Soil-water utilisation and sustainability in a semi-arid grassland

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Abstract

The impact of different botanical composition classes, viz. poor, moderate and good, on soil-water balance, water-use efficiency (WUE: crude protein produced per unit of evapotranspiration), productivity and soil temperature were determined in a semi-arid grassland during four growing seasons (1995/96 to 1998/99). In addition, the same measurements were also made on an undisturbed bare soil surface and soil cultivated twice per annum, only for the last four years. Evapotranspiration was determined by quantifying the soil-water balance equation with the aid of runoff plots and soil-water content measurements. Crude protein content calculated from N-content (Kjeldahl-method) of the leaves, stems and seed was determined. Though the percentage crude protein content of grassland in good condition was generally lower ($P<0.01$) than that of grassland in poor condition, crude protein production was still significantly ($P<0.01$) higher when expressed as total quantity of above-ground phytomass produced. Water-use efficiency declined significantly ($P\leq0.01$) with grassland degradation. Grassland in good condition averaged a WUE of 0.29 kg crude protein·ha^{-1}·mm^{-1} during four growing seasons. Higher surface runoff occurring in grassland in poor condition due to less vegetation cover, caused soil-water content to be much lower than that of grassland in good condition. Soil-water storage increased by 31% due to cultivation. Veld degradation resulted in soil temperature increasing up to 8.5 °C at a depth of 50 mm during December. An important requirement for sustainable grassland production in semi-arid climates, is effective soil-water management, which is only possible when the veld is in good condition.

Introduction

It is estimated that 82% of the land available in South Africa for agricultural purposes or 68 million ha veld (native pasture), can only be effectively utilised by grazing ruminants (Snyman, 1998). The South African veld types are extremely diverse in terms of botanical composition (Acocks, 1988), productivity in terms of nutritive value (O’Connor and Bredenkamp, 1997), and therefore the ability to sustain animal production. Furthermore, large variations in grassland production, primarily due to differences in annual rainfall as well as its distribution, occur at any specific site between years and are invariably reflected in animal performance (De Waal, 1990).

The cyclic nature of the annual precipitation and the unreliable distribution of the seasonal rainfall of Southern Africa, result in long extensive droughts and shorter seasonal droughts (O’Connor and Bredenkamp, 1997). Greater incidence of drought is relevant to the risks associated with ranching activities. Accurate balancing of the stored soil water with the expected water deficit for grasslands in different conditions is a means of lowering risk in fodder flow planning (Snyman, 1999b). This requires a sound knowledge of the soil-water balance and the quantification of each component thereof.

In South Africa, grasslands and forestry together utilise approximately 62%, and dryland crop production 12%, of the rainfall (Bennie et al., 1997). As rainfall is the limiting environmental factor that determines grassland production in the arid and semi-arid areas (Snyman, 1998), sustainable utilisation of the grassland ecosystem must emphasise the capturing and efficient use of water. Community composition has a decisive influence on the productivity and eventually on the grazing capacity expected from grasslands (Snyman, 1997a). Although the farmer cannot control the rainfall on his farm, he can directly and/or indirectly influence its effectiveness, since grassland condition is influenced by management practices (Snyman, 1999a).

Water-use efficiency (WUE) (expressed in kg above-ground phytomass production or kg crude protein for each mm of evapotranspiration) is a convenient and suitable tool to evaluate the productivity of a grassland ecosystem. In calculating WUE, most researchers (Le Houérou, 1984; Snyman, 1988; 1998; 1999b; Snyman and Fouché, 1991) only express it in terms of the quantity of dry matter (DM) produced per unit water consumed, while its calculation in terms of crude protein produced per unit of water consumed, receives little attention at present. The latter calculation can make a large contribution to the estimation of short-term nutritive value of grassland in a specific condition, given the quantity of rainfall received or water consumed.

The purpose of this study was to investigate the ability of veld to efficiently utilise limited soil-water in the semi-arid Central grassland and to identify the influence of veld degradation on water-use efficiency and productivity. This study identified the seasonal soil-water withdrawal pattern generally occurring under different compositional states, as well as the extent of water loss from bare soil.

Procedure

Site description

The study was conducted in Bloemfontein (28°50’S; 26°15’E, altitude 1 350 m), which is situated in the semi-arid summer rainfall (annual average 560 mm) region of the Republic of South Africa. Rain falls almost exclusively during summer (October to April), with an average of 78 rainy days per year. Mean maximum monthly temperatures range from 17°C in July to 33°C in January, with an

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average of 119 frost days per annum (Schulze, 1979).

The data were collected from a typical Dry Sandy Highveld Grassland (Grassland Biome) (Bredenkamp and Van Rooyen, 1996), with a slope of 3.5%. The soil is a fine sandy loam soil of the Bloemdal Form (Roodepoort family – 3 200) (Soil Classification Working Group, 1991). The percentages of clay increases down the profile from 10% in the A-horizon (0 to 300 mm depth), to 24% in the B1-horizon (300 to 600 mm) and 42% in the B2-horizon (600 to 1 200 mm depth). The bulk densities were 1 484 kg·m^{-3} for horizon A, 1563 kg·m^{-3} for horizon B1 and 1 758 kg·m^{-3} for horizon B2. The upper limit of the soil-water holding capacity for the layers 0 to 300 mm (A-horizon); 300 to 600 mm (B1-horizon); 600 to 900 mm (B2-horizon) and 900 to 1 200 mm (B2-horizon) are 69 mm; 73 mm; 82 mm and 82 mm respectively.

