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Analysis of Climatic Variables and Management Systems in Relation to Spatial Variation in Rangeland Productivity in the North West Province, South Africa

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Abstract

Rangelands occupy about 40-50% of the land area on Earth and are a critical resource for sustainable livelihoods in communities that depend on them. The productivity of these ecosystems depends on several factors such as water and nutrient availability, rangeland management strategies and complex adaptation processes. In South Africa, rangelands have been severely affected by anthropogenic activities such as imbalanced utilization and neglect of proper management processes and physical factors particularly rainfall and temperature. A randomized block sampling technique based on the rangeland management regimes and three rainfall zones characteristic of the North West province was employed to harvest biomass. The collected material was used to quantify above ground biomass (AGB). Results showed that rainfall (R^2=0.44) and temperature (R^2=0.43) distribution had significant impact on AGB productivity. Significant differences were also detected among rangeland management regimes [F(2,177)=85.20; P<0.001] in terms of AGB productivity. High rainfall areas produced higher quantity AGB, while low productivity is associated with low rainfall areas. Private ranches produced the highest AGB quantity and the communal areas produced the lowest. Based on these findings we can conclude that environmental factors such as temperature and rainfall and rangeland management activities are the most important factors that determine rangeland productivity in the North West province, South Africa. The study recommends proper management systems to maximise rangelands productivity.

Keywords: Above ground biomass; Communal lands; Private ranches; Protected areas; Rangeland regimes; Rangelands

Introduction

Rangeland productivity is characterised by several factors such as water and nutrient availability [1-7], rangeland management strategies [8] and complex adaptation processes. For example, low and variable annual rainfall and the high evapotranspiration rate together coupled with nutrient poor soil and poor rangeland management strategies can cause strong limitations in the overall production of rangelands. The balance between rainfall and potential evapotranspiration rate determines a plants biological situation [3,9-15]. Precipitation-evapotranspiration levels interact and influence the rates of the carbon and nitrogen cycles. Evaporation rates are dependent on temperature: as average temperature decreases, evaporation rate decreases; as temperature increases, evaporation rate increases [16-19]. Water is the primary limiting resource on rangelands, and vegetation production depends heavily on water availability and suitable growing temperatures [20-22]. The combined effects of temperature and precipitation influence the quantity and quality of plant growth and can limit livestock production if not considered during the preparation of long term rangeland management plans [23-29]. Thus, the productivity of rangelands is a factor of climatic elements which determine the quantity of above ground biomasses in grasslands and rangeland management strategies [30-35].

The semi-arid and arid regions of South Africa have greater evapotranspiration with higher demand of precipitation; and they are characterised by high proportion of bare ground. This situation intensifies the occurrence of some forbs and weedy species because of their ability to exploit the open spaces [35-40]. Rangelands have been severely affected by anthropogenic disturbances, imbalanced utilisation [41-49], and neglect of proper management and restoration [24]. These ecosystems are exposed to degraded soil fertility, acute shortage of water and unstable micro environmental conditions, which would strongly constrain their productivity. Moreover, in South Africa, land use is generally based on ecological situation and historical backgrounds [42]. Communal areas which are engaged in subsistence agricultural activity are characterised by high human population, soil erosion, excessive wood harvesting and increase in unpalatable plant species [19,46]. Commercial and protected areas are also believed to have similar problems but with lower magnitude [42] as quoted from [10].

Finding a way of restoration and sustainable use of these ecosystems is a fundamental subject in order to increase productivity, improve environmental conditions and achieve sustainable livelihoods to the communities who directly depend on these natural resources. Several studies have been conducted to assess the spatial patterns of above ground biomass and its relationship with precipitation and rangeland management strategies [25,42]. Plant biomass quantification, a crucial biophysical parameter of vegetation, is an essential procedure for rangeland management. Vegetation biomass estimation not only is necessary for studying productivity, carbon sequestration, and

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nutrition allocation in terrestrial ecosystems but also crucial to the natural resource management since the quantity of vegetation biomass directly impacts human usage of surface vegetation and affects other biophysical parameters [30]. However, there is limited information on the level of rangeland productivity in different rainfall zones of the North-West province of South Africa. This region is characterised by spatial variation in precipitation, temperature and the impact of different rangeland management systems. The purpose of this study is to investigate conditions of rangelands in this province and assess the magnitude of variations in terms of forage productivity in the study sites due to environmental factors such as precipitation and temperature; and internal spatial disparities due to rangeland management strategies.

Materials and Methods

Study area

The North West Province of South Africa is located between 22°39'21" E and 25°17'28" E and 24°43'36"S and 28°00'00"S (Figure 1). It includes four districts namely: Ngaka Modiri Molema, Bojanala, Dr. Kenneth Kaunda, and Dr. Ruth Segomotsi Mompati. Most of the Province (71%) falls within the Savanah Biome, while the remaining part falls within the Grassland Biome [32]. According to Hudson [21] and Schultze [45], there are four types of ecological zones in the Province, namely: the Highveld in the South-east, the Bushveld in the north-east, and the Middleveld as a narrow zone between the Highveld and the Bushveld, and the Kalahari Desert in the west. The province has the most uniform terrain of all the provinces, with an altitude ranging between 920 and 1782 metres above sea level [32]. The data which were used in this study included harvesting of aboveground biomass from different study sites, climatic data and rangeland management systems.

Field data

A field survey was conducted during late February to early April 2014 when the vegetation reaches its maximum growth level in the study region. The sample sites were considerably selected in terms of cost and accessibility and these study sites were sampled along a pre-defined rangeland moisture gradient. To overcome the problems of subjective sampling, such as lack of repeatability and the tendency to only sample areas representative of "good" rangelands, a randomized block sampling technique was employed (Figure 2).

The data were collected from different spatial locations by dividing the North West Province into three distinctive zones. The major criteria for categorizing the study sites into different zones were amount of precipitation. The climate of the province is characterised by well-defined seasons with hot summers and cool sunny winters. According to FAO's annual rainfall distribution and climatic classification in South Africa, the North West Province can be classified into three major rainfall zones based on the average rainfall received, namely: arid (low rainfall zones (200-400 mm)), semi-arid (medium rainfall zones, (401-600 mm)), and sub-humid (high rainfall zone, (601-800 mm)) (FAO, 2009) (Figure 1).

Rainfall varies from the more mountainous and wetter eastern region to the drier, semi-desert plains of the Kalahari in the west. The rainy season usually occurs from October to March which is summer season with more sunshine days and warm temperatures. In addition, there are three major types of rangeland regimes in the province, namely: protected areas, communal lands and private ranches. From each rainfall zones three rangeland regimes were selected randomly in close proximity to each other. Thereafter, the sites were subdivided into low and high grazing intensity units using ocular cover estimate technique [9] based on the quantity of forage available on the fields. Thus, rainfall, rangeland regimes and grazing intensity were used to define sampling classes based on the assumption that these are major factors affecting the quality and conditions of the rangelands.

A total of thirty-six field plots (each plot measuring 100 m by 100 m) were sampled from the entire study area. Five 2 m×2 m sub-plots were sampled within each plot, one at the centre of the plot and four at the four corners of each sub-plot using a quadrat [38] for harvesting AGB. Within each plot and sub-plot, latitudinal and longitudinal coordinates (m) using a Garmin GPS at ± 3 m accuracy level. Thereafter, all the grass in the sub-plots in which the boundary was set using a quadrat covering 4 m^2 were cut at the ground level and immediately weighed to obtain a wet weight (kg) of the grass.

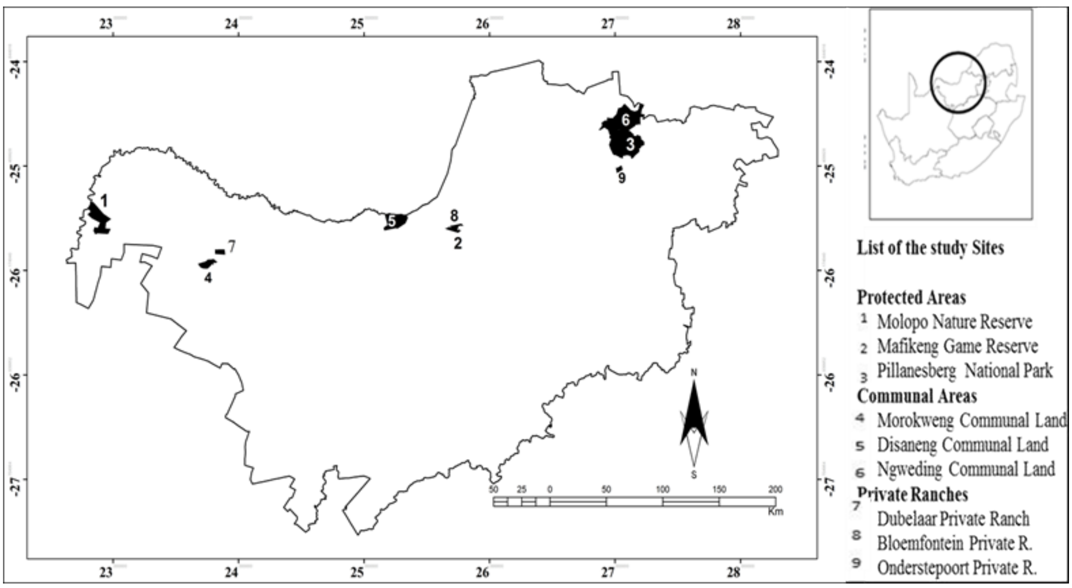
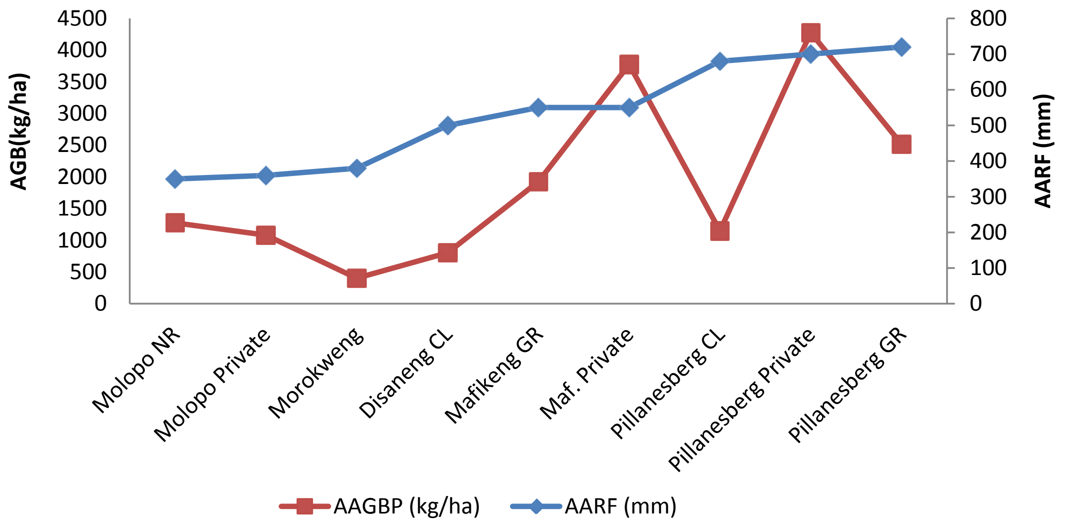


Figure 1: Map of the North West Province and the locations of the study sites.



(Note: AAGBP: Aggregate aboveground biomass, AARF: Annual average rainfall, CL: Communal land, PR: Private Ranch, GR: Game reserve)

Figure 2: Above ground biomass production in relation to distribution of rainfall.

Climatic data

Rainfall data and temperature records from 1993-2014 of the study sites were collected from the South African weather services.

Data analysis

The collected biomass material from the different sites was transferred to a laboratory where the samples were dried in the oven at 75°C for 72 hrs. and weighed again to measure the water content and total dry biomass. Mean growing season rainfall and temperature between the years 1993 and 2014 was computed from the climatic data that was collected from the South African Weather Service. As rainfall and temperature are the principal climatic elements playing major roles in dictating vegetation health and distribution in tropical and subtropical regions, analyzing the amount and distribution of rainfall and temperature over time is extremely important to assess the extent to which rangelands could recover through the natural process.

Relationships between AGB and rainfall, temperature and management strategies were assessed using regression analysis based on eqn. (1).

$$Y=\beta_{\circ}+\beta x+\epsilon \qquad Y=\beta_{\circ}+\beta x+\epsilon \tag{1}$$

Where:

Y=AGB

x=Precipitation and growing season's temperature

β and $\beta_{\circ}$=the model regression coefficients

∈=a random disturbance or error.

Differences in rangeland productivity were also assessed among the three rangeland management systems using analysis of variance (ANOVA). The relationship between precipitation (x) and growing season average temperature (y) was also assessed using Pearson's correlation coefficient eqn. (2). The result was used to determine the relationship of these variables and the resultant impact over rangeland productivity across the study sites.

$$r=\frac{\frac{1}{n}\sum xy-\bar{x}\bar{y}}{S_x S_y} \tag{2}$$

Where

$$S_x=\sqrt{\frac{1}{n}\sum x^2-\bar{x}^2};\quad S_y=\sqrt{\frac{1}{n}\sum y^2-\bar{y}^2} \tag{3}$$

Results and Discussion

This section describes results obtained from analysis of the impacts of rainfall distribution and temperature conditions on rangelands of the North-West province. The regression analysis between different variables yielded acceptable results. There was a positive relationship between rainfall distribution and aboveground biomass production in all study sites. A negative relationship was detected between rainfall distribution and temperature. High rainfall areas are associated with low temperature while low rainfall areas generally experience higher temperature.

Effects of rainfall and temperature on AGB productivity

The average AGB from the low rainfall zone was the lowest (907 kg/ha) followed by the medium rainfall zone (2148 kg/ha) while the high rainfall zone produced the highest average AGB (2646 kg/ha) with the exception of the Ngweding communal area (Figure 2). As the rainfall decreased from east to west (i.e., from high rainfall zone to low rainfall zone) the AGB production also decreased. The impact of the spatial distribution of rainfall and temperature on the AGB production was significant (R^2=0.44) (Figure 2). The rainfall distribution and growing season temperature were negatively correlated (R=-0.94625) (Figure 3). The impact of temperature on the AGB production was significant (R^2=0.4347) with higher temperature being associated with low AGB production (Figure 4).

Rainfall had a significant effect on the above ground biomass production with an R^2 value of 0.44 (Figure 3). Lower precipitation inhibited aboveground biomass, whereas higher precipitation stimulated aboveground biomass production (Table 1). On average,

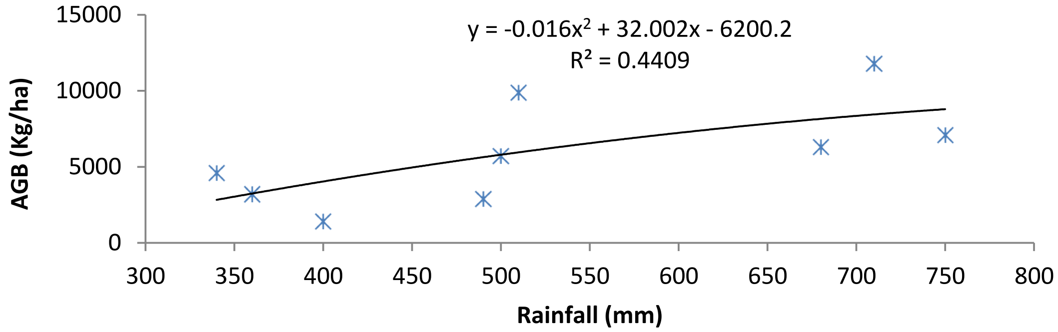


Figure 3: Relationship between rainfall and temperature in the study areas.

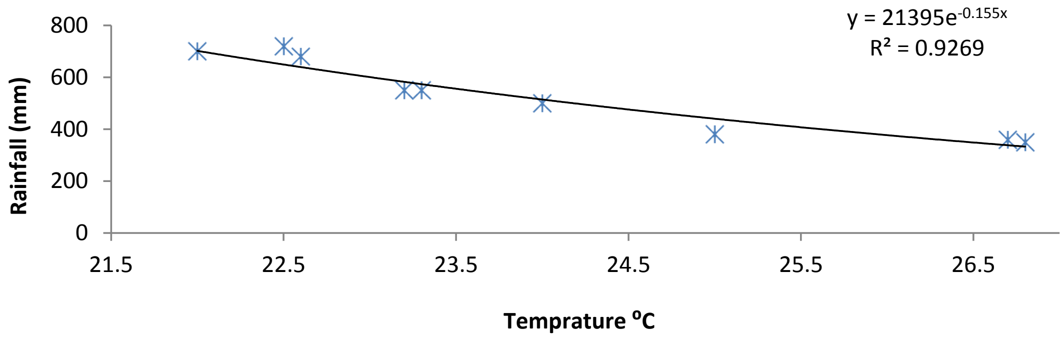


Figure 4: Relationship between temperature and above ground biomass.

Study Sites	HGI1 (kg/ha)	HGI2 (kg/ha)	LGI1 (kg/ha)	LGI2 (kg/ha)	Average biomass (kg/ha)	AARF (mm)	AAGBP (kg/ha)	T (°C)
Molopo NR	680	700	1810	1850	1260	350	1275	26.8
Dubbelaar PR	652	750	1390	1415	1052	360	1082.5	26.7
Morokweng	310	315	515	490	408	380	402.5	25
Disaneng CL	689	658	880	950	794	500	804	24
Mafikeng GR	1335	1250	2450	2600	1909	550	1925	23.3
Lenric PR	3158	3050	4260	4500	3742	550	3775	23.2
Ngweding	870	800	1370	1500	1135	680	1150	22.6
Onderstepoort PR	3280	3350	4260	5200	4023	700	4275	22
Pillanesberg NP	1390	1430	3752	3600	2543	720	2515	22.5

Abbreviations: NR: Nature Reserve; PR: Private Ranch; CL: Communal Land; GR: Game Reserve; NP: National Park.

Table 1: Aboveground biomass across the study sites and their corresponding average annual rainfall and temperature.

higher rainfall and medium rainfall zones produced 188% and 135% more AGB than the low rainfall zone, respectively. There is close similarity in terms of AGB production between the high rainfall zone and medium rainfall zone with the high rainfall zone producing 22% more average AGB. AGB decreased significantly from the high rainfall zone to low rainfall zone. The mean AGB was 2800 kg/ha in the high rainfall zone, 2158 kg/ha in the medium rainfall zone, and 920 kg/ha in the low rainfall area.

Besides, water availability and rainfall conditions were identified as crucial factors in controlling the spatial distribution of rangeland vegetation and aboveground biomass productivity in the regions as observed from the strong relationship between aboveground biomass and precipitation. This finding is in agreement with other authors [5,14,44] who indicated that gross ecosystem productivity has a higher sensitivity to higher precipitation that favors carbon sequestration. Conversely, lower precipitation can reduce nutrient availability because lack of water limits soil microbial processes [43]. Lower precipitation not only suppresses plant biomass and physiological processes, it can also cause mortality of plants [36]. Semi-arid and arid regions are characterised by low levels of soil water availability and extended periods of water shortages. While small events of rainfall can briefly improve these problems and recover plant-water relations [41], the high evaporation and evapotranspiration rate rapidly removes this water from the soil [26]. Moreover, the precipitation patterns change frequently with a shift to larger, less frequent events [14]. This scenario can bring larger quantities of water to the ecosystem in a short period of time and can increase the amount of water availability in the soil for plants. However, these ecosystems have low vegetation coverage unlike the high rainfall zones and surface runoff in these region occurs more frequently and strongly [2,26]. This phenomenon's accelerate nutrient loss and eventually reduce plant response to the sporadic water additions [27].

There was a negative relationship between temperature and rainfall distribution (r=-0.9269). As the temperature decreased the amount of rainfall increased (Figure 4). Though there is no a clear indication of one variable influencing the other, the combined effects of these factors clearly influenced vegetation distribution and AGB production. As the temperature increased, rainfall decreased and AGB decreased; on contrary, as the temperature decreased, rainfall increased and AGB productivity of rangelands also increased.

Temperatures regulate rates of physical processes and influence the growth and development of plants [25,31]. However, plants response to temperature is conditioned by other environmental factors such as soil moisture and human activities [16,28]. Brown et al. [4] stated that soil moisture is the most crucial factor that limits the growth and survival of rangeland plants. When rate of transpiration exceeds rate of absorption of water, water deficit develops in plant tissues causing a slowing down of root and leaf growth. This is in line with the findings of this study that in the low rainfall zone, temperatures were higher, soil moisture was lower, and the quantity of AGB was low. Conversely, in the medium and high rainfall zones, temperatures were relatively lower, precipitation was higher, and there was relatively higher quantity of AGB.

A moderate relationship was detected between temperature and AGB (R^2=0.5325). AGB increased with a slight decrease of temperature from the high rainfall zone to low rainfall zone. In this study, the above ground biomass was negatively correlated to the average temperature proving that higher temperature has a negative impact on the AGB in the study area mainly due to higher evaporation and evapotranspiration rate causing moisture stress and limiting vegetation growth. The results confirm the findings reported in previous studies, which highlighted the relationships between high temperature and lower rainfall in arid and semi-arid regions [50,51].

According to Knapp et al. [26], warm temperatures and low precipitation in South Africa result in a large deficit of water balance in the overall ecosystem during the dormant season resulting into extremely low levels of soil moisture. In the lowland South African savannahs and grasslands, the limitation in soil moisture defines the growing seasons and the conditions of the AGB [17]. Because in these regions, soil moisture is low early in the growing season, these grasslands are very sensitive to inter-annual variability of water inputs at this time of the year. In addition, several studies have shown that decomposition rates increase with the increase of temperature, provided that there is enough amount of water [7,37] ensuring the availability of important nutrients in the soil. However, lack of sufficient amount of rainfall in the low land savannahs of South Africa hinders faster decomposition of dead biomasses, limiting the amount of available nitrogen and carbon in the soil [34]. It is due to this reason that the AGB in cooler rangeland ecosystems have stronger positive response to warm temperature compared to warmer dry and semi dry ecosystems [39].

Relationship between rangeland management strategies and AGB productivity

AGB was harvested from three rainfall zones associated with three distinct types of rangeland management regimes, namely: communal lands, private ranches and protected areas. Results revealed that there was a significant difference in AGB production among these rangeland regimes [$F(2,177)=85.20;P<0.001$] (Table 2). Biomass production from the communal lands was the lowest compared to the protected areas and the private ranches across the rainfall zones with the private ranches yielding the highest AGB. The average AGB production from the three rangeland management strategies in ascending order: communal rangeland (990 kg/ha), protected areas (3530 kg/ha) and private ranches (5972 kg/ha).

AGB production from the private ranches and protected areas were higher as compared to the communal areas in all rainfall zones. This is attributed to higher maintenance and management processes such as keeping recommended stocking rates [33]. Hence, AGB productivity in the private and protected areas is healthy and high. Generally, rangelands under private and protected areas were characterised by lower indicators of erosion, higher AGB productivity and composed of high quality palatable grasses [34]. The hypothesis of this study was consistent with other studies [6,17,42] indicating that communal rangelands were less productive as compared to the surrounding private ranches and protected areas due to higher number of population where everyone strives to maximize an output at the expense of the natural environment without taking any cautionary measure to protect these rangelands.

Variations of AGB productivity between rainfall zones

Low rainfall zones

AGB production level in the low rainfall zone is presented (Table 3). In this region, AGB average production was 408 kg/ha from the communal lