody species. However, with increasing woody density there is an increase in the amount of bare soil. This situation arises from the fairly heavy defoliation of the herbaceous component in these areas, resulting in no grass litter build up, as suggested by a significant negative correlation ($r = -0.915$) between litter and bare soil (table 10). With a decrease in woody density there is an increase in dung on the soil surface.

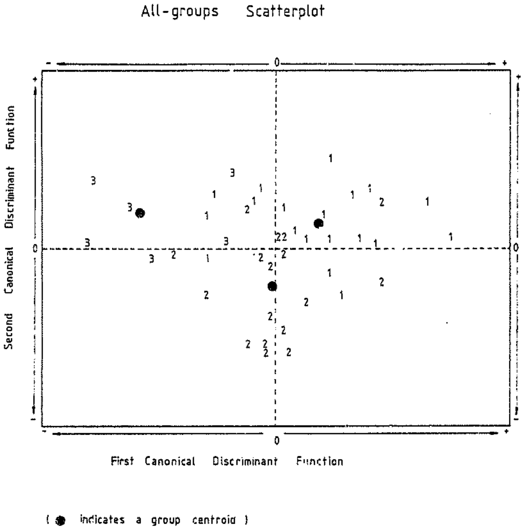


Fig. 18. The spatial orientation of the Mara sites in discriminant function space.

Standardized canonical discriminant function coefficients

Variable	Function 1	Function 2
Litter	-0.02437	1.48615
Open disturbed ground	-0.19438	0.26085
Open undisturbed ground	1.07832	1.51085
Algal capping	0.52443	0.65186
Clay capping	-0.34277	-0.22309
Rocks	0.06052	-0.55794
Dung	0.91299	1.27567
Topsoil conductivity	-0.35322	-0.1[illegible]
Subsoil conductivity	0.36915	-0.61[illegible]
Topsoil pH	0.56114	-0.44364
Subsoil pH	-0.60755	-0.14271
Subsoil sand	-1.46708	-0.20336
Topsoil clay	0.34130	-0.02556
Subsoil clay	0.16487	0.28654
Topsoil silt	0.63576	0.38376
Soil depth	0.26855	-0.56554

Table 9. Standardized discriminant function coefficients for the Mara sites.

Variable	Correlation coefficients.
Litter - open undisturbed ground	-0.915
Subsoil sand - topsoil silt	-0.787
Topsoil clay - subsoil clay	-0.879

Table ificant correlations (r values with probabilities ss than 0.001) of variables from the Mara sites.

Loosely interpreted, this implies that the animals may spend more of the time in the areas of a low woody density, probably because of the high palatability and availability of the herbaceous component, mostly Digitaria eriantha and Schmidtia pappophoroides.

In dense sites there is a decrease in the topsoil pH and an increase in the subsoil pH. This indicates, as in previous areas, that nutrients are being lost from the topsoil and are accumulating in the subsoil. The interpretation is that with an increase in woody density there is a reduction in the herbaceous component which is unable to use all the water entering the soil. As a result, some of this water percolates to the subsoil carrying some of the nutrients with it. This accounts for the lowered pH status of the topsoil and the more basic nature of the subsoil.

Of the causal variables, there is an increase in subsoil sand content and topsoil silt content, and a decrease in topsoil clay content, with increasing woody density. This is confirmed by a significant negative correlation ($r = -0.787$) between subsoil sand and topsoil silt, which was determined independently of the discriminant analysis (table 10).

4.4.1.4.4 Woody species composition.

As described earlier, woody species diversity in this mixed bushveld is high, and the most common woody species are :

- Acacia tortilis
- Grewia monticolor
- Acacia permixta
- Mundulea sericea
- Spirostachys africana
- Commiphora pyracanthoides

Of these, Acacia tortilis is the most widespread species, but the sites with highest woody density were usually localized stands of Grewia monticolor, Acacia permixta, or Mundulea sericea, which is not regarded as an encroaching species. The dense stands of Spirostachys africana are limited to alluvial deposits along water courses, and can therefore not be regarded as encroaching species.
Where encroachment does occur within this region it s usually associated with localized areas of disturbance with Acacia species being the most common woody species.

4.4.1.5 Umfolozi and Hluhluwe.

4.4.1.5.1 Description.

These sites are located in the Umfolozi and Hluhluwe

4.4.1.4.4 Woody species composition.

As described earlier, woody species diversity in this mixed bushveld is high, and the most common woody species are :

<u>Acacia tortilis</u>
<u>Grewia monticolor</u>
<u>Acacia permixta</u>
<u>Mundulea sericea</u>
<u>Spirostachys africana</u>
<u>Commiphora pyracanthoides</u>

Of these, <u>Acacia tortilis</u> *is the most widespread species*, but the sites with highest woody density were usually localized stands of <u>Grewia monticolor</u>, <u>Acacia permixta</u>, or <u>Mundulea sericea</u>, which is not regarded as an encroaching species. The dense stands of <u>Spirostachys africana</u> are limited to alluvial deposits along water courses, and can therefore not be regarded as encroaching species.
Where encroachment does occur within this region it is usually associated with localized areas of disturbance with <u>Acacia</u> species being the most common woody species.

4.4.1.5 *Umfolozi and Hluhluwe.*

4.4.1.5.1 Description.

These sites are located in the Umfolozi and Hluhluwe game reserves under the jurisdiction of the Natal Parks Board. The areas fall into the Zululand thornveld and lowveld vegetation types of Acocks (1953). The rainfall ranges from 500 to 750mm per annum, falling mostly in the summer, and the climate is hot. The soils are fairly fine in texture with a high silt and clay content.

Since both areas are in game reserves, there is a presence of both grazing and browsing herbivores. A strict management policy governs the numbers of these.

4.4.1.5.2 *Interrelationships of site variables and woody density.*

An initial attempt was made to analyse these data using correlations of all variables and by graphic representation of these versus woody density. However, no significant relationships were obtained between any of the variables and woody density (Appendix 2). Some significant correlations between site variables were obtained, and these are discussed in the following section.

4.4.1.5.3 Discriminant analysis.

The all-groups scatterplot (table 19) shows three fairly distinct groups of woody density, with the first discriminant function accounting for 70% of the variance between groups. The first discriminant function shows a separation of groups, but does not show a continuum from one extreme of woody density to the other. However, when both discriminant functions are considered in geometrical space a trend from less woody to very woody sites can be shown, i.e. from groups with negative co-ordinates for the group centroids to groups with positive co-ordinates for group centroid. The distances (geometrical) between group centroids are not large, which may indicate that the set of variables used to discriminate between the degrees of woody density is not sufficient. The overlap between groups is also high, indicating a continuum effect rather than discrete grouping.

With an increase in litter there is a decrease in the amount of algal capping. This is an opposite effect to that observed on sandy soils, where there is an increase in litter and algal capping with an increase in woody density. The amount of dung on the soil surface also increases with woody density, probably because the animals spend more time in the sheltered sites. Also, indigenous herbivores may be able to move through the dense woody sites with greater ease than domestic livestock.

Topsoil pH decreases and subsoil pH increases with woodiness, again implying that nutrients are being leached out of the topsoil in sites with a high woody density, into the subsoil. Under sites with a low

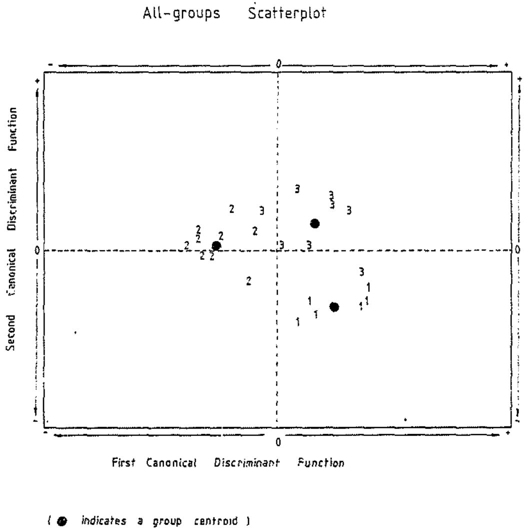


Fig. 19. *The spatial orientation* of the Umfolozi and Hluhluwe sites *in discriminant* function space.

Standardized canonical discriminant function coefficients

Variable	Function 1	Function 2
Litter	0.56150	0.97691
Open disturbed ground	5.48007	2.28942
Open undisturbed ground	4.73011	2.51511
Algal capping	-0.97876	-1.08115
Rocks	0.26380	-0.92226
Dung	0.72858	-0.12781
Topsoil conductivity	-0.12944	-1.20257
Subsoil conductivity	-0.55455	1.33044
Topsoil pH	-3.31317	2.55538
Subsoil pH	4.16035	-2.70049
Subsoil sand	-1.06233	-1.83249
Topsoil clay	1.28448	1.08703
Subsoil clay	0.30784	2.51208
Subsoil silt	1.70512	2.75134
Soil depth	-0.86744	0.13642

Table 11. Standardized discriminant function coefficients for the Umfolozi and Hluhluwe sites.

Variable.	Correlation coefficients
Herb basal area - open disturbed ground	0.833
Grass height - open disturbed ground	0.756
Open undisturbed ground - open disturbed ground	-0.874
Topsoil pH - subsoil pH	0.941
Subsoil sand - topsoil silt	0.957
Topsoil clay - subsoil clay	-0.904

Table 12. Significant correlations (r values with probabilities of less than 0.001) of variables from the Umfolozi and Hluhluwe sites.

woody density the opposite effect is observed.

Of the causal variables, there is an increase in topsoil silt content, a decrease in topsoil clay content, and an increase in subsoil clay content with increasing woody density. This is confirmed by a significant negative correlation between topsoil and subsoil clay content (table 12). Topsoil sand and topsoil silt also show a significant positive correlation (table 12). This implies, indirectly, that as the topsoil sand content increases so the woody density increases, although this is not apparent from the discriminant analysis. There is also a strong negative association between soil depth and increasing woody density, which is opposite to the observations from sites on sandy soils.

4.4.1.5.4 Woody species composition.

The most common woody species, in order of abundance, on these sites are :

Acacia tortilis
Acacia karroo
A. nigrescens
Euclea undulata
Maytenus heterophylla

Of these, Acacia karroo and Euclea undulata are considered to be potential encroaching species by the local field workers. On sites which have previously had a low woody density, these species tend to develop into uniform size thickets. Because of the high rainfall, the climatic climax in these areas is probably a woodland consisting of mature trees with an understorey of shrubs. Where disturbance has occurred, a localized scrub thicket of Maytenus heterophylla may develop.

4.4.1.6 Adelaide.

4.4.1.6.1 Description.

The majority of the sites from this district are situated on the Adelaide experimental farm belonging to the Department of Agriculture, with the remaining sites situated in the Adelaide, Bedford and Fort Beaufort districts. The sites fall into the false thornveld vegetation type as described by Acocks (1953) with many elements of the valley bushveld occurring on the slopes. The rainfall ranges from 400mm - 650mm per annum with most of it falling during the early and late summer.

According to Acocks (ibid.) this vegetation type is a previously grass dominated veld which is being invaded by thorn bushclump veld, with Acacia karroo being the dominant woody species. The farms are all grazed by cattle, and in many areas the boer goat is farmed in association with cattle in an attempt to utilize the woody plants, which are fairly palatable.

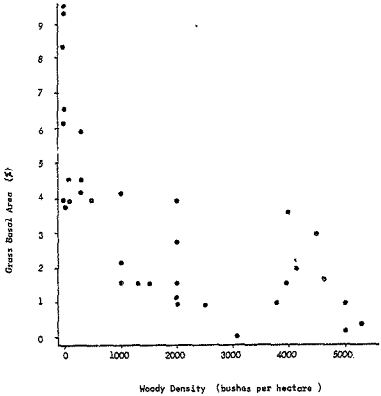


Fig.20 The relationship between woody density and grass basal area in the Adelaide sites.

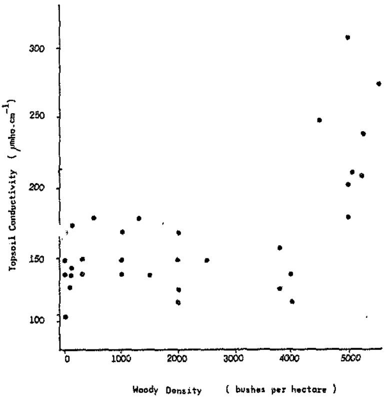


Fig. 21 The relationship between woody density and topsoil conductivity in the Adelaide sites.

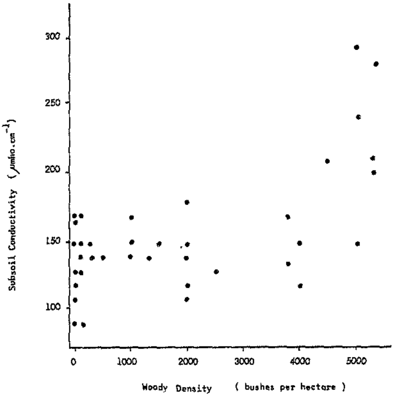


Fig. 22 The relationship between woody density and subsoil conductivity in the Adelaide sites.

4.4.1.6.2 Interrelationships of site variables and woody density.

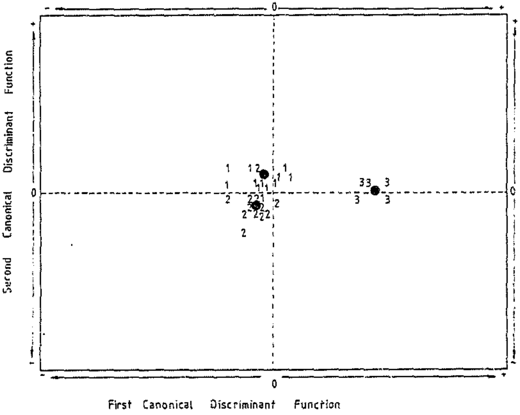
Grass basal area, topsoil and subsoil conductivity showed significant relationships with woody density. Grass basal area decreases (fig. 20), and topsoil and subsoil conductivity increase with increasing woody density (fig. 21 and fig. 22, respectively).

4.4.1.6.3 Discriminant analysis.

The all-groups scatterplot (fig. 23) shows that there is a trend from low to a very high woody density in the geometrical space created by the two discriminant functions. There is a great amount of overlap between the two lower classes of woody density (fig. 23) with the group centroids very close to each other in discriminant function space. Some support for this is added by the views of local farmers and extension officers, who maintain that a light infestation of woody plants (i.e. up to 15 [illegible] bushes per hectare) does not have a significant de[illegible]sion on the production of the herbaceous layer in this region. The high density sites (i.e. those with a bush density of above 3000 stems per hectare) can be regarded as a distinct group.

The first canonical function accounts for 56% of the variance and therefore provides a significant trend for identifying the main variables, showing a distinct

All-groups Scatterplot



(● indicates a group centroid)

Fig. 23. The spatial orientation of the Adelaide sites in *discriminant function space.*

trend from a low to moderate woody density to sites with a very high woody density. Many variables show an association with this trend, but most can be considered as consequences of a high woody density (table 13).

Under high densities there is an increase in the amount of litter and a decrease in the amount of bare ground. There is a decrease in the amount of dung on the soil surface of very dense sites, probably as a result of these sites being impenetrable to livestock. This is confirmed by a significant negative correlation between grass height and bare ground, suggesting that the herbaceous component is not grazed to the same extent under sites with a high woody density as those with a light or moderate woody density (table 14).

Woody density is positively correlated with topsoil pH and negatively correlated with subsoil pH. Because there is not a dramatic reduction in grass basal cover in the woody sites, the apparent leaching of the soils, observed in other areas, does not appear to be operating. The increase in the pH of the topsoil in the very woody sites may come about as a result of an increase in leaf litter in these areas, providing a higher cation input than that which is leaching out. This is confirmed by positive associations of topsoil conductivity and the topsoil:subsoil ratio of calcium with increasing woody density (table 13). These

Variable	Function 1	Function 2
Algal capping	1.30523	0.17342
Rocks	1.71502	-0.59138
Open undisturbed ground	0.39425	0.51575
Topsoil conductivity	1.93014	-0.00812
Subsoil conductivity	-2.50241	-0.52287
Topsoil pH	1.53427	1.91360
Subsoil pH	-0.89472	0.44571
Topsoil sand content	0.25010	-0.10057
Subsoil sand content	2.11008	1.57622
Topsoil clay content	1.53686	-1.10235
Subsoil clay content	2.34576	-0.12539
Topsoil silt content	0.34443	-0.44238
Subsoil silt content	3.85190	1.04748
Topsoil:subsoil magnesium	-0.58249	0.13266
Topsoil:subsoil potassium	-0.80432	0.64321
Topsoil:subsoil sodium	0.76055	-1.05629
Soil depth	-0.59268	0.81849

Table 13. Standardized discriminant function coefficients for the Adelaide sites.

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Variable	Correlation coefficients
Grass height - open ground	-0.889
Stones - rocks	0.956
Topsoil conduct. - subsoil conduct.	0.891
Subsoil conductivity - subsoil pH	0.783
Topsoil sand - subsoil sand	0.962
Topsoil sand - topsoil clay	-0.858
Topsoil sand - subsoil clay	-0.843
Topsoil sand - topsoil silt	0.725
Topsoil sand - subsoil silt	0.766
Subsoil sand - topsoil clay	-0.875
Subsoil sand - subsoil clay	-0.869
Subsoil sand - topsoil silt	0.728
Subsoil sand - subsoil silt	0.738
Topsoil clay - subsoil clay	0.983
Topsoil clay - topsoil silt	-0.781
Topsoil clay - subsoil silt	-0.790
Subsoil clay - subsoil silt	-0.751
Topsoil silt - subsoil silt	0.966
Subsoil clay - topsoil silt	-0.795

Table 14. *Significant correlations (r values with probabilities of less than 0.001) of variables from the* Adelaide sites.

indicate an overall higher nutrient status of the topsoil in sites with a high woody density than in sites with a low woody density.

The variables which may be related to the cause of bush thickening also show strong associations with a high woody density. There is a two layered soil structure, based on soil texture in this region. Under high woody densities there is an increase in topsoil clay and a reduction in subsoil clay content. Also there is a reduction in subsoil sand content and an increase in topsoil silt content with increasing woody density.

The highest woody densities were found on sites with a high clay and silt content in the topsoil, and a low clay and sand content in the subsoil. However, the topsoil and subsoil clay content are the most important variables associated with high woody densities in this region (table 13).

4.4.1.6.4 Woody species composition.

The vegetation of this area consists almost entirely of mono-dominant stands of Acacia karroo. However, on some of the steeper slopes some valley bushveld (Acocks, 1953) elements may become more common, but do not occur in very dense stands. These include woody species such as Azima tetracantha.

4.5 *Soil cation analysis.*

One of the hypotheses regarding the determinants of savanna structure is that proposed by Walter (1971), i.e. that the soil profile in a savanna is bilayered; an upper grass rooting layer, and a deeper tree rooting layer. This idea has been further expanded by Walker (1980b) to include the affects of competition for basic resources (water and nutrients). These resources and their movement through the soil profile may play an important role in governing the structure and dynamics of savanna vegetation.

To test this hypothesis, paired sites were measured where the two opposite extremes of woody density occur side by side, on the same soil type. These conditions were brought about by different management actions applied to the same vegetation type for approximately five years, resulting in fence-line contrasts, where on one farm a high woody density may be found as opposed to an open savanna on a neighbouring farm. To find such sites proved difficult at first, but some sites were measured in the Thabazimbi and Zeerust districts and on the Alice experimental farm of the University of Fort Hare. In both regions the woody species had been controlled on the sites. On the Thabazimbi and Zeerust sites the woody vegetation was killed using an arboricide leaving the dead trees standing on the site, whereas on the Alice sites the woody vegetation was killed by fire and the trees were therefore destroyed.

Soil samples were taken from three specific depths in the soil profile, a topsoil sample (from the first 150mm), an intermediate sample (300 - 400mm below the soil surface), and a subsoil sample from bedrock, or as deep as possible with the instruments available.

4.5.1 Thabazimbi and Zeerust sites.

Twenty pairs of sites were measured from this region and the nutrient content differed widely between them. Therefore to be able to compare the abundances of each cation, the absolute v[illegible] were relativised by expressing each value as a [illegible]ion of the summed value for that cation in each site. These data are further divided into open sites (with few or no woody elements) and woody sites (with medium to high woody density), and the relativised cation data summed for each category. The relativised data are expressed graphically to allow for easier interpretation of trends. In each case the mean of the summed relativised value for each cation (ΣR) and the standard error around the mean is plotted against the relative soil profile position.

There are differences in the relative amounts of cations from different positions in the soil profile. In general, there is a greater absolute amount of

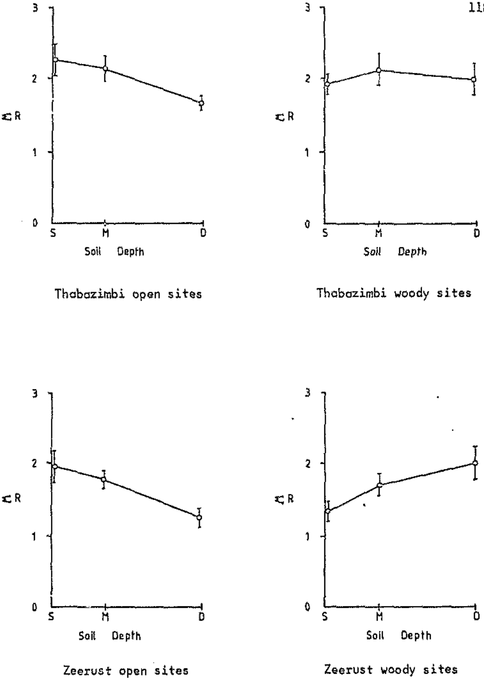

Fig. 24 Electrical conductivity in the soil profile of the Thabazimbi and Zeerust sites (where ΣR is the summed relativised conductivity at shallow (S), medium (M), and deep (D) soil depth).

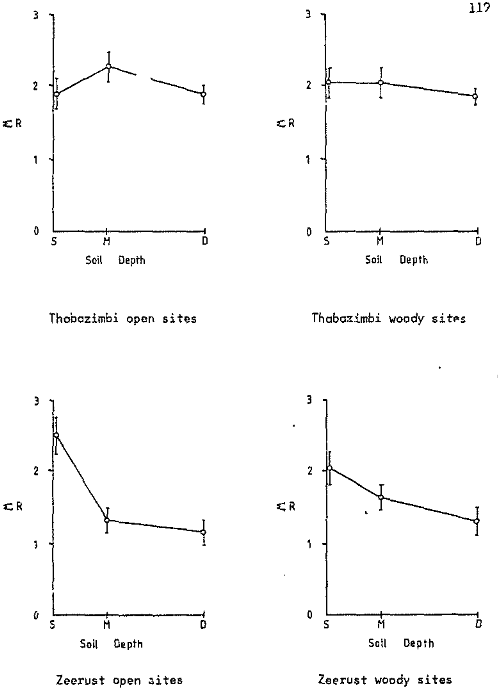

Fig. 25 The distribution of potassium in the soil profile of the Thabazimbi and Zeerust sites (where ΣR is the summed relativised amount of the cation at shallow (s), medium (m), and deep (d) soil depths).

cations in the topsoil samples of woody sites than in open sites (Appendix 1). This is probably caused by the high litter content under the woody species which are mostly deciduous. The open sites, with a high grass cover, do not show a high litter build up due to a high stocking rate of grazers.

Electrical conductivity gives a rough estimate of the amount of nutrients in a soil sample (Buckman and Brady, 1969). It appears that there is a decline in soil conductivity with increasing soil depth in open sites, as opposed to a slight increase in woody sites. This indicates that with a decrease in grass cover, usually associated with an increase in woody density, there is a loss of nutrients from the topsoil, via a downward leaching process, to the subsoil where the woody component has preferential access to them (fig. 24).

No significant results were obtained from the analyses for potassium and sodium. There is a general reduction in the amount of potassium with increasing soil depth in both open and woody sites (fig. 25). The sodium content of the soil samples is very variable and it would appear that either the technique used for sodium determination is unsuitable, or that the absolute amounts of this cation are very low and not easily detected.

The analyses for calcium show similar trends as those for electrical conductivity (fig. 26). With an increase

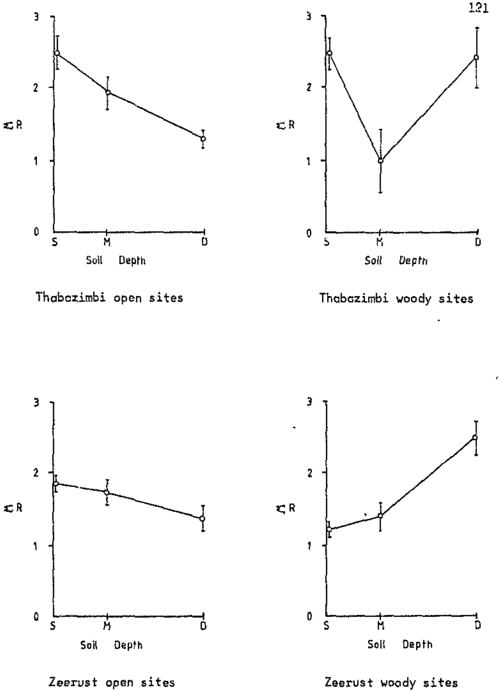

Fig. 26 The distribution of calcium in the soil profile of the Thabazimbi and Zeerust sites (where ΣR is the summed relativised amount of the cation at shallow (s), medium (m), and deep (d) soil depth).

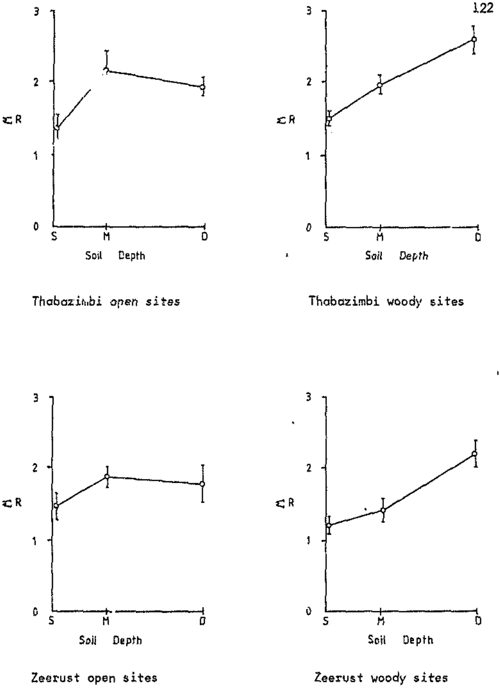

Fig. 27 The distribution of magnesium in the soil profile of the Thabazimbi and Zeerust sites (where ΣR is the summed relativised amount of the cation at shallow (s), medium (m), and deep (d) soil depth).

i· soil depth there is an increase in the soil calcium content in open areas, and an increase in soil calcium content in woody sites. This is supported by Donahue, et al., (1971), who found that calcium is the most mobile soil cation. In sites with a well developed herbaceous layer the calcium is maintained in the topsoil, probably through a rapid cycling process. However, with a decrease in the herbaceous layer, there is a downward loss of calcium to the subsoil.

According to Donahue, et al., (ibid.) magnesium, like calcium is a fairly mobile cation. However, there seems to be an overall increase in the relative amounts of magnesium with increasing soil depth in both open and woody sites. In the Thabazimbi sites the trend for magnesium is similar to that for calcium and conductivity (fig. 27). With increasing soil depth there is a slight decrease in the amount of magnesium (although this may not be significant), whereas in woody sites there is an increase in magnesium with soil depth.

The Thabazimbi and Zeerust sites both occur on sandy soils which are prone to leaching. To obtain more general evidence for the hypothesis, sites were selected on soils with a heavier texture (i.e. soils with a higher clay content).

4.5.2 Alice experimental farm.

Trollope (1974) has been able to maintain different combinations of ody and grass species within the false thornveld of the Eastern Cape (Acocks, 1953) by applying fire and follow up treatment with goats. These sites are located in close proximity to each other and provided an opportunity to test the movement of soil cations with respect to different woody densities on a soil with a fairly fine texture.

The experimental procedure is identical to that used in the Thabazimbi and Zeerust sites, with the exception that the results are presented as absolute values. The means for a number of replicates and the confidence limits are expressed graphically (fig. 28). In this case it is not necessary to use relativised data because the sites all occur within close proximity of each other.

The graphic representation of the topsoil:subsoil ratios of soil cations shows that different distributions of cations exist in the soil profile with respect to different degrees of woody density. Calcium, magnesium and sodium all show similar trends, that with an increase in woody density there are significant increases in the amounts of these cations in the subsoil.

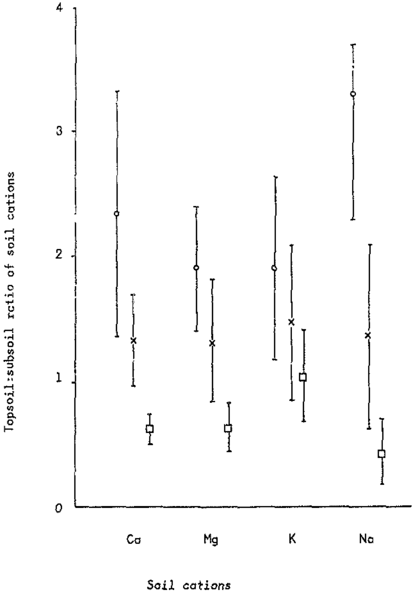

Fig. 28 Topsoil:subsoil ratios of the measured cations (calcium, magnesium, potassium, sodium) from the Adelaide sites in relation to different woody densities (where the sites are grouped as open (o), slightly woody (×), and very woody (□)).

However, potassium, unlike the Thabazimbi and Zeerust sites where there is a decrease in the amounts with increasing soil depth, shows no significant differences in the topsoil:subsoil ratios of this cation with respect to different woody densities.

The general deduction that follows from these data is similar to that from the *Thabazimbi and Zeerust sites*. On sites with a *high grass cover some of the soil cations are maintained within the topsoil (active grass rooting zone)*, probably due to a rapid cycling by the herbaceous component, with a minimal loss to the subsoil via downward leaching.

In sites with a high woody density the reverse situation exists. Accompanied by an increase in woody density there is a reduction in grass cover. This allows some cations to be leached into the subsoil *because the herbaceous component is no longer efficient in maintaining these in the topsoil*. This leads to *an accumulation* of some cations (calcium, magnesium and sodium - probably with their associated anions) in the subsoil where the extensive woody roots have preferential access to them.

As in the Thabazimbi and Zeerust sites, the Alice sites show a higher cation content of the topsoil in sites with a high woody density than in open, well grassed sites (Appendix 1). *This is derived from* the leaf litter of the almost mono-dominant woody species occurring on the sites, Acacia karroo. In the well grassed sites there is little build up because the vegetation is maintained in an open state by fire, and the excess grass is grazed off every season. A secondary effect of the increased nutrient status of the topsoil under woody elements can be the establishment of shade-loving, highly palatable grass species such as Panicum maximum (Kennard and Walker, 1973). These species may provide good grazing if the woody canopy is high enough for cattle to pass underneath. However, high woody densities often occur as thickets and the palatable species under the shrubs are unavailable to grazers.

The distribution of cations in the soil profile with respect to different degrees of woody density lends some support to the water linked hypothesis of Walter (1971) on the structure of semi-arid savannas, both in fine and coarse textured soils. It seems that the distribution of soil cations and the movement of water through the soil profile are inseparably linked. However, the distribution of soil cations in the profile must be considered to be a result of change in the grass-tree combination, and not as a factor causing this.

4.5.3 General discussion.

Some soil cations, mainly calcium, magnesium and sodium, show a change in their relative distribution in the soil profile as a result of a change in the bush-grass community. The results from the Thabazimbi, Zeerust and Alice districts show that this process occurs on both fine textured and coarse textured soils. However, the sites situated in the Thabazimbi and Zeerust districts (on coarse textured soils) appear to have attained the change in the topsoil to subsoil ratio cations over a shorter period of time than those from the Alice experimental station (fine textured soils). In the former sites which had been bush cleared three years prior to sampling, most of the cations were maintained in the topsoil by increasing grass cover. The sites on an adjoining property, which had not been bush cleared, showed a reduction in grass cover with increased woody density, and an accumulation of some soil cations in the subsoil.

In the Alice sites, a similar distribution of cations occurred due to the management actions taken. However, these sites had been maintained in this state for about ten years prior to sampling.

The time and soil textural differences between these two regions do not imply that a longer period of time is required to obtain the distribution pattern of soil cations in the soil profile of sites with a fine textured soil than coarse textured soil, with respect to changes in the grass-bush community. To test the rates of change of cation distribution in the soil profile, regular short term sampling will have to be carried out. It seems that cations do not continue accumulating in the subsoil in sites with a high woody density. There rather appears to be a particular topsoil to subsoil ratio, greater than one, which is obtained and probably maintained by a cycling of these cations through the woody component. To test this hypothesis, long term experiments need to be designed with regular measurement of the soil cations in the soil profile in sites with a high woody density and a low grass cover.

The amount of cations is higher in the topsoil of sites with a high woody density than in sites with a low woody density and a good grass cover (fig. 29). This arises from the high leaf litter input from the woody species which are mostly deciduous. However, the rate of leaf litter decomposition is much slower (about three years) than that for grass litter (about six months) (Kelly, 1973). Because of the large amounts of litter derived from the woody species, there is a continuous input of nutrients into the topsoil under a dense woody canopy. Also, many of these areas are heavily stocked with grazers and consequently there is little litter build up in the sites

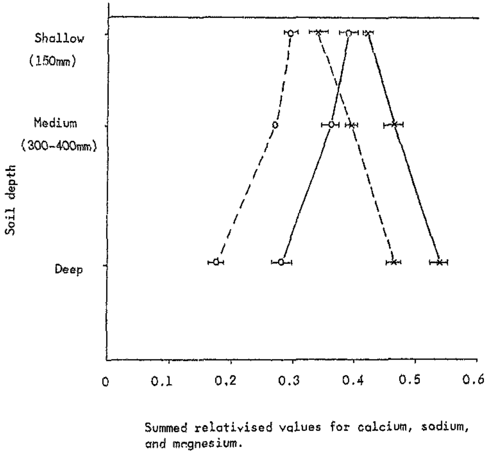

Fig. 29. A generalized distribution profile of some soil cations with respect to soil depth, on open (o) and woody (x) sites on fine (---) and coarse textured (——) soils.

with a good grass cover. The cations that enter the soil in these areas are probably rapidly cycled by the grass species, maintaining higher cation levels in the topsoil than in the subsoil. The reduction of a good grass cover in sites with a high woody density is not as a result of a reduction of cations in the topsoil, but probably as a result of competition for light (Knoop, 1983).

An increase in woody density is probably not detrimental to the soil as far as the nutrient status is concerned. The detrimental effect is that with an accompanying reduction in grass cover, erosion may increase with a resultant loss in topsoil stability. However, because of the overall increase in the amounts of soil cations (and probably their associated anions) in the topsoil of sites with a high woody density, the establishment of a good grass cover, once the woody species have died or been removed, can rapidly take place. But, in these sites a low topsoil to subsoil ratio of some cations exists, as a consequence of increased woody density. If the woody plants are removed the cations in the subsoil will be unavailable to the regenerating grass cover. This would mean an overall loss of cations to the system. In the case of natural succession, Walter (1971) maintains that most of the savanna woody species have a relatively short lifespan and that although they may form thickets, the older plants will gradually die out, being replaced by a herbaceous component which, although much reduced, is still present, even under very high woody densities. If succession exists, a reversion to a higher grass to tree ratio would result in a smaller loss of cations to the subsoil than if the area was cleared of bush. This is, however, not a feasible solution to the cattle rancher, who cannot afford to wait for a long time period for the woody plants to die out so that natural succession may restore a good herbaceous cover.

5. Conclusions.

5.1 Regional analyses.

There is no single *variable or group of variables* that separate degrees of woody density in all the sampled areas included in the study (see table 15, which summarises the main findings). However, when climatological and pedological factors are taken into consideration some trends do exist.

On sandy soils, there appears to be an association of soil depth with increasing woody density. In these sites the highest woody densities were found on deep soils. The reverse situation exists on fine textured soils, where the highest woody densities were found on shallow soils. This probably arises directly from the hypotheses of Walter (1971) and Walker (1980) on *savanna structure.* In sandy soils, which are freely drained, much of the incoming precipitation infiltrates to the subsoil where the tree roots *have sole, or at* least preferential, access to this water. This feature is enhanced by the already reduced herbaceous layer which occurs in these areas, allowing the deeper rooting woody species to establish. On fine textured soils, which have a slower rate of vertical infiltration, and, generally a higher herbaceous cover, much of the water is *held in the topsoil where tree and grass roots*

	Consequential Variables											Causal Variables									
	Litter	Bare soil	Algal capping	Clay capping	Dung	C..cium	Potassium	Topsoil Cond.	Subsoil Cond.	Topsoil pH	Subsoil pH	Rocks	Topsoil Sand	Subsoil Sand	Topsoil Silt	Topsoil Clay	Subsoil Clay	Soil depth	Discriminant Function Direction	Rainfall (mm.)	Soil type
Messina	+ + +	+ + +	+	–	–			– –	+	+	+	+			–			+	1 → 32	375	Sand
Zeerust	+ +	–	+ + +								+ +			+ + +				+ + +	12 → 3	450	Sand
Molopo	+ +	+ +	+ +			–		– – –	+ +	+		+	+ + +		+ + +				21 → 3	350	Sand
Mara		+ + +			+ +					+	–			– – –	+ +				3 → 21	450	Loamy sand
Umfolozi	+		–		+					–	+				+	–	+ + +	– –	2 → 3, 1	700	Loamy sand
Adelaide	+	– – –			– –	+ +		+		+ +	–			– –	+ +	+ + +	– – –		1, 2 → 3	500	Sandy loam

Table 15. A summary of the discriminant analyses (key overleaf).

Table 15 (contd.)

Key to the symbols used in the summary of the discriminant analyses.

The signs (positive or negative) show the association of the indicated variables with the discriminant function accounting for the greatest variance for the particular region.

+++ = a strong positive association
++ = a positive association
+ = a weak positive association
- = a weak negative association
-- = a negative association
--- = a strong negative association

The symbols used to indicate the trend of the discriminant function are as follows:

1 = sites with a low woody density
2 = sites with a medium woody density
3 = sites with a high woody density

compete actively for water. However, on shallow soils the water will percolate into cracks and fissures in the rock substratum, and accumulate there. The roots of the woody species will again have preferential access to this water.

On fine textured soils, the *soil texture variables* play a more significant role in discriminating between degrees of woody density than in sites on coarse textured soils, because of the higher number of important coefficients on the discriminant functions of the fine textured sites (table 15). A bilayered soil profile with respect to clay content appears to *exist in fine textured soils. The highest* woody densities on these soils were found on sites with a high topsoil clay content and a low subsoil clay content on the Adelaide experimental farm. However, in the Umfolozi and Hluhluwe game reserves, the opposite occurred. In these areas the highest woody densities were found on sites with a low topsoil clay content and *a high subsoil clay* content. This may be because of the effect of soil depth in these areas. In the Hluhluwe and Umfolozi sites the soils are generally shallow but the tree roots may have preferential access to the water in fissures in the rock substratum, whereas in the Adelaide sites the soils are generally deep, with a high topsoil clay content, giving this layer a higher water holding capacity.

Some of the consequential variables show different trends under different soil conditions. Litter increases as woody density increases in all sites. This is as a result of dropped leaf material from the woody species which are generally deciduous. All regions were fairly heavily grazed by herbivores and this accounts for the small amount of litter in sites with a low woody density.

Algal capping also increases with increasing woody density on sandy soils. This seems to be associated with increased leaf litter on the soil surface and a decrease in grass basal area. On fine textured soils there appears to be a decrease in the amount of algal capping although there is an increase in litter with increasing woody density. One reason for this may be that in sites on fine textured soils with a low woody density, there is a high water holding capacity in the topsoil. With incoming precipitation the infiltration into the soil profile is slower and ponding of water on the soil surface occurs. This gives a higher ... moisture on the soil surface in grass sites than in sites under a high woody density because the increased litter on the surface increases the infiltration rate in the latter sites. The formation of microfloral crusts is more likely in the open, well grassed sites on fine textured soils. On coarse textured soils, through which water infiltrates very rapidly, the increased amount of litter under high woody densities may give a slightly higher moisture status to the soil surface, *encouraging the formation of microf ral crusts.*

Bare soil also shows an increase with increasing amounts of woody species in sites on sandy soils, whereas in sites on fine textured soils, there is a decrease in the amount of bare soil with increasing woody density. This phenomenon is attributed to a dramatic decrease in grass basal area in sites with a high woody density on sandy soils, whereas on fine textured soils the decrease is not as severe. In the sandy sites (Messina, Thabazimbi, Zeerust and Molopo) the decrease in grass basal area was 80% on average, often to virtually zero percent rooted basal area, with the greatest decrease in the Messina sites (93%). The fine textured soils do not show this severe decrease, (50% in the Adelaide sites and only 7% in the Umfolozi and Hluhluwe sites) usually down to 1 - 2% rooted grass basal area, which still provides some grazing. This phenomenon is ascribed to the higher water holding capacity of the topsoil in the fine textured soil sites.
Knoop (1983) found that on fine textured soils the herbaceous component was the controlling element of the vegetation as suggested by Walter (1971). In contrast, on coarse textured soils the herbaceous vegetation appeared to be the tolerated component.

This study showed that the competition between trees and grasses is very strong in sites on sandy soils, whereas on fine textured soils this competition does not have the same depressive effect on the herbaceous vegetation.

The above factors may lend some support to the two layered soil profile structure in South African savannas as proposed by Walter (1971), but some of the factors which are associated with this hypothesis must be considered as consequences of a change in the bush-grass community, even though they contribute to the present dynamics of the system.

The highest measured woody densities occurred on sites with sandy soils and a low annual rainfall. These sites have the lowest grass basal area, below 0.5% in many cases, with the most common woody species being Acacia spp. and Colophospermum mopane. Initially it was expected that the mesic sites, i.e. with a rainfall exceeding 600mm per annum, would produce high woody densities. However, in these sites the climax vegetation appears to be a closed woodland consisting of larger, mature woody species rather than a thicket type consisting of multistemmed species.

There appear to be hardly any links between the measured variables which may be attributed to the cause of an increase in woody density and the actual process, with the exception of soil depth and some textural characteristics of the soil. This may support the suggestions of West (1968) that the climax over much of the bushveld region is woodland.

5.2 Criticisms and future research.

It is not possible to predict the degrees of woody density on a wide scale from the variables used in the analyses. This appears to be one general criticism of the study, that the sites measured do not reflect areas of potential encroachment. To compensate for this measured of sites where different stages of encroachment occur could be made, to determine how the measured variables change with respect to different age classes of woody species.

The determination of infiltration rate may provide a more complete impression of the dynamics of woody thickening. However, because of the low kinetic energy produced by the rainfall simulator used, these data were not considered in the analyses. Using a simulator providing a higher kinetic energy, this problem may be overcome resulting in a more complete set of variables characterising each site, and providing a more satisfactory measure to identify and predict areas of potential encroachment.

5.3 Management practices.

The bushveld can be maintained in a particular combination of grass-bush through management actions. This has been shown by Trollope (1974) in the eastern Cape and by some farmers in the Zeerust district.

However, clearing already encroached areas is costly and very labour intensive, and often the desired effect is only maintained for a few seasons. The use of goats and fire has been shown to be very successful on a small scale in the eastern Cape over a ten year period, and its application on a large scale in other regions in South Africa may be worth investigating. The experiment appears to be fairly stable and some farmers in the region have implemented this as a control measure against Acacia karroo with varied success.

The use of fire and goats will not necessarily be successful to maintain a particular bush-grass community in other savanna regions, because of the low grass basal area found in the more arid, sandy regions. There is not a sufficient fuel load to maintain an intense fire to kill the woody species. Also, there are severe animal husbandry problems with goats in these regions (Aucamp, 1980).

In the more arid, sandy sites the use of a foliar arboricide has produced successful results, but this is a costly process often exceeding the value of the land, and to maintain a successful increase in grass basal area, follow up applications have to be made.

Therefore, bush control may be applied in all savanna areas, but in some, especially the more arid (with rainfall below 450mm per annum), sandy areas, the maintenance of increased grass production will be overshadowed by the costs involved in bush clearing.

5.4 Present status of the bushveld with respect to woody thickening.

One observation which is not directly apparent from the discriminant analysis is that the central area of the Transvaal bushveld, and other areas of mixed bushveld, with an annual rainfall of 500mm, does not always tend to a woody climax. In these areas woody densities do not reach the same extremes as in the more arid regions (the maximum bush density recorded was 3000 bushes per hectare as opposed to 7000 bushes per hectare in the arid areas). Even though bush thickening does occur in the mixed bushveld, usually confined to overgrazed areas around watering points, on the whole it does not seem to rate as an area of severe bush thickening. However, regular monitoring of the status of woody density in these areas should be enforced.

In the mesic areas the climax vegetation appears to be mature woodland, but some thickening does occur and should be regarded as areas of potential encroachment. Although the highest woody biomass may be found in mesic sites, the highest woody densities were found in the more arid sites on sandy soils.

Sandy soils cover about 50 - 60% of the bushveld and in these areas, especially where rainfall is below 450mm, bush thickening appears to be widespread.

These areas seem to be very prone to an increase in woody density, and if the constraints that previously maintained the vegetation in an open state are removed, or if continuous heavy grazing is applied, this process is sharply accentuated.

Because of the gravity of the situation in these areas, the Department of Agriculture has recently decided to grant financial aid for bush clearing in the Molopo region which is severely encroached by *Acacia mellifera*. However, because these areas appear to be prone to severe woody thickening it may prove to be a waste of financial input. The costs involved in clearing existing woody vegetation, and in maintaining a low woody density, would exceed the monetary return in the resulting increased grazing capacity. Also, if recommended stocking rates are not strictly adhered to, these areas will return to a very dense state over a short period of time. Bush clearing in these areas will not be successful as the financial and labour inputs will exceed the benefits over the long term.

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Appendix I Raw Data Tables

Grass basal area Herbaceous basal area	(percentage of stand surface area)
Mean grass height	(centimetres)
Litter Open ground Algal capping Clay capping Stones Rocks Dung Woody basal area	(percentage of stand surface area)
Woody density	(bushes per hectare)
Woody canopy area	(percentage of stand surface area)
Soil conductivity	($umho.cm^{-1}$)
Soil pH	(log H^+ concentration)
Soil sand content Soil clay content Soil silt content	(percentage of soil sample)
Calcium Magnesium Potassium Sodium	(Topsoil:Subsoil ratio unless absolute amounts specified parts per million)
Soil depth	(centimetres)

Table 16. Units for Variables in Raw Data Tables

Sites	Grass Basal Area	Herb Basal Area	Mean Grass Height	Litter	Open Disturbed Ground	Algal Capping	Clay Capping	Stones	Rocks	Open Undisturbed Ground	Dung	Woody Basal Area	Woody Density	Woody Canopy Area	Topsoil Conductivity	Subsoil Conductivity	Topsoil pH	Subsoil pH	Topsoil Sand	Subsoil Sand	Topsoil Clay	Subsoil Clay	Topsoil Silt	Subsoil Silt	Topsoil : Subsoil Ratio. Calcium	Magnesium	Potassium	Sodium	Soil Depth
Mes 7	0.4	0.0	7.6	5.9	0.0	1.4	0.0	0.0	[illegible]	75.0	0.5	0.7	1075	12	80	110	7.5	8.4	88	88	0	1	12	11					47
Mes 8	0.5	0.0	7.3	6.1	0.0	2.1	0.0	0.0	0.9	64.1	0.0	0.8	350	10	120	110	8.4	8.7	75	77	2	1	23	22					43
Mes 11	0.4	0.6	6.8	19.9	0.0	2.0	0.0	0.0	0.0	76.0	1.1	1.0	1050	25	70	60	6.0	6.3	85	84	1	1	14	15					45
Mes 13	0.4	0.4	3.9	6.6	0.0	1.0	0.0	0.0	0.0	91.6	0.0	2.2	800	38	60	50	6.2	6.0	82	85	4	3	14	12					20
Mes 14	0.3	0.8	5.8	7.6	0.0	2.3	0.0	0.0	0.0	88.9	0.3	1.3	800	41	70	70	6.0	6.2	86	85	9	5	6	10					21
Mes 16	0.3	[illegible]	5.6	6.4	0.0	1.9	0.0	0.0	0.0	91.0	0.0	0.9	550	15	50	30	5.5	5.9	89	87	1	1	10	12					88
Mes 19	0.0	0.1	2.6	3.5	0.0	0.0	0.0	0.0	0.0	94.0	0.0	0.7	550	20	90	70	5.8	7.0	83	87	4	3	13	10					47
Mes 20	0.0	0.1	2.6	6.3	0.0	0.0	0.0	0.0	2.6	92.0	0.0	1.0	525	24	60	70	6.7	6.8	82	82	2	3	16	15					39
Mes 1	0.5	0.0	25.0	13.0	0.0	0.0	0.0	0.0	0.5	85.0	1.3	1.7	1875	38	90	150	8.2	8.6	88	89	1	1	11	10					67
Mes [illegible]	0.5	0.0	14.1	7.0	0.0	0.0	0.0	0.3	0.6	91.0	0.5	1.6	2075	50	80	150	7.2	8.8	92	92	1	0	7	8					77
Mes 3	0.1	0.0	7.1	8.8	0.0	0.0	0.0	0.4	0.5	89.5	0.8	1.8	1475	36	110	160	8.6	9.0	89	90	0	0	11	10					48
Mes 4	0.1	0.0	6.0	9.0	0.0	1.0	0.0	0.0	0.0	89.0	0.5	1.4	1100	26	90	130	7.0	8.7	85	87	1	0	14	13					100
Mes 5	0.0	0.0	2.0	8.0	0.0	0.0	0.0	0.0	0.0	92.0	0.0	4.0	2250	61	60	140	6.5	8.0	93	92	2	1	5	7					43
Mes 6	0.0	0.0	5.0	9.0	0.0	0.0	0.0	0.0	0.0	91.0	0.0	2.7	1650	42	90	80	7.4	7.2	87	87	3	1	10	12					26
Mes 9	0.3	0.4	7.0	29.0	0.0	0.0	0.0	0.0	0.0	66.0	0.0	1.5	1550	49	60	50	5.8	6.5	85	84	1	1	14	15					62
Mes 10	0.3	1.1	6.9	24.6	0.0	0.0	4.0	0.0	0.0	69.0	0.6	0.9	1150	39	50	50	6.0	5.8	88	85	0	1	12	14					55
Mes 12	0.3	0.0	5.9	32.0	0.0	3.0	0.0	0.0	0.0	65.0	0.0	[illegible]	1425	41	40	30	6.0	5.8	92	92	2	2	6	6					79
Mes 15	0.8	0.5	8.0	15.0	0.0	2.0	0.0	0.0	0.0	82.0	0.0	3.0	1400	68	40	30	6.0	5.5	87	85	3	3	10	12					55

Raw Data from the Messina Agricultural Research Station (Mes).

SITES	GRASS BASAL AREA	HERB BASAL AREA	MEAN GRASS HEIGHT	LITTER	OPEN DISTURBED GROUND	ALGAL CAPPING	CLAY CAPPING	STONES	ROCKS	OPEN UNDISTURBED GROUND	DUNG	WOODY BASAL AREA	WOODY DENSITY	WOODY CANOPY AREA	TOPSOIL CONDUCTIVITY	SUBSOIL CONDUCTIVITY	TOPSOIL PH	SUBSOIL PH	TOPSOIL SAND	SUBSOIL SAND	TOPSOIL CLAY	SUBSOIL CLAY	TOPSOIL SILT	SUBSOIL SILT	Topsoil : Subsoil Ratio. CALCIUM	MAGNESIUM	POTASSIUM	SODIUM	Soil Depth
Mes 21	0.0	0.1	2.0	5.0	0.0	0.0	0.0	0.0	0.0	94.0	1.0	1.9	2125	51	80	110	7.8	8.0	93	92	1	1	6	7					15
Mes 22	0.3	0.0	1.0	7.0	0.0	0.0	0.0	0.0	1.0	91.0	0.0	1.1	1250	29	30	40	6.4	7.3	88	88	0	2	12	10					37
Mes 23	0.1	0.0	1.3	5.0	0.0	0.0	0.0	0.0	1.0	94.0	0.0	1.4	2225	43	40	170	6.8	8.3	98	98	1	1	1	1					57
Mes 24	0.1	0.0	2.0	8.0	0.0	0.0	0.0	0.0	1.0	92.0	0.0	1.6	2000	31	50	60	6.6	7.2	95	94	1	1	4	5					48
Mes 25	0.0	0.0	1.0	7.0	0.0	0.0	0.0	1.0	1.0	91.0	0.0	2.5	4300	43	150	150	8.2	8.5	92	92	2	1	6	7					33
Mes 26	0.0	0.0	1.7	6.0	0.0	0.0	0.0	1.0	1.0	92.0	0.0	2.1	3800	57	110	140	7.7	8.2	98	95	0	0	2	5					36
Mes 27	0.0	0.0	1.0	37.0	0.0	0.0	0.0	2.0	4.0	57.0	1.0	2.2	3850	66	120	160	8.4	8.3	96	95	1	1	3	4					30
Mes 28	0.0	0.0	1.0	45.0	0.0	0.0	0.0	1.0	4.0	49.0	1.0	2.1	3650	60	150	190	8.4	8.3	92	93	1	0	7	7					23
Mes 18	0.0	0.0	12.0	3.0	0.0	0.0	0.0	0.0	3.0	96.0	0.0	2.4	3350	76	160	120	7.7	8.4	95	96	1	0	4	4					13
Mes 17	0.0	0.0	1.0	1.0	0.0	0.0	0.0	0.0	2.0	97.0	0.0	3.1	4200	77	110	110	7.7	6.0	97	98	0	0	3	2					37
Mes 25	0.0	0.0	1.0	7.0	0.0	0.0	0.0	1.0	1.0	91.0	0.0	2.5	4300	43	150	150	8.2	8.5	92	92	2	1	6	7					33

Raw Data from the Messina Agricultural Research Station (Mes).

SITES	Tha 1	Tha 4	Tha 6	Tha 8	Tha 10	Tha 12	Zee 1	Zee 6	Zee 9	Zee 10	Zee 12	Tha 2	Tha 3	Tha 5	Tha 7	Tha 9	Tha 11	Zee 2	Zee 4
Soil Depth	70	70	89	70	43	42	75	75	75	75	75	70	70	70	70	70	57	61	75
Topsoil : Subsoil Ratio. SODIUM																			
Topsoil : Subsoil Ratio. POTASSIUM																			
Topsoil : Subsoil Ratio. MAGNESIUM																			
Topsoil : Subsoil Ratio. CALCIUM																			
SUBSOIL SILT	22	20	16	21	13	51	40	8	36	35	59	21	20	18	19	11	42	37	33
TOPSOIL SILT	15	37	12	10	11	46	31	26	30	40	49	15	12	14	12	9	40	28	26
SUBSOIL CLAY	1	1	1	1	3	2	1	3	2	1	2	1	1	2	2	1	1	2	2
TOPSOIL CLAY	2	2	1	2	3	2	1	6	2	1	2	1	1	1	2	2	2	5	4
SUBSOIL SAND	77	79	83	78	84	47	59	79	62	64	39	78	79	80	79	88	57	61	65
TOPSOIL SAND	83	61	87	88	86	52	68	68	68	59	49	84	87	85	86	89	58	67	70
SUBSOIL PH	6.8	6.8	6.8	6.6	7.1	7.2	6.1	5.0	6.6	6.5	7.1	6.8	6.8	6.7	6.6	6.9	7.2	6.7	6.6
TOPSOIL PH	7.0	5.9	6.8	6.7	7.1	7.2	6.5	6.5	6.2	6.5	6.9	6.6	6.8	6.7	6.4	6.9	7.0	6.6	6.5
SUBSOIL CONDUCTIVITY	140	120	100	52	180	440	240	670	270	310	210	41	120	52	74	60	420	160	80
TOPSOIL CONDUCTIVITY	700	150	54	52	200	260	240	460	250	280	250	52	130	91	57	200	310	190	160
WOODY CANOPY AREA	100	80	30	75	50	75	75	5	10	38	55	26	10	25	20	10	0.2	10	5
WOODY DENSITY	3500	2000	2000	2750	2000	4100	4500	2300	1000	2000	1750	650	50	1750	1200	750	50	750	300
WOODY BASAL AREA	5.5	4.5	4.5	4.0	2.5	6.0	5.0	1.5	4.5	4.0	4.5	1.4	0.8	3.0	3.0	1.5	0.4	1.2	1.5
DUNG	0.0	0.0	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	10.0
OPEN UNDISTURBED GROUND	78.0	63.0	73.0	65.0	71.0	76.0	0.0	82.0	72.0	72.0	78.0	60.0	90.0	73.0	83.0	85.0	85.0	66.0	64.0
ROCKS	0.0	0.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	2.0	1.0	0.0	1.0	1.0	0.0	0.0	0.0	0.0
STONES	0.0	0.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	2.0	1.0	0.0	1.0	1.0	0.0	1.0	0.0	0.0
CLAY CAPPING	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ALGAL CAPPING	2.0	0.0	0.0	3.0	3.0	12.0	0.0	3.0	0.0	0.0	3.0	1.5	0.0	0.0	3.0	0.0	0.0	0.0	0.0
OPEN DISTURBED GROUND	0.0	0.0	0.0	0.0	0.0	0.0	65.0	0.0	0.0	0.0	0.0	0.0	0.0	10.0	0.0	0.0	4.0	0.0	0.0
LITTER	10.0	15.0	25.0	30.0	24.0	11.0	35.0	15.0	23.0	23.0	15.0	10.0	10.0	15.0	12.0	15.0	10.0	32.0	26.0
MEAN GRASS HEIGHT	27.0	11.0	40.0	30.0	17.0	15.0	15.0	25.0	35.0	25.0	28.0	17.0	7.0	41.0	43.0	17.0	33.0	55.0	5.0
HERB BASAL AREA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GRASS BASAL AREA	2.0	2.0	2.1	3.0	1.2	1.2	1.5	1.5	2.0	1.5	2.0	2.0	1.5	3.5	4.0	3.0	4.0	6.2	6.0

...w Data from sites in the Thabazimbi (Tha) and Zeerust (Zee) districts.

Raw Data From sites in the Zeerust district (Zee).

SITES	Zee 5	Zee 7	Zee 8	Zee 11
Soil Depth	70	75	75	16
Topsoil : Subsoil Ratio. SODIUM				
Topsoil : Subsoil Ratio. POTASSIUM				
Topsoil : Subsoil Ratio. MAGNESIUM				
Topsoil : Subsoil Ratio. CALCIUM				
SUBSOIL SILT	50	26	41	57
TOPSOIL SILT	31	30	22	58
SUBSOIL CLAY	1	3	1	3
TOPSOIL CLAY	1	1	5	2
SUBSOIL SAND	49	61	58	40
TOPSOIL SAND	78	69	73	40
SUBSOIL PH	6.7	5.9	6.5	6.2
TOPSOIL PH	7.0	6.7	6.8	6.6
SUBSOIL CONDUCTIVITY	170	230	130	75
TOPSOIL CONDUCTIVITY	150	240	52	360
WOODY CANOPY AREA	37	5	5	5
WOODY DENSITY	1750	50	50	70
WOODY BASAL AREA	3.0	0.4	0.4	0.5
DUNG	6.0	9.0	9.0	0.0
OPEN UNDISTURBED GROUND	70.0	68.0	68.0	70.0
ROCKS	0.0	0.0	0.0	0.0
STONES	0.0	0.0	0.0	0.0
CLAY CAPPING	0.0	0.0	0.0	12.0
ALGAL CAPPING	0.0	0.0	0.0	0.0
OPEN DISTURBED GROUND	0.0	0.0	0.0	0.0
LITTER	24.0	22.0	23.0	12.0
MEAN GRASS HEIGHT	15.0	47.0	57.0	70.0
HERB BASAL AREA	0.0	0.0	0.0	0.0
GRASS BASAL AREA	3.0	7.0	8.0	6.0

SITES		Mol 6	Mol 7	Mol 20	Mol 23	Tsc 6	Mol 5	Mol 8	Mol 16	Mol 18	Mol 21	Mol 22	Tsc 5	Mol 1	Mol 2	Mol 3
Soil Depth		100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Topsoil : Subsoil Ratio.	SODIUM	1.4	1.1	1.4	1.0	0.9	2.1	1.1	1.2	1.3	1.3	1.4	1.1	1.0	1.2	0.6
	POTASSIUM	1.1	1.3	1.5	1.1	1.0	1.0	2.1	0.6	0.7	1.9	0.8	0.6	4.4	0.7	1.6
	MAGNESIUM	1.6	0.8	2.4	1.6	1.4	0.7	2.4	0.8	0.7	0.9	0.8	0.7	1.7	0.8	1.6
	CALCIUM	2.8	1.4	1.8	1.9	2.3	2.3	3.2	1.7	1.8	1.8	1.4	1.3	4.4	0.6	1.2
SUBSOIL SILT		3	4	4	2	3	4	5	4	3	3	4	5	3	3	3
TOPSOIL SILT		3	4	4	2	3	3	3	4	4	2	2	3	2	3	3
SUBSOIL CLAY		3	3	2	3	3	2	2	3	3	3	3	2	3	3	3
TOPSOIL CLAY		3	3	3	3	3	3	3	3	2	3	3	3	3	3	3
SUBSOIL SAND		94	93	94	95	94	94	93	93	94	94	93	93	94	94	94
TOPSOIL SAND		94	93	93	95	94	94	94	93	94	95	95	94	95	94	94
SUBSOIL PH		7.5	7.3	7.5	7.4	7.3	7.5	7.3	7.4	7.4	7.5	7.4	7.5	7.5	7.4	7.5
TOPSOIL PH		7.5	7.3	7.5	7.4	7.4	7.5	7.3	7.5	7.4	7.8	7.4	7.4	7.5	7.4	7.5
SUBSOIL CONDUCTIVITY		100	70	85	90	95	135	100	110	130	140	110	120	150	140	130
TOPSOIL CONDUCTIVITY		100	95	110	125	100	135	100	105	140	135	110	130	120	135	110
WOODY CANOPY AREA		5	5.5	5.0	2.0	8.0	5.5	7.5	30	15	8.0	15	6.0	25	50	35
WOODY DENSITY		250	400	400	50	50	500	500	4500	4750	500	1750	650	5000	7000	5250
WOODY BASAL AREA		1.5	1.0	2.0	0.4	0.8	2.0	2.0	5.0	4.5	1.5	3.0	1.4	6.0	6.5	5.5
DUNG		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OPEN UNDISTURBED GROUND		92.8	95.3	92.5	78.7	80.5	95.5	93.2	65.0	78.0	90.8	74.0	84.5	94.3	87.3	91.7
ROCKS		0.0	0.5	1.0	3.5	0.0	0.5	0.5	0.0	2.0	0.5	1.0	1.0	1.0	2.0	1.0
STONES		0.0	0.5	1.0	3.5	0.0	0.5	1.0	0.0	2.0	0.5	1.0	1.0	1.0	2.0	1.0
CLAY CAPPING		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ALGAL CAPPING		1.5	0.0	1.0	0.0	0.0	0.0	1.0	0.0	3.0	1.5	0.0	1.5	0.5	3.0	2.5
OPEN DISTURBED GROUND		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LITTER		5.0	2.0	3.0	22.0	11.0	2.5	3.0	35.0	15.0	5.0	24.0	10.0	2.5	5.0	3.5
MEAN GRASS HEIGHT		20.0	30.0	30.0	47.0	7.0	25.0	25.0	15.0	28.0	20.0	15.0	17.0	40.0	35.0	41.0
HERB BASAL AREA		1.0	0.7	1.0	0.0	0.0	0.5	0.5	0.0	0.0	0.7	0.0	0.0	0.5	0.1	0.2
GRASS BASAL AREA		0.7	1.0	0.5	2.3	1.5	0.5	0.8	0.5	0.2	1.0	2.0	2.0	0.2	0.3	0.2

Raw Data from sites in the Molopo Region (Mol and Tsc).

SITES	GRASS BASAL AREA	HERB BASAL AREA	MEAN GRASS HEIGHT	LITTER	OPEN DISTURBED GROUND	ALGAL CAPPING	CLAY CAPPING	STONES	ROCKS	OPEN UNDISTURBED GROUND	DUNG	WOODY BASAL AREA	WOODY DENSITY	WOODY CANOPY AREA	TOPSOIL CONDUCTIVITY	SUBSOIL CONDUCTIVITY	TOPSOIL PH	SUBSOIL PH	TOPSOIL SAND	SUBSOIL SAND	TOPSOIL CLAY	SUBSOIL CLAY	TOPSOIL SILT	SUBSOIL SILT	Topsoil : Subsoil Ratio. CALCIUM	MAGNESIUM	POTASSIUM	SODIUM	Soil Depth
Mol 4	0.3	1.0	30.0	3.0	0.0	3.0	0.0	0.5	0.5	91.7	0.0	6.5	6500	60	95	100	7.5	7.5	93	93	3	3	4	4	0.4	0.6	1.0	5.0	100
Mol.9	0.0	0.1	5.0	15.0	0.0	0.0	0.0	1.0	1.0	82.9	0.0	2.0	5250	35	130	150	7.4	7.4	93	94	4	3	4	3	2.6	2.0	1.2	0.1	100
Mol 10	0.5	0.0	10.0	19.0	0.0	0.0	0.0	0.0	0.0	80.5	0.0	2.5	5000	25	120	140	7.3	7.4	95	95	4	4	1	1	2.5	0.8	0.6	0.8	100
Mol 11	0.3	0.5	7.0	30.0	0.0	0.5	0.0	0.5	0.5	67.7	0.0	5.0	6750	50	110	140	7.1	7.3	94	94	3	3	3	3	1.0	0.7	1.0	1.1	100
Mol 12	0.5	0.3	5.0	20.0	0.0	0.0	0.0	1.0	1.0	78.2	0.0	4.5	5500	30	100	110	7.4	7.4	94	94	3	2	3	4	0.9	0.8	0.7	0.8	100
Mol 17	0.3	[illegible]	25.0	15.0	0.0	3.0	0.0	0.0	0.0	82.0	0.0	4.5	5000	25	95	95	7.8	7.3	94	93	3	3	4	4	0.5	1.3	1.3	1.0	100
Mol 19	0.0	0.5	12.0	15.0	0.0	7.5	0.0	0.5	0.5	86.0	0.0	6.2	6500	50	140	140	7.4	7.5	94	94	2	3	5	3	0.9	1.6	1.1	1.1	100
Tsc 1	0.0	0.4	0.0	5.0	0.0	7.0	0.0	1.0	1.0	86.1	0.0	6.5	5500	60	130	135	7.4	7.4	95	94	3	3	2	3	1.1	0.6	0.6	0.8	100
Tsc 2	0.0	0.5	0.0	10.0	0.0	5.0	0.0	0.0	0.0	84.5	0.0	6.0	5000	45	110	130	7.5	7.5	95	93	3	3	2	4	0.8	0.8	0.9	1.0	100
Tsc 3	0.1	0.0	12.0	8.0	0.0	7.0	0.0	0.5	0.5	83.9	0.0	7.1	5500	50	110	130	7.5	7.5	94	93	3	2	3	5	2.1	0.7	1.0	0.7	100
Tsc 4	0.2	0.3	15.0	15.0	0.0	10.0	0.0	1.0	1.0	72.5	0.0	6.2	6250	60	120	125	7.4	7.4	94	94	3	3	3	3	0.6	0.9	0.7	0.3	100

Raw Data from sites in the Molopo Region (Mol and Tsc).

		Mar 19	Mar 20	Mar 25	Mar 26	Mar 28	Mar 29	Mar 30	Mar 31	Mar 33	Mar 35	Mar 36	Mar 37	Mar 41
Soil Depth		22	15	14	16	15	18	86	96	25	22	15	69	44
Topsoil : Subsoil Ratio.	SODIUM													
	POTASSIUM													
	MAGNESIUM													
	CALCIUM													
SUBSOIL SILT		18	15	14	13	15	18	15	15	30	18	15	18	22
TOPSOIL SILT		19	14	16	12	14	19	24	19	30	19	12	12	19
SUBSOIL CLAY		2	1	1	2	1	2	1	1	0	0	0	0	2
TOPSOIL CLAY		0	1	2	2	1	0	1	0	0	0	1	1	2
SUBSOIL SAND		80	84	85	85	84	80	84	84	70	82	85	82	76
TOPSOIL SAND		81	85	85	86	85	81	75	81	70	81	87	87	79
SUBSOIL PH		6.0	5.5	5.5	6.7	5.6	5.3	5.5	5.6	5.3	4.9	4.8	5.6	6.6
TOPSOIL PH		[illegible]	5.5	[illegible]	[illegible]	5.6	4.6	4.1	4.6	5.4	4.3	6.1	5.7	6.6
SUBSOIL CONDUCTIVITY		120	90	170	120	130	50	40	220	120	70	[illegible]	30	150
TOPSOIL CONDUCTIVITY		100	70	130	170	120	70	70	180	140	70	[illegible]	[illegible]	30
WOODY CANOPY AREA		46	62	30	16	29	43	21	52	30	32	39	29	9
WOODY DENSITY		2050	1600	1750	1125	1500	1650	1325	1750	1125	1625	2150	2200	2150
WOODY BASAL AREA		4.4	1.1	1.1	1.6	5.4	1.6	1.1	2.0	1.5	4.0	4.2	0.8	0.1
DUNG		0.0	0.6	1.0	2.0	0.0	0.0	0.0	0.6	0.0	1.0	1.0	2.0	1.0
OPEN UNDISTURBED GROUND		84.0	87.0	87.0	90.0	86.0	85.0	86.0	87.0	88.0	52.0	54.0	65.0	60.0
ROCKS		0.0	0.0	0.0	3.0	1.0	1.0	1.0	0.0	0.0	0.0	1.0	0.0	0.0
STONES		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CLAY CAPPING		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ALGAL CAPPING		12.0	6.0	8.0	8.0	12.0	12.0	9.0	10.0	9.0	19.0	17.0	0.0	10.0
OPEN DISTURBED GROUND		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LITTER		4.0	7.0	3.0	0.0	2.0	3.0	4.0	2.0	2.0	26.0	27.0	32.0	28.0
MEAN GRASS HEIGHT		23.0	19.0	7.0	7.0	26.0	27.0	24.0	14.0	21.0	28.0	33.0	23.0	31.0
HERB BASAL AREA		0.0	0.0	0.3	0.0	[illegible]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GRASS BASAL AREA		0.5	0.4	1.4	0.9	0.3	1.0	0.8	0.4	1.0	2.0	2.0	1.3	1.4
SITES		Mar 19	Mar 20	Mar 25	Mar 26	Mar 28	Mar 29	Mar 30	Mar 31	Mar 33	Mar 35	Mar 36	Mar 37	Mar 41

Raw Data From the Mara Agricultural Station (Mar).

Soil Depth		32	19	20	21	56	58	65	68	50	39	41	70	67	61	15
Topsoil : Subsoil Ratio.	SODIUM															
	POTASSIUM															
	MAGNESIUM															
	CALCIUM															
SUBSOIL SILT		20	21	24	20	27	20	38	33	33	20	28	26	26	31	22
TOPSOIL SILT		21	22	24	20	29	26	28	31	31	26	29	26	28	31	24
SUBSOIL CLAY		1	0	1	1	0	0	0	0	0	0	0	0	0	0	1
TOPSOIL CLAY		0	0	1	1	0	0	0	0	0	[illegible]	0	0	0	0	1
SUBSOIL SAND		79	79	75	79	73	80	62	67	67	80	72	74	74	69	77
TOPSOIL SAND		79	78	75	79	71	74	72	69	69	74	71	74	72	69	75
SUBSOIL PH		7.0	6.5	5.9	6.8	6.3	6.5	5.3	6.1	5.2	5.3	6.1	7.1	7.3	6.8	8.5
TOPSOIL PH		6.3	6.7	7.1	7.3	5.1	5.8	5.6	5.8	6.8	5.6	5.6	6.0	5.0	5.0	7.2
SUBSOIL CONDUCTIVITY		100	70	90	100	90	100	70	70	110	130	240	270	270	150	150
TOPSOIL CONDUCTIVITY		80	90	80	90	140	110	120	230	110	90	140	120	160	130	200
WOODY CANOPY AREA		25	27	23	13	10	10	5	6	13	10	10	9	23	20	20
WOODY DENSITY		1000	925	950	400	325	350	200	200	650	750	525	625	525	825	725
WOODY BASAL AREA		0.9	2.3	2.2	1.4	0.4	0.1	0.1	0.2	2.5	3.4	0.6	1.9	0.7	0.5	1.4
DUNG		0.0	0.6	0.0	3.5	0.0	0.0	0.5	0.0	1.1	1.2	0.0	0.0	0.0	0.0	1.9
OPEN UNDISTURBED GROUND		85.0	84.0	86.9	87.6	59.0	69.0	67.0	65.0	71.0	72.0	87.0	75.9	83.0	80.1	85.0
ROCKS		0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6
STONES		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CLAY CAPPING		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
ALGAL CAPPING		3.5	3.0	2.9	3.5	12.0	10.0	3.5	12.0	0.2	1.2	1.3	0.0	7.8	12.1	0.0
OPEN DISTURBED GROUND		0.0	3.3	0.5	0.4	0.4	0.0	0.0	0.0	0.0	0.0	4.3	8.5	0.0	0.0	0.0
LITTER		9.4	6.9	7.3	6.3	26.0	19.0	27.0	21.0	26.0	27.0	6.6	7.9	8.6	7.1	3.8
MEAN GRASS HEIGHT		31.0	19.3	25.1	28.1	35.0	37.0	35.0	35.0	44.0	38.0	17.0	24.0	29.7	26.0	10.9
HERB BASAL AREA		0.0	0.4	0.0	0.0	[illegible]	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
GRASS BASAL AREA		2.6	2.0	2.3	2.3	2.0	2.5	2.5	2.3	1.9	1.1	1.0	0.9	1.1	0.6	2.8
SITES		Mar 1	Mar 2	Mar 3	Mar 4	Mar 5	Mar 6	Mar 7	Mar 8	Mar 11	Mar 12	Mar 13	Mar 14	Mar 15	Mar 16	Mar 21

Raw Data from the Mara Agricultural Station (Mar)

Soil Depth	39	45	60	19	20	32	17	81	56	39	64	61	16	18
Topsoil : Subsoil Ratio. SODIUM														
Topsoil : Subsoil Ratio. POTASSIUM														
Topsoil : Subsoil Ratio. MAGNESIUM														
Topsoil : Subsoil Ratio. CALCIUM														
SUBSOIL SILT	19	14	9	18	20	21	11	11	18	21	30	15	30	18
TOPSOIL SILT	16	14	10	19	16	19	10	9	21	20	31	20	30	19
SUBSOIL CLAY	2	1	2	2	1	0	0	0	4	4	0	2	0	2
TOPSOIL CLAY	2	1	2	2	2	2	0	1	4	4	0	1	0	2
SUBSOIL SAND	79	85	89	80	79	79	89	89	78	75	70	83	70	80
TOPSOIL SAND	82	85	88	79	82	7.	90	90	75	76	69	79	70	79
SUBSOIL PH	6.4	5.9	7.0	5.2	5.9	5.8	6.1	6.6	6.2	5.8	6.1	6.2	6.6	6.2
TOPSOIL PH	6.8	5.8	6.5	5.6	5.9	5.7	6.2	6.2	5.9	6.0	5.7	5.5	6.7	5.4
SUBSOIL CONDUCTIVITY	230	80	110	130	100	130	50	50	80	60	120	100	160	140
TOPSOIL CONDUCTIVITY	270	80	60	120	100	150	70	90	120	130	70	90	160	110
WOODY CANOPY AREA	5	8	10	20	32	15	4	3	24	18	25	14	46	34
WOODY DENSITY	100	325	525	1125	875	750	500	550	1650	1125	2150	2300	1350	1150
WOODY BASAL AREA	0.4	0.2	0.9	1.4	0.9	1.1	0.5	0.4	1.1	1.0	2.4	1.9	1.5	1.1
DUNG	1.3	0.4	0.1	0.0	0.0	0.0	0.0	0.0	2.4	0.9	0.9	0.0	0.0	0.1
OPEN UNDISTURBED GROUND	82.6	82.4	81.6	81.8	82.9	82.9	74.9	58.4	48.3	61.5	62.0	[illegible]	93.0	94.0
ROCKS	0.4	3.3	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
STONES	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CLAY CAPPING	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ALGAL CAPPING	0.0	0.0	2.8	15.4	9.4	11.6	3.0	8.3	1.8	12.3	9.0	7.0	0.0	1.0
OPEN DISTURBED GROUND	0.0	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LITTER	12.1	8.9	14.0	1.6	5.9	4.5	20.4	31.4	45.0	24.1	27.0	25.0	6.0	5.0
MEAN GRASS HEIGHT	9.1	29.1	26.7	14.1	10.7	30.3	9.2	39.1	9.0	26.9	31.0	33.0	15.0	14.0
HERB BASAL AREA	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.4
GRASS BASAL AREA	3.6	1.3	1.5	0.4	1.0	1.0	1.8	2.0	2.6	1.3	1.6	2.1	0.5	0.5
SITES	Mar 22	Mar 23	Mar 24	Mar 27	Mar 32	Mar 34	Mar 38	Mar 39	Mar 40	Mar 42	Mar 9	mar 10	Mar 17	Mar 18

Raw Data from the Mara Agricultural Station (Mar)

SITES	GRASS BASAL AREA	HERB BASAL AREA	MEAN GRASS HEIGHT	LITTER	OPEN DISTURBED GROUND	ALGAL CAPPING	CLAY CAPPING	STONES	ROCKS	OPEN UNDISTURBED GROUND	DUNG	WOODY BASAL AREA	WOODY DENSITY	WOODY CANOPY AREA	TOPSOIL CONDUCTIVITY	SUBSOIL CONDUCTIVITY	TOPSOIL PH	SUBSOIL PH	TOPSOIL SAND	SUBSOIL SAND	TOPSOIL CLAY	SUBSOIL CLAY	TOPSOIL SILT	SUBSOIL SILT	Topsoil : Subsoil Ratio. CALCIUM	MAGNESIUM	POTASSIUM	SODIUM	Soil Depth
Ugr 1	3.8	0.3	2.5	6.4	0.0	0.0	0.0	0.3	0.1	87.0	0.6	0.2	1100	15	310	310	7.8	7.8	68	69	1	1	31	30					70
Ugr 3	5.0	0.1	3.7	14.0	2.1	0.0	0.0	3.0	0.3	74.5	1.0	0.5	4925	23	230	230	6.2	6.2	64	61	2	2	34	37					3
Ugr 4	3.3	0.3	4.8	23.5	0.3	0.0	0.0	0.3	0.0	72.1	0.4	0.1	1375	38	300	300	6.5	6.6	65	65	1	1	34	34					70
Ugr 5	6.2	0.4	3.9	11.1	1.5	0.0	0.0	0.1	6.1	73.0	1.3	0.4	2325	23	210	220	7.3	7.6	80	98	2	1	18	1					25
Ugr 6	5.0	0.5	2.1	14.8	1.8	0.0	0.0	0.1	3.5	74.4	0.0	0.8	1375	18	350	260	7.3	7.7	97	98	1	1	2	1					36
Ugr 8	2.3	0.1	3.7	29.3	3.3	0.0	0.0	1.0	1.1	63.0	0.0	0.9	1475	95	260	220	6.2	6.3	74	75	3	3	23	22					29
Ugr 12	0.5	0.6	4.3	10.3	2.0	1.3	0.0	0.0	0.0	85.0	0.9	1.1	1850	95	260	240	5.9	5.9	71	72	4	4	24	24					70
Ugr 13	2.3	0.5	3.8	23.0	0.9	0.0	0.0	0.5	0.4	70.0	2.3	0.2	1800	10	800	800	7.0	7.0	71	71	1	1	28	28					70
Ugr 14	2.8	0.3	5.1	41.0	6.4	0.0	0.0	0.0	0.4	49.0	0.0	1.0	1250	75	320	130	7.2	7.2	82	81	2	2	16	31					34
Ugr 15	2.5	0.3	2.7	43.0	6.4	0.0	0.0	0.0	0.4	48.0	0.0	0.5	1700	38	430	250	7.4	7.7	83	88	1	1	16	11					37
Ugr 16	2.6	0.3	4.7	39.0	6.6	0.0	0.0	0.0	0.1	48.1	2.4	0.9	1125	95	440	260	6.8	7.1	89	90	1	1	10	9					70
Hlu 1	3.1	1.3	19.0	32.0	26.0	0.0	0.0	0.3	2.9	33.0	2.9	0.6	2200	37	420	240	5.9	6.0	74	75	1	1	25	24					107
Hlu 2	3.6	0.9	21.0	27.0	42.0	0.0	0.0	0.0	1.9	42.0	0.7	0.9	3225	20	290	180	5.9	6.0	79	75	1	1	20	24					79
Hlu 5	1.4	0.3	12.0	26.0	1.9	0.0	0.0	0.0	0.0	69.0	1.4	0.3	1400	50	200	270	5.4	5.6	75	76	2	1	23	23					39
Hlu 6	1.8	0.3	19.0	26.0	2.3	0.0	0.0	0.0	0.0	68.0	1.1	2.9	5350	45	250	160	5.3	6.4	86	86	1	1	13	13					35

Raw Data for Umfolozi (Ugr) and Hluhluwe (Hlu) Game Reserves.

SITES	GRASS BASAL AREA	HERB BASAL AREA	MEAN GRASS HEIGHT	LITTER	OPEN DISTURBED GROUND	ALGAL CAPPING	CLAY CAPPING	STONES	ROCKS	OPEN UNDISTURBED GROUND	DUNG	WOODY BASAL AREA	WOODY DENSITY	WOODY CANOPY AREA	TOPSOIL CONDUCTIVITY	SUBSOIL CONDUCTIVITY	TOPSOIL PH	SUBSOIL PH	TOPSOIL SAND	SUBSOIL SAND	TOPSOIL CLAY	SUBSOIL CLAY	TOPSOIL SILT	SUBSOIL SILT	Topsoil : Subsoil Ratio. CALCIUM	MAGNESIUM	POTASSIUM	SODIUM	Soil Depth
Hlu 9	2.1	0.4	18.0	30.0	1.8	0.0	0.0	0.0	0.0	65.0	1.5	1.5	1800	55	210	150	5.5	5.8	87	88	1	1	12	11					34
Ugr 2	3.6	0.0	5.1	18.2	0.3	0.0	0.0	0.0	0.0	78.0	0.3	7.1	700	45	270	270	7.9	7.8	68	68	2	2	30	30					70
Ugr 7	2.4	0.1	4.5	30.0	3.3	0.0	0.0	1.1	1.3	62.1	1.3	2.9	975	45	150	150	6.5	6.5	79	78	2	3	19	19					42
Ugr 8	1.9	0.1	2.1	14.0	0.8	0.0	0.0	0.0	0.4	83.0	0.0	0.5	900	40	270	270	6.7	6.7	84	82	2	2	16	16					70
Ugr 11	4.3	0.0	4.5	26.1	2.9	0.0	0.0	0.0	0.0	66.0	0.5	0.2	250	8	160	160	6.2	6.2	61	62	8	8	31	30					70
Hlu 3	3.1	1.3	23.0	13.0	24.0	0.0	0.0	0.3	0.6	34.0	1.0	0.6	625	9	150	260	5.9	5.7	73	74	1	1	25	25					89
Hlu 4	3.9	1.1	30.0	38.0	23.0	0.0	0.0	0.0	0.9	33.0	0.8	0.1	1025	2	333	210	5.8	5.8	79	78	2	1	19	21					82
Hlu 7	3.8	1.0	7.0	25.0	11.0	0.7	0.0	0.0	0.0	59.5	1.5	0.1	175	1	140	650	5.5	6.0	82	80	3	3	15	17					18
Hlu 8	4.0	1.0	2.5	22.0	6.0	0.0	0.0	0.0	0.0	65.0	2.0	0.1	450	3	220	230	5.6	5.9	75	75	1	1	25	24					21

Raw Data for Umfolozi (Ugr) and Hluhluwe (Hlu) Game Reserves.

Soil Depth		40	39	45	41	42	40	35	40	29	39	37	37	37	35	41
Topsoil : Subsoil Ratio.	SODIUM	5.0	5.0	1.2	1.2	3.0	3.5	0.5	1.0	2.3	0.4	0.5	3.0	0.3	0.2	0.1
	POTASSIUM	3.3	1.9	1.5	1.4	1.7	1.7	2.5	1.6	0.9	0.9	0.7	1.4	1.6	0.5	1.7
	MAGNESIUM	2.5	1.2	1.9	1.8	1.8	1.9	1.2	0.9	0.8	1.5	2.1	1.0	0.6	0.5	1.2
	CALCIUM	4.51	1.7	1.3	1.5	2.3	1.7	2.0	1.1	1.4	1.2	0.9	1.1	0.5	0.5	0.7
SUBSOIL SILT		24	24	32	23	40	22	28	25	32	33	33	27	22	37	25
TOPSOIL SILT		23	26	30	23	40	24	28	23	30	33	33	22	42	36	25
SUBSOIL CLAY		35	35	24	34	12	35	28	35	24	19	20	28	35	14	35
TOPSOIL CLAY		34	31	26	34	10	30	28	34	26	17	20	30	12	18	35
SUBSOIL SAND		41	41	44	43	48	43	44	41	44	48	47	45	43	49	40
TOPSOIL SAND		43	43	44	43	50	46	44	43	44	50	47	48	46	48	40
SUBSOIL PH		6.8	7.0	6.9	6.8	6.9	7.0	6.8	6.8	6.9	6.9	6.9	6.9	7.1	6.9	7.0
TOPSOIL PH		[illegible]	6.8	6.9	7.0	6.8	6.8	6.8	6.7	6.9	6.9	6.8	6.9	6.8	6.9	6.8
SUBSOIL CONDUCTIVITY		190	200	150	200	200	190	150	170	190	120	205	180	150	180	150
TOPSOIL CONDUCTIVITY		250	205	180	210	220	210	180	[illegible]	130	200	190	180	220	200	120
WOODY CANOPY AREA		0.6	0.9	1.1	0.8	0.9	0.9	2.5	[illegible]	2.5	1.0	2.5	2.0	25	40	40
WOODY DENSITY		50	75	75	100	50	50	500	400	[illegible]	250	450	450	5000	4750	5000
WOODY BASAL AREA		0.7	1.5	0.9	0.9	1.2	1.1	1.5	1.0	1.4	1.0	1.5	1.2	4.1	5.0	4.8
DUNG		1.0	1.5	0.0	1.5	0.0	2.0	0.0	1.0	0.0	0.0	1.0	1.0	0.5	0.5	1.0
OPEN UNDISTURBED GROUND		78.8	74.7	78.9	70.8	73.4	74.7	82.0	82.5	78.2	84.3	83.1	82.7	79.7	74.8	73.5
ROCKS		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
STONES		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CLAY CAPPING		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ALGAL CAPPING		2.0	5.0	4.5	5.0	4.5	3.5	7.5	6.0	5.5	7.0	6.3	7.5	3.5	3.0	5.3
OPEN DISTURBED GROUND		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LITTER		11.0	12.0	9.5	15.0	15.0	10.5	3.0	5.0	11.0	2.5	[illegible]	2.5	11.0	7.2	15.0
MEAN GRASS HEIGHT		20.0	20.0	15.0	17.0	20.0	21.0	10.0	17.0	15.0	13.0	13.0	15.0	15.0	17.0	20.0
HERB BASAL AREA		0.0	0.0	0.1	0.0	0.0	0.5	0.0	1.5	1.5	1.0	1.5	1.1	1.0	0.0	1.1
GRASS BASAL AREA		7.2	6.8	7.0	7.7	7.1	7.7	5.0	4.5	3.7	5.2	5.0	5.1	4.3	5.0	5.1
SITES		Alc 13	Alc 14	Alc 15	Alc 16	Alc 17	Alc 18	Al- 7	Alc 8	Alc [illegible]	Alc 10	Alc 11	Alc 12	Alc 1	Alc 2	Alc 3

Raw Data for the Alice Experimental Station (Alc)

SITES	GRASS BASAL AREA	HERB BASAL AREA	MEAN GRASS HEIGHT	LITTER	OPEN DISTURBED GROUND	ALGAL CAPPING	CLAY CAPPING	STONES	ROCKS	OPEN UNDISTURBED GROUND	DUNG	WOODY BASAL AREA	WOODY DENSITY	WOODY CANOPY AREA	TOPSOIL CONDUCTIVITY	SUBSOIL CONDUCTIVITY	TOPSOIL PH	SUBSOIL PH	TOPSOIL SAND	SUBSOIL SAND	TOPSOIL CLAY	SUBSOIL CLAY	TOPSOIL SILT	SUBSOIL SILT	Topsoil : Subsoil Ratio. CALCIUM	MAGNESIUM	POTASSIUM	SODIUM	Soil Depth
Alc 4	4.8	0.5	15.0	12.5	0.0	5.0	0.0	0.0	0.0	72.2	0.0	4.0	4500	25	180	205	6.7	7.1	43	43	34	34	23	23	0.6	0.3	0.6	1.0	37
Alc 5	4.5	0.0	17.0	7.9	0.0	4.7	0.0	0.0	0.0	72.4	0.5	5.1	5250	50	200	200	6.8	6.9	50	48	15	12	40	40	0.7	0.6	0.5	0.3	39
Alc 6	5.1	0.0	20.0	14.5	0.0	4.1	0.0	0.0	0.0	76.0	0.3	4.9	5000	50	130	150	6.9	6.9	43	43	34	35	23	22	0.5	0.5	1.4	0.4	40
																									Absolute amounts				
Adl 6	4.5	0.0	10.0	3.0	0.0	0.0	0.0	8.0	9.0	75.5	0.0	1.5	250	2.5	140	150	6.5	6.7	43	43	24	24	23	23	17.4	2.7	3.4	0.1	8
Adl 7		0.0	10.0	3.5	0.0	0.0	0.0	10.0	9.0	73.4	0.0	1.2	300	2.0	140	140	7.1	7.2	49	49	14	14	37	37	17.9	2.6	2.9	0.1	15
Adl J		0	10.0	2.5	0.0	4.5	0.0	0.0	0.0	86.0	3.0	0.1	50	1.0	130	170	7.2	7.2	40	40	35	35	25	25	16.7	3.3	4.9	0.1	40
Adl 1		0	4.0	5.0	0.0	2.5	0.0	0.0	0.0	88.0	0.5	0.5	100	2.5	175	150	7.3	7.2	43	44	30	33	27	23	13.7	2.5	4.7	0.1	100
Adl 21	-	.0	7.0	3.0	0.0	1.5	0.0	0.5	0.5	87.0	1.0	0.0	0	0	165	150	7.4	7.1	43	43	24	24	23	23	9.1	2.2	4.9	0.1	70
Adl 22	6.0	0.0	6.0	3.0	0.0	1.0	0.0	1.0	1.0	87.5	0.5	0.1	250	1.0	150	150	7.1	7.0	44	44	28	28	28	28	20.4	2.9	5.7	0.1	70
Adl 25	4.5	0.0	8.0	1.5	0.0	0.0	0.0	2.5	3.0	86.5	2.0	1.5	100	2.5	145	140	6.8	6.8	43	41	34	35	23	24	14.2	2.7	5.6	0.1	60
Adl 26	4.0	0.0	10.0	2.0	0.0	0.0	0.0	3.0	3.0	87.0	1.5	1.5	100	3.0	140	130	6.9	6.8	43	41	31	35	26	24	23.4	3.3	4.9	0.1	60
Adl 27	4.1	0.0	9.0	2.5	0.0	0.0	0.0	2.0	3.0	81.4	1.0	1.0	250	2.5	150	150	6.8	6.8	44	44	26	24	30	32	17.6	2.9	6.9	0.1	60
Adl 28	4.0	0.0	10.0	10.0	0.0	1.5	0.0	2.5	2.5	78.5	1.0	1.5	500	5.0	180	140	6.8	7.1	43	43	24	24	23	23	19.8	3.1	6.3	0.2	60
Krm 1	9.5	0.0	10.0	41.0	0.0	0.0	0.0	0.0	0.0	54.0	5.0	0.0	0	0.0	150	150	6.9	6.8	50	48	10	12	40	40	8.4	1.7	2.7	0.1	100

Raw Data from the Alice Experimental Station (Alc) and the Adelaide district (Adl and Krm).

Soil Depth		100	70	100	100	100	100	100	65	100	100	58	70	75
Topsoil Absolute Amounts	SODIUM	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.1	0.1	0.2	0.5	0.1	0.2
	POTASSIUM	2.5	4.4	4.9	6.9	6.4	5.0	4.2	3.8	1.8	10.2	9.7	1.7	3.2
	MAGNESIUM	3.7	3.9	2.7	2.6	2.8	2.5	2.5	3.1	3.2	2.4	3.1	2.4	2.5
	CALCIUM	13.1	14.9	16.9	12.9	14.5	15.9	13.1	20.2	17.9	10.1	21.9	15.3	21.2
SUBSOIL SILT		24	32	23	40	33	34	32	23	30	35	37	40	23
TOPSOIL SILT		26	30	23	40	33	32	30	23	30	35	37	40	23
SUBSOIL CLAY		35	24	24	12	20	14	24	24	21	18	14	16	24
TOPSOIL CLAY		31	26	24	10	20	14	36	24	21	18	14	16	24
SUBSOIL SAND		41	44	43	48	47	52	44	43	49	47	49	44	43
TOPSOIL SAND		43	44	43	50	47	52	44	43	49	47	49	44	43
SUBSOIL PH		6.9	6.8	7.1	7.1	7.2	6.9	7.2	7.1	7.3	7.1	7.4	7.4	7.1
TOPSOIL PH		6.8	6.8	6.9	7.1	7.0	7.1	7.1	7.2	7.3	7.4	7.5	7.5	7.1
SUBSOIL CONDUCTIVITY		110	170	180	170	150	120	150	135	150	210	290	200	240
TOPSOIL CONDUCTIVITY		130	170	170	160	140	120	150	130	180	240	310	210	205
WOODY CANOPY AREA		19.0	5.0	7.5	35.0	20.0	60.0	15.0	38.0	35.0	50.0	45.0	70.0	65.0
WOODY DENSITY		2000	1000	2000	3750	4000	2000	2000	3750	5000	5250	5000	5750	5000
WOODY BASAL AREA		4.5	3.0	3.5	4.5	4.0	2.5	2.5	5.0	3.5	5.9	4.5	6.0	5.5
DUNG		0.0	2.0	2.0	0.5	0.0	1.0	1.0	1.5	0.0	5.0	1.0	0.0	0.0
OPEN UNDISTURBED GROUND		83.9	88.5	81.0	92.5	92.3	92.8	92.0	81.5	55.0	45.3	77.4	79.9	69.8
ROCKS		0.0	0.0	0.0	0.0	1.0	0.5	0.5	1.0	1.0	0.0	2.0	3.5	4.0
STONES		0.0	0.0	0.0	0.0	0.0	0.5	0.5	1.0	1.0	0.0	2.0	3.5	4.0
CLAY CAPPING		0.0	0.0	0.0	0.0	0.0	[illegible]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ALGAL CAPPING		12.0	5.0	3.0	0.0	0.0	[illegible]	1.5	2.0	3.5	0.0	15	7.5	15.0
OPEN DISTURBED GROUND		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	15.5	0.0	0.0	0.0
LITTER		3.0	3.0	10.0	5.0	5.0	1.5	3.0	12.0	30.0	35.0	15.0	5.0	10.0
MEAN GRASS HEIGHT		3.0	6.0	5.0	3.0	3.5	4.0	5.0	3.5	35.0	7.0	5.0	2.0	2.0
HERB BASAL AREA		0.0	0.0	0.0	0.0	0.0	[illegible]	0.0	0.0	0.0	0.0	0.0	0.5	1.0
GRASS BASAL AREA		1.1	1.5	4.0	1.0	1.7	2.7	1.5	1.0	4.5	4.2	1.1	0.4	0.2
SITES		Adl 11	Adl 12	Adl 15	Adl 16	Adl 17	Adl 23	Adl 24	Adl 29	Krm 4	Krm 8	Adl 30	Adl 31	Adl 32

Raw Data from the Adelaide district (Adl and Krm).

Variable	Krm 2	Krm 13	Krm 3	Krm 5	Krm 6	Krm 9	Krm 10	Krm 7	Adl 1	Adl 2	Adl 3	Adl 4	Adl 5	Adl 8	Adl 9
Soil Depth	100	100	100	10	15	100	100	100	60	60	100	25	12	21	40
Topsoil Absolute amounts. SODIUM	0.2	0.1	0.1	0.2	0.1	0.1	0.3	0.3	0.1	0.1	0.2	0.2	0.5	0.1	0.1
Topsoil Absolute amounts. POTASSIUM	3.8	2.7	2.7	2.6	1.0	1.4	6.4	5.3	6.1	4.0	9.3	7.0	6.8	4.2	4.4
Topsoil Absolute amounts. MAGNESIUM	1.6	1.7	1.7	2.3	2.9	2.7	1.9	2.6	2.3	3.1	2.8	2.9	2.9	2.8	2.6
Topsoil Absolute amounts. CALCIUM	7.9	8.4	8.7	8.8	12.9	15.4	7.9	7.8	13.7	13.7	16.7	13.8	32.1	20.1	13.4
SUBSOIL SILT	38	40	37	33	35	34	32	23	23	37	25	23	23	28	25
TOPSOIL SILT	33	40	37	33	32	34	30	23	23	37	25	27	23	28	23
SUBSOIL CLAY	12	12	12	20	17	14	19	20	24	14	35	33	24	28	35
TOPSOIL CLAY	14	10	12	20	18	14	19	20	24	14	35	30	24	28	34
SUBSOIL SAND	50	48	51	47	48	52	49	47	43	49	40	44	43	44	41
TOPSOIL SAND	53	50	51	47	50	52	51	47	43	49	40	43	43	44	43
SUBSOIL PH	6.8	6.7	6.8	6.9	7.1	6.8	6.8	6.7	7.2	7.2	7.2	7.1	7.0	7.1	7.0
TOPSOIL PH	7.0	7.1	6.5	6.7	7.1	7.1	6.5	6.5	7.1	7.2	7.2	7.4	7.1	6.9	7.0
SUBSOIL CONDUCTIVITY	135	140	120	120	110	165	170	210	140	140	150	140	150	130	120
TOPSOIL CONDUCTIVITY	140	140	140	140	110	170	170	250	140	150	140	180	150	150	120
WOODY CANOPY AREA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	60	7.5	17.5	7.0	[illegible]	.5	21.0	17.5
WOODY DENSITY	0	0	0	0	0	0	0	4500	1000	20	[illegible]	[illegible]	100	2500	4000
WOODY BASAL AREA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.2	3.2	2.5	3.0	3.1	2.9	4.5	2.5
DUNG	0.0	5.0	2.0	0.0	0.0	2.0	0.0	2.0	1.0	0.0	4.0	2.0	5.0	0.0	1.0
OPEN UNDISTURBED GROUND	75.5	50.0	54.2	81.0	82.3	80.9	78.0	49.5	78.9	89.3	79.5	83.5	77.2	72.3	81.3
ROCKS	9.0	0.0	0.0	1.0	1.0	0.0	0.0	0.0	3.0	3.0	7.0	7.0	7.0	15.0	1.0
STONES	8.0	0.0	0.0	0.0	0.0	0.0	0.0	[illegible]	2.0	2.0	5.0	5.0	5.0	9.0	1.0
CLAY CAPPING	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ALGAL CAPPING	0.0	0.0	0.0	3.0	0.0	3.5	[illegible]	[illegible]	0.0	2.0	0.0	0.0	0.0	0.0	0.0
OPEN DISTURBED GROUND	0.0	0.0	0.0	[illegible]	0.0	0.0	[illegible]	[illegible]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LITTER	3.0	45.0	43.0	11.0	9.0	7.5	[illegible]	[illegible]	11.0	2.5	3.0	3.0	3.5	2.5	11.0
MEAN GRASS HEIGHT	10.0	13.0	50.0	30.0	[illegible]	30.0	[illegible]	[illegible]	2.5	3.0	2.0	2.5	3.5	2.8	3.6
HERB BASAL AREA	0.0	0.1	0.5	0.0	0.0	0.0	[illegible]	[illegible]	0.0	0.0	0.0	0.0	0.0	0.0	1.2
GRASS BASAL AREA	4.5	8.5	9.3	4.0	3.7	6.1	[illegible]	[illegible]	4.1	1.2	1.5	1.5	2.3	1.1	3.5

Raw Data from the Adelaide district (Adl and Krm).

Appendix II.

Correlation coefficients of the variables and woody density for all the sites (the upper figure is the correlation coefficient and the lower value is the probability of obtaining the correlation value).

	Mara	Messina	Umfolozi	Molopo	Adelaide	Thabazimbi
Grass basal area	-0.590	-0.309	-0.530	-0.573	-0.523	-0.575
	0.001	0.090	0.997	o.175	0.001	0.004
Herb basal area	-o.270	-0.358	-0.115	-0.256	-0.213	-0.340
	0.071	0.047	0.589	0.290	0.309	0.111
Grass height	-0.009	-0.357	0.217	0.471	0.413	0.265
	0.950	0.048	0.306	0.015	0.378	0.242
Rocks	-0.086	-0.015	-0.086	-0.109	0.101	-0.365
	0.568	0.673	0.689	0.593	0.713	0.086
Litter	-0.075	0.072	-0.066	0.186	0.172	-0.034
	0.619	0.697	0.759	0.631	0.691	0.876
Algal capping	-0.229	-0.456	-0.221	-0.339	-0.145	0.131
	0.124	0.009	0.173	0.095	0.514	0.549
Bare undisturbed	0.174	-0.202	0.068	-0.214	-0.022	0.227
	0.246	0.274	0.749	0.292	0.746	0.296
Bare disturbed	-0.155	0.076	-0.040	-0.066	-0.003	0.213
	0.302	0.684	0.852	0.752	0.884	0.328

	Mara	Messina	Umfolozi	Molopo	Adelaide	Thabazimbi
Dung	-0.921 0.542	0.518 0.003	0.131 0.539	0.132 0.527	0.218 0.543	0.885 0.001
Topsoil pH	0.486 0.001	0.603 0.003	-0.211 0.320	0.227 0.263	-0.328 0.348	0.208 0.340
Subsoil pH	-0.356 0.014	0.408 0.022	-0.066 0.755	-0.222 0.273	-0.216 0.452	-0.031 0.886
Topsoil conduct.	-0.215 o.151	0.143 0.440	0.073 0.734	0.477 0.013	0.715 0.001	0.076 0.729
Subsoil conduct.	-0.224 o.132	0.191 0.303	-0.189 0.376	0.179 0.332	0.731 0.001	-0.054 0.803
Topsoil sand	0.060 0.690	0.317 0.750	0.127 0.615	-0.032 0.873	0.119 0.595	-0.313 0.145
Subsoil sand	-0.307 0.037	-0.247 0.176	-0.219 0.303	0.012 0.950	-0.195 0.401	-0.034 0.636
Topsoil clay	-0.101 0.490	-0.679 0.001	0.004 0.983	-0.180 0.376	0.085 0.876	-0.257 0.235
Subsoil clay	0.133 0.370	0.712 0.001	0.033 0.875	0.224 0.209	0.207 0.901	0.013 0.952
Topsoil silt	0.199 0.184	-0.399 0.025	-0.267 0.206	0.136 0.507	0.221 0.525	0.038 0.863
Soil depth	-0.095 0.529	0.413 0.734	-0.243 0.250	0.495 0.137	0.845 0.019	0.834 0.795

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