Treatments

The experimental layout was a fully randomised design consisting of five treatments with three replications. Grassland in three different compositional classes (good, moderate and poor), undisturbed bare soil surface and a soil cultivated twice per annum (December and June) were studied from 1995/96 to 1998/99. The treatments were intended to reflect the compositional states which could arise as a result of different grazing histories on this vegetation type, described by Potts (1923); Mostert (1958); Van den Berg et al. (1975) and Snyman (1988; 1997a), as being in good, moderate and poor condition. In this grassland, grazing is not random but involves certain functional groups of plants being advantaged, leading in time to fundamental changes in community organisation. A distinct composition and basal cover therefore characterises each treatment.

The study involved 15 runoff plots, each measuring 2 m x 15 m, with an average slope of 3.5%. Plot edging was done by overlapping short lengths of iron sheeting, placed in the soil to a depth of 200 mm. The water was collected with a gutter fixed at the bottom end of each plot and sampled in 1 000 l water tanks (placed into the soil). Basal cover and botanical composition were determined with a bridge-point apparatus (Walker, 1970; Snyman and Fouché, 1991). During each growing season 500 points (nearest plant and strikes) were recorded per plot. From 1995 the grassland had been artificially kept in the above-mentioned condition classes. After determining the basal cover and botanical composition, all undesirable or invader species (with respect to each specific veld condition class) were actively removed with minimum disturbance.

Grassland condition was determined according to the method of Fourie and Du Toit (1983). When the species were classified, the desirability in terms of grazing value (dry-matter production, palatability, nutritive value, whether perennial or annual, and grazing resistance) as well as the ecological status (decreaser and increaser species), as defined by Foran et al. (1978), were taken into consideration. The classification of dry *Themeda - Cymbopogon* grassland into different ecological groups as described by Fourie and Visagie (1985) was used.

Data collection

Monthly herbage production that was determined for each grassland condition class, by clipping 10 m^2 of plants to a height of 30 mm in each treatment at the end of each month by Snyman and Oosthuizen (1999), was used to determine the crude protein content. A calorimetric technique (Technicon, 1977) was used to determine N-content following Kjeldahl digestion of the plant material in concentrated sulphuric acid. Crude protein content, calculated from N-content of the whole above-ground organs (leaves, stems and seed), was determined in the middle and at the end of each month.

Water-use efficiency (WUE) is defined as the quality (crude protein content) of dry matter produced per unit of water evapotranspired. Evapotranspiration (Et) was determined by quantifying the soil-water balance equation (Hillel, 1971). Rainfall was measured daily with rain gauges. The runoff data used in the soil-water balance were taken from Snyman and Oosthuizen (1999). The soil-water content was monitored with the aid of a neutron hydroprobe (Model CPN 503). Two neutron probe access tubes were placed in each plot, to a depth of 1.5 m. The soil-water content was monitored at 200 mm depth intervals every fourth day. The neutron hydroprobe was calibrated for each horizon (Snyman et al., 1987).

Soil temperature was recorded with mercury thermometers once a week in each plot at 14:00 at 50, 100 and 200 mm depths for all treatments. Although the thermometers were not properly ventilated, they were shielded. All data were analysed using a one-way analysis of variance technique (Winer, 1974).

Results and discussion

Botanical composition and basal cover

The average grassland condition score (expressed as a percentage of that in a benchmark site) during the experimental period ranged from 92.21% to 32.01% and the basal cover from 9.00% to 3.40% (Table 1). Grassland in good, moderate and poor condition was respectively dominated by *Themeda triandra, Eragrostis chloromelas* and *Tragus koelerioides,* which formed 56%, 38% and 40% respectively of the species composition of each grassland condition class (Table 1). Grassland in good condition consisted of 66% Decreaser species, grassland in moderate condition of 61% Increaser II(a) species, and an average of 63% of the species in grassland in poor condition, were Increaser II(c) species.

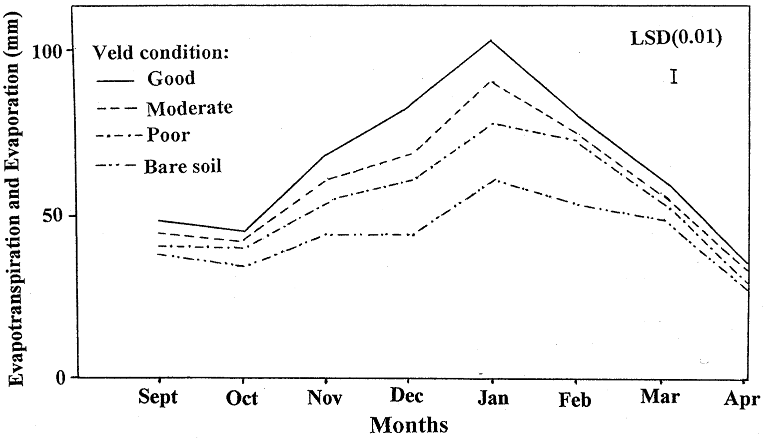


Figure 1

Monthly average evapotranspiration (mm) for veld in different condition classes (good, moderate and poor) and evaporation (mm) from bare soil from the 1995/96 to the 1998/99 growing seasons.

TABLE 1
Percentage Species Composition, Ecological Status Totals, Basal Cover and Veld Condition Score for Each Condition Class from the 1995/96 to the 1998/99 Season

Ecological status	Species	Veld condition status			
		Bench-mark	Good	Moderate	Poor
Decreaser	*Digitaria eriantha*	0.17	7.10	0.10	
	Panicum stapfianum		0.20		
	Sporobolus fimbriatus	0.52	2.16	0.10	
	Themeda triandra	81.06	56.10	3.10	
Decreaser total		**81.75**	**65.56**	**3.30**	
Increaser II(a)	*Cymbopogon plurinodis*	1.21	4.14	1.15	
	Digitaria argyrograpta	4.24	3.17	4.12	1.00
	Eragrostis chloromelas	8.13	10.16	38.16	11.05
	Eragrostis lehmanniana		2.92	13.15	14.20
	Eragrostis superba		1.11	2.00	
	Heteropogon contortus	0.37			
	Setaria sphacelata var. sphacelata		2.11	2.11	1.00
Increaser II(a) total		**13.95**	**22.81**	**60.69**	**27.25**
Increaser II(b)	*Cynodon hirsitus*			2.00	3.04
	Eragrostis obtusa	0.09	0.10	8.47	2.10
	Elionurus muticus		7.00	10.12	
	Triraphis andropogonoides	0.09		9.12	5.16
Increaser II(b)total		**0.18**	**7.10**	**29.71**	**10.30**
Increaser II(c)	*Aristida congesta*	0.26	2.20	4.14	19.70
	Lycium tenue	1.12			
	Tragus koelerioides	1.47	2.33	2.16	40.20
	Walafrida saxatilis	1.30			2.55
Increaser II(c)total		**4.12**	**4.53**	**6.30**	**62.45**
Increaser II total		**18.25**	**34.44**	**96.70**	**100.00**
Veld condition score		919.85	848.20	582.97	294.40
Veld condition (%)		100	92.21	63.38	32.01
Basal cover (%)		9.06	9.00	6.15	3.40

Evapotranspiration (Et) and evaporation (Es)

The average Et of the plant covered treatments and Es of the bare soil treatments differed significantly ($P \leq 0.01$) from each other for every month of the growing season, except the cultivated treatments (not given in Fig. 1), which differed non-significantly ($P>0.05$) from grassland in moderate condition (Fig. 1). With veld degradation, Et decreased significantly ($P \leq 0.01$) (Fig. 1). Grassland in good condition evapotranspirated on average 22% more water than grassland with a poor vegetation composition over the four growing seasons.

In all treatments the highest Et and Es occurred during the 1996/97-season, during which 18% more rain fell than the long-term average for the area. The highest Et and Es were measured during January for all treatments (Fig. 1). During this month the highest average rainfall occurred, during the four years of the trial, which is 12% more than its long-term average.

The bare uncultivated area had a 35% lower Es than the Et obtained from grassland in good condition during the experimental period. The direct Es from the bare uncultivated soil was 69% of the infiltrated rainfall for this treatment.

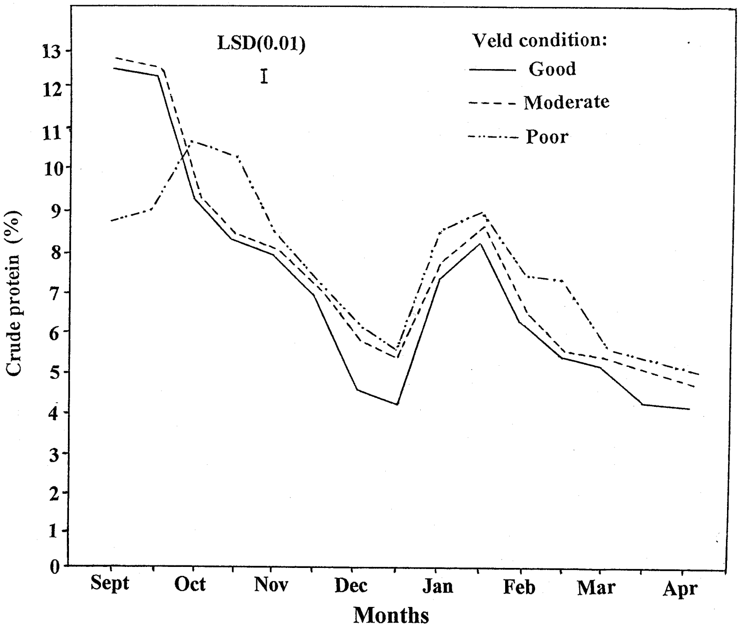


Figure 2
Average crude protein for different veld condition classes (good, moderate and poor) as measured during the middle and end of each month from the 1995/96 to the 1998/99 growing season.

TABLE 2
Seasonal (September To April) Crude Protein and Water-use Efficiency (WUE) (Maximum-Minimum Monthly Ranges in Brackets) for Different Veld Conditions, from the 1995/96 to the 1998/99 Seasons. Least Significant Differences (LSD) are Calculated at the 1% Level.

Year	Rainfall (mm)	Crude protein (kg·ha^{-1})				WUE (kg crude protein ha^{-1}·mm^{-1})			
		Veld condition			LSD	Veld condition			LSD
		Good	Moderate	Poor		Good	Moderate	Poor	
1995/96	591	174.00 (47.66-3.07)	108.24 (45.22-0.73)	56.72 (23.18-1.87)	40.96	0.29 (0.48-0.05)	0.18 (0.23-0.01)	0.10 (0.27-0.03)	0.05
1996/97	598	215.68 (70.00-0.74)	136.64 (32.65-3.29)	50.72 (15.63-1.16)	74.00	0.36 (0.61-0.02)	0.23 (0.35-0.12)	0.08 (0.30-0.05)	0.09
1997/98	454	134.80 (57.85-0.40)	105.04 (50-78-1.64)	38.80 (20.76-0.86)	25.68	0.29 (0.39-0.04)	0.23 (0.35-0.04)	0.085 0.15-0.06)	0.02
1998/99	369	76.08 (15.42-1.95)	64.00 (17.56-2.93)	25.52 (10.49-0.82)	10.48	0.21 (0.37-0.06)	0.17 (0.44-0.09)	0.07 (0.28-0.09)	0.02
Average	503	150.14	103.48	42.94		0.29	0.20	0.08	

Crude protein

Grassland in poor condition had the highest ($P \leq 0.01$) crude protein in all growing seasons, except for September and the beginning of October (Fig. 2). The highest crude protein content occurred in middle September, where it formed an average of 12.61% and 12.84% of the dry material for grassland in good and moderate condition respectively. The lower crude protein content found in plant material as grassland condition improves, is possibly caused by the soil reserves of water being used for high dry matter production per unit area delivered by grassland in good condition. The removal of grass tufts in a semi-arid area could increase grass leaf N-content of the remaining tufts (Van de Vijver, 1999). Van de Vijver attributes this effect to increased availability of soil N per individual grass tuft due to the reduction of the number of grass tufts per area. The significantly low crude protein in plant material occurring in grassland in poor condition during September (Fig. 2) can be ascribed to most of the plants occurring in this compositional class, being pioneers. These poorly perennial plants have a disadvantage compared to the perennial plants, in that limited soil reserves of water are available for regrowth in spring (Oosthuizen and Snyman, 1999). The perennial plants with their better distributed root system (Snyman, 1993) are also better adapted for rapid regrowth than pioneer plants, which is a further reason for better regrowth in spring as compositional state improves.

The gradual decrease in percentage crude protein occurring after the spring and reaching a low at the end of December, can be ascribed to most of the plants being in full seed at that stage and gradually becoming dormant. The crude protein percentage of grassland in good condition was as low as 4.21% at the end of December, almost similar to that reached in middle April when the first frost occurred. Most of the growing seasons were characterised by a mid-summer drought (middle December to middle January) that could also contribute to a decrease in crude protein percentages (Fig. 2). The central grassland area is normally characterised by a second growing season, which usually starts during the middle of January, resulting in a second peak in crude protein at the end of January (Fig. 2). About the middle of February, during most seasons, the grasses start becoming reproductive again with a rapid decrease in crude protein as the season progresses and the plants become dormant. Remarkably, similar seasonal variation and trends in crude protein content of the diet selected by oesophageally fistulated sheep on the same veld type is documented (De Waal, 1990).

The seasonal crude protein (expressed in $kg\cdot ha^{-1}$) differed significantly ($P \leq 0.01$) between the different grassland conditions (Table 2). Though grassland in poor condition had for most of the year a significantly ($P \leq 0.01$) higher seasonal percentage of crude protein than grassland in good condition, the crude protein, expressed in $kg\cdot ha^{-1}$ was very low (Table 2) due to lower ($P \leq 0.01$) above-ground dry matter production accompanying veld degradation. Grassland in good, moderate and poor condition produced on average respectively 2145; 1317 and 551 kg dry $matter\cdot ha^{-1}$ per season (Snyman and Oosthuizen, 1999). The lowest seasonal production (1 126 $kg\cdot ha^{-1}$) obtained for grassland in good condition, was still significantly higher than the highest (731 $kg\cdot ha^{-1}$) for grassland in poor condition.

The highest crude protein per hectare for grassland in good condition was obtained during the high rainfall season (1996/97) (Table 2). Regardless of the quantity of rainfall occurring in a season, grassland in poor condition had a notably low production in crude protein per area (Table 2). The better the grassland condition, the more effective the reaction obtained in terms of crude protein production per hectare. A general conclusion is that in semi-arid grassland, annual primary production depends mainly on the interaction between rainfall and composition/basal cover.

Soil-water content

Though soil-water content was monitored for every treatment in every growing season, only a typical water uptake pattern (1997/98 season) is presented graphically (Figs. 3 and 4). As the first half of this season was accompanied by notably low rainfall and therefore mirrored a small variation in soil-water content, the latter is graphically presented only from 26 December 1997. Considering that the soil-water content in all treatments was almost ($P>0.05$) the same at the start of the experiment, it was lower during only four years by an average of 12% due to poorer compositional state. The soil-water content of the bare uncultivated sites was on average 53% lower during the study period than that of veld in good condition. Water storage increased in the cultivated plots as the seasons progressed due to periodic cultivation resulting in high infiltration and the fact that there was no vegetation for water withdrawal.

After only three years of cultivation the A; B1 and first half of the B2 horizon were filled to full storing capacity, while the rest of the B2 horizon was only filled up to 60% of the storage capacity (Fig. 4). Therefore, the upper limit (drained upper limit) soil-water holding capacity for the layers 0 to 300 mm; 300 to 600 mm and 600 to 900 mm for this soil form are 68 mm; 73 mm and 80 mm (obtained from the cultivated treatment without plants (Fig. 4)).

This specific season (1997/98) was accompanied by significantly low runoff losses in all treatments (Snyman and Oosthuizen, 1999), making the soil-water withdrawal pattern for the different grassland conditions in Figs. 3 and 4 still more significant. The soil-water content, as graphically presented in Fig. 3 can thus be seen mainly as a presentation of the cumulative effect of vegetation changes during four years on the soil-water content.

A considerable variation occurred in the utilisation and water withdrawal pattern in all compositional classes, especially in the first 300 mm soil depth, during the growing season (Fig. 3). Resulting from sparser vegetation covering and higher ($P \leq 0.01$) surface runoff accompanying grassland deterioration (Snyman and Oosthuizen, 1999), soil-water content of grassland in poor condition was significantly ($P \leq 0.01$) lower than that of the better compositional states especially over the first 600 mm depth. The contribution of Es on the plant covered treatments may be much more with grassland degradation than previously believed. This is supported by Snyman (1998) who states that the largest percentage of soil drying immediately after wetting, in the semi-arid areas, can be ascribed to evaporation (Es) from the soil surface. The magnitude of direct Es from the soil surface in arid and semi-arid grasslands might range from 20% to 70% of the infiltrated rain (Le Houérou, 1984). Though it could be expected that climax plants of grassland in good condition will withdraw more water (Et) from the top soil layer, due to their better distributed root system (Snyman, 1994) and higher production (Snyman and Fouché, 1991) than pioneer grassland with a weakened root system, the reverse was proved during this study. From 20 January 1998 to 4 February 1998 the water withdrawal (during which no rain occurred) from grassland in good condition was, for example, 60 mm over the first 300 mm depth vs. the water loss of 77 mm for deteriorated grassland. According to Van de Vijver (1999), removal of grass tufts in a semi-arid Savanna could not significantly affect soil-water content, but increased grass leaf N-content of the remaining tufts. Higher root density of deteriorated grassland in the top 0 to 300 mm layer could be associated with higher Et in this study.

It is clear from Fig. 3 that the 300 to 600 mm layer for veld in good condition, maintained a high soil-water content (nearly filled to full water storing capacity) during a great deal of the season. The stronger supplementation of water to this layer due to low runoff (Snyman and Oosthuizen, 1999) and also greater withdrawal of water by the deeper roots of the climax species (Snyman, 1994), could be the reasons for this high soil-water content. Though more than 80% of the root mass of perennial veld grasses is found in the top 150 to 200 mm soil layer (Tainton, 1981; Moore, 1990; Snyman, 1994) and is responsible for production, the importance of deeper roots contributing towards survival of the plant during water stress must not be underestimated. Climax grasses have been known to withdraw water from deeper than 2 m during drought periods (Snyman, 1994). Unfortunately no root depths or root densities were measured during this study.

In all compositional classes, the soil-water content to a depth of 900 mm was only slightly supplemented over the growing season (Fig. 3). Due to the variable and low rainfall of semi-arid regions, the general tendency is that the perennial herbaceous layer withdraws water from throughout the whole soil profile during the growing season and can store much water for a following growing season or period (Fig. 3). Grasses in these areas generally grow optimally for relatively short periods before temporary wilting takes place (Snyman, 1993; 1998). Deep percolation beyond the root zone (i.e. more than 900 mm) did not occur under plant cover in this study (Fig. 3). Similarly, Snyman and Fouché (1991) did not find evidence of deep percolation (up to 800 mm) in the same semi-

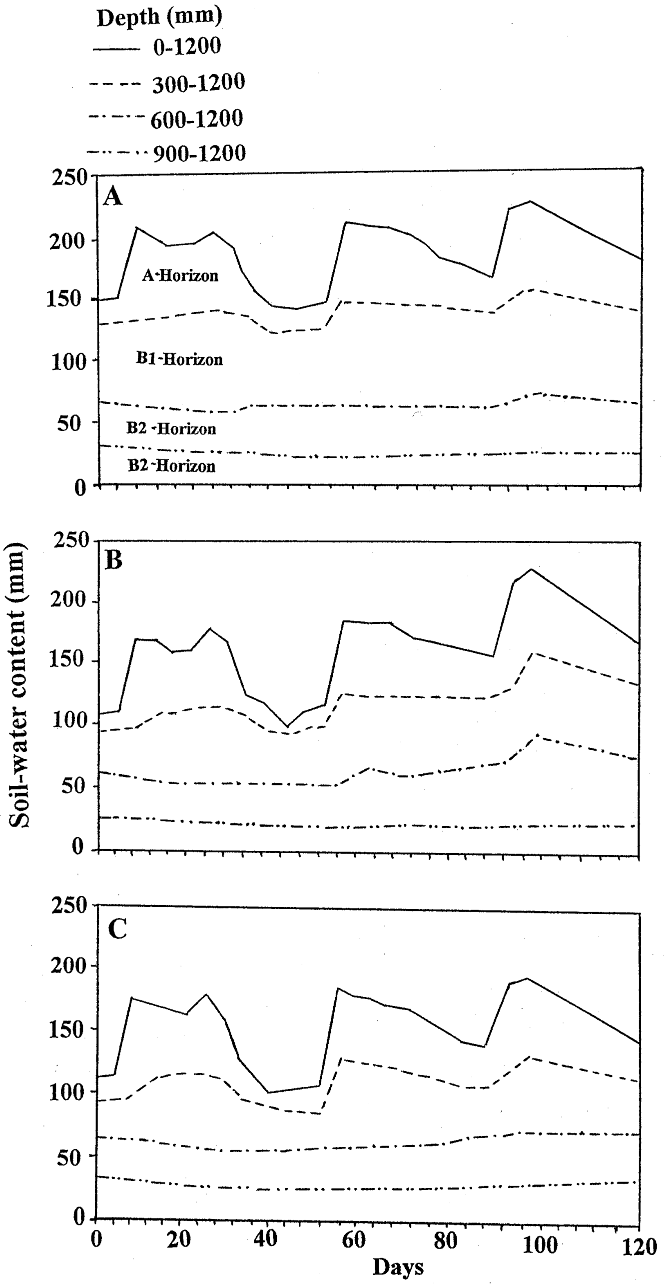


Figure 3
Soil-water content (mm) (measured every fourth day) over different depths for veld in good (A), moderate (B), and poor (C) condition for the period 26 December 1997 to 24 April 1998

arid grassland over a 12-year study period. It appears that in the arid and semi-arid areas, deep percolation only occurs under extremely high rainfall conditions (Fischer and Turner, 1978; Scholes and Walker, 1993; Snyman, 1994; 1997b; Bennie et al., 1994; Snyman and Oosthuizen, 1999). The long-term seasonal percolation of water through a soil profile covered by vegetation is therefore negligible in these areas. The lower limit plant available water for the different layers 0 to 300 mm; 300 to 600 mm; 600 to 900 mm and 900 to 1200 mm for this veld ecotope obtained from the plant covered treatments are 15 mm; 25 mm; 28 mm and 22 mm (Fig. 3). The quantity of water which can be stored in the soil profile varies mainly with the silt plus clay content and depth (Bennie, 1991) while the type of clay minerals and organic matter content (Van de

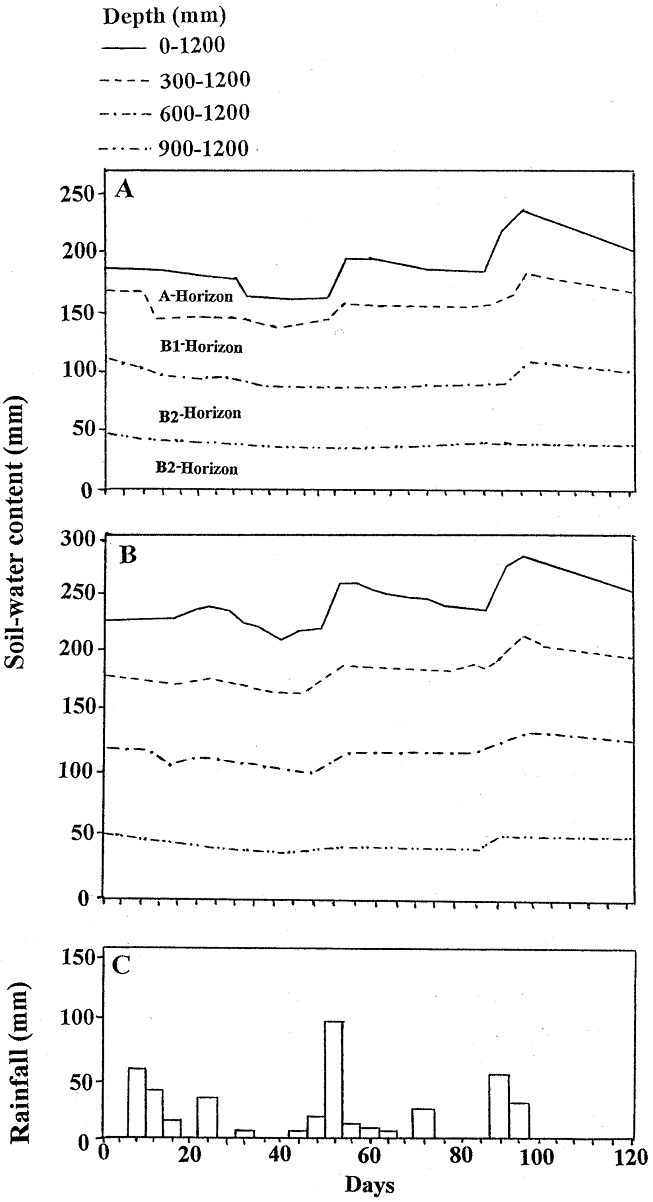
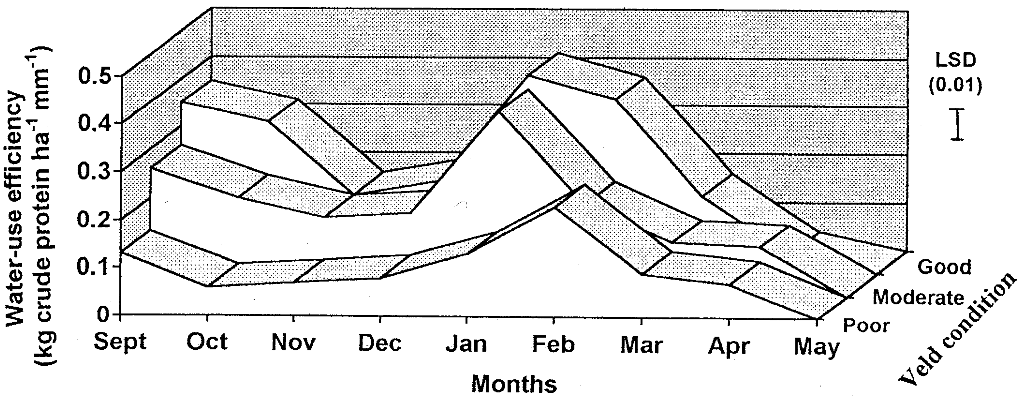


Figure 4
Soil-water content (mm) (measured every fourth day) over different depths for bare (A) and cultivated (B) soil, as well as rainfall (C) for the period 26 December 1997 to 24 April 1998

Vijver, 1999) can also make a contribution. The storage capacity of available water for grasses of most soils in the semi-arid areas of Southern Africa where grassland is found, varies between 100 and 120 mm·m^{-1} depth (Bennie, 1991), which is more or less the same for this study.

About three years after starting the trial, the water withdrawal period (30 December 1997 to 20 April 1998) showed that soil-water content of grassland in good condition was 30; 20; 15 and 5 mm higher at the depths, 300; 600; 900 and 1 200 mm than that of grassland in poor condition as presented in Fig. 3. The soil-water content of the bare uncultivated areas over the first 300 mm depth did not vary as much during the season, as was the case with the vegetated sites. The soil-water content of the bare uncultivated sites (Fig. 4) was significantly ($P \leq 0.01$) lower than those of the denser plant-covered sites for periods of successive rainfall, up to 300 mm deep, and higher during the drier periods. The conclusion

Figure 5
Monthly average water-use efficiency (kg crude protein ha^{-1}·mm^{-1}) for the different veld conditions (good, moderate and poor) from the 1995/96 to the 1998/99 growing season.



can be made that the extent of Es from the soil surface in bare uncultivated soil is considerable just after a rain shower, while more water is withdrawn (Et) by vegetation during more arid periods from the top soil layers, as the plant cover grows denser.

Up to a depth of 600 mm, the soil-water content of the bare uncultivated areas was significantly ($P \leq 0.01$) higher during the season than that of the plant-covered sites. The reason for these differences is the water withdrawal by plant roots of the vegetation in the plant-covered sites over these depths. The soil-water content of the bare, uncultivated soil was as much as 15 mm higher than those of the plant-covered sites up to a depth of 1 200 mm on average for the season. This again emphasises the conclusion that the different compositional classes withdraw water over the whole soil profile. Deeper than 600 mm, the soil-water content of the bare sites which were cultivated and undisturbed, differed non-significantly ($P > 0.05$) from each other. The soil-water content of the cultivated sites was significantly ($P \leq 0.01$) higher than all other treatments to a depth of 600 mm and even 85 mm higher than those of the plant-covered sites over the first 300 mm depth (Fig. 4).

Water-use efficiency (WUE)

The low WUE during November/December and March/April (Fig. 5), occurred within the reproductive phase of most grass species within a specific grassland compositional class. With the onset of the season all the compositional states had a reasonably high WUE, which can be ascribed to the markedly high crude protein content of the plant material during that period (Fig. 5). Most grasses underwent another active growing period, after the reproductive phase at the end of December, which can be observed in Fig. 5 in the WUE increase, due to an increase in crude protein.

The seasonal average WUE of 0.29 kg crude protein ha^{-1}·mm^{-1} obtained for grassland in good condition over the experimental period, is markedly higher than the 0.11 kg crude protein ha^{-1}·mm^{-1} obtained by Snyman (1994) on the same grassland type. The average WUE for grassland in moderate and poor condition were respectively 0.20 and 0.08 kg crude protein ha^{-1}·mm^{-1} over the experimental period. The highest monthly (January/February) WUE occurring respectively in grassland in good, moderate and poor condition, were 0.41, 0.38 and 0.23 kg crude protein ha^{-1}·mm^{-1}. Snyman et al. (1980) also obtained the highest WUE during the last half of the growing season on the same compositional classes, contrasting with the findings of Snyman (1988) that the first half of the growing season was the most efficient.

The highest seasonal WUE occurred during the 1996/97-season (Table 2), during which grassland in good, moderate and poor condition produced 0.36, 0.23 and 0.08 kg crude protein ha^{-1}·mm^{-1} respectively. The annual WUE differed significantly ($P \leq 0.01$) between the different compositional states for all the growing seasons.

Soil temperature

The mean monthly soil temperature at a depth of 50 mm, is graphically presented in Fig. 6 for the different compositional states and bare soil. At this depth, soil temperature did not differ significantly ($P > 0.05$) between grassland in moderate condition and the cultivated soil surface and the latter is therefore not shown in Fig. 6. A significant increase in soil temperature did occur with veld degradation for most months (Fig 6). This could be one of the reasons for the lower soil-water content over the season, especially for the top soil layer of veld in poor condition.

With the exception of the spring months, August and September, and also the winter months, May, June and July, soil temperatures differed significantly ($P \leq 0.01$) between the different compositional states and bare uncultivated soil. In all treatments the highest soil temperatures occurred at a depth of 50 mm during December. For this month, which was also characterised by a mid-summer drought for most growing seasons, the soil temperature of the bare soil surface, poor, moderate and good condition grassland was 47.0°C; 44.5°C, 41.5°C and 36.0°C (Table 3). In all treatments, soil temperatures showed a sharp increase from August, reached a peak in November/December, after which they gradually evened out towards winter. During May, June and July the soil temperatures of grassland in good and moderate condition were almost the same ($P > 0.05$) with grassland in poor condition and bare soil surface the same ($P > 0.05$).

For most months, soil temperatures did not differ significantly ($P > 0.05$) between treatments for the 100 and 200 mm depths. Only the soil temperature of the bare soil surface differed significantly ($P \leq 0.01$) from other treatments at 100 mm depth for the months November, December and January. The soil temperatures did not show much variation at 200 mm depth during the season in all treatments. Over these three months the biggest difference in soil-water content occur between the plant-covered treatments and bare soil for the top 300 mm soil layer. The difference between maximum and minimum soil temperatures for all depths was always the highest for the bare soil surface.

With the onset of the growing season (September to October), the highest temperature measured on top of the bare soil surface (40°C), and on top of soil in grassland in good condition (39°C), did not differ much. As the season continued and vegetation afforded better protection to the soil surface, these differences became much greater with grassland degradation. The higher soil temperatures with grassland degradation are supported by Du Preez and Snyman (1993) and Snyman (1999a). The highest temperatures on top of

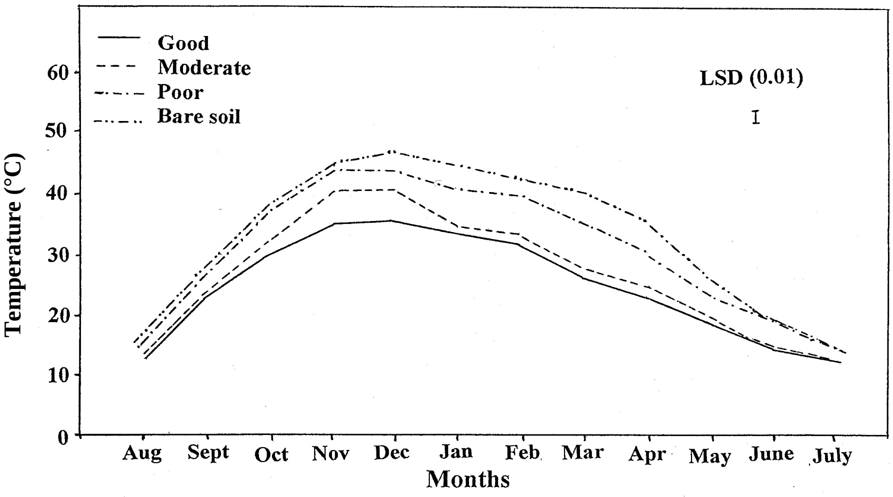


Figure 6
Monthly average soil temperature (°C) taken at ± 14:00 at 50 mm depth for different veld condition classes (good, moderate and poor) and bare soil.

TABLE 3
MAXIMUM - MINIMUM RANGES OF SEASONAL SOIL TEMPERATURES IN A SEMI-ARID CLIMATE, MEASURED AT APPROXIMATELY 14:00

Depth	Soil temperature (°C)				
	Veld condition			Bare soil	Cultivated
	Good	Moderate	Poor		
50	36.0-13.0	41.5-14.0	44.5-15.5	47.0-16.0	38.5-14.0
100	35.0-12.0	38.5-11.5	40.5-12.5	46.0-14.5	45.5-12.0
200	24.0-14.0	25.5-14.0	30.0-14.5	34.0-15.0	28.0-14.0

the soil of 65°C and 49°C respectively for bare uncultivated soil and grassland in good condition, occurred during December.

Conclusion

Rainfall is the limiting environmental factor determining or influencing sustainable plant production throughout the growing season in semi-arid areas. Therefore, improving rainfall efficiency must be thoroughly planned. Though grasses in these areas prepare themselves for drought survival by accumulating carbohydrates in the stubble (Oosthuizen and Snyman, 1999), water utilisation by grassland in good condition is the most stable across the season. This study shows that it is important to keep grassland in optimal condition to efficiently manage and utilise limited soil-water for sustainable plant and therefore animal production. It is clear that grassland in good condition does not only deliver a higher production than degraded veld, but also has significantly higher total crude protein content and water-use efficiency than grassland in poor condition.

It is clear that veld degradation caused an enormous decrease in plant available water in the soil profile during the season, specifically because of high losses due to runoff and Es. This limited available water, together with variable rainfall, contribute to increased drought risks in the semi-arid areas. Fodder flow planning and risk management are therefore much more complicated due to lower production of grassland in poor condition. Regardless of the quantity of rainfall on degraded veld, it reacted inefficiently in terms of production, and therefore almost no reserve fodder source could be accumulated for the drier years. Periodic droughts also have an enormously detrimental effect on the crude protein available to animals in the plant material. The farmer should therefore provide for these critical periods in the management programme. The risk increases greatly as compositional state deteriorates. The efficiency and risk with which rainfall is converted into plant production by fodder plants and eventually gross farming income, without deterioration of natural resources, forms the basis of sustainability of the grassland ecosystem.

The notably high soil temperatures accompanying veld degradation impede the establishment of new plants and therefore the improvement of species composition. In some circumstances where grassland is in very poor condition, mechanical measures leading to improved infiltration and microclimate, will be the only way of upgrading the condition.

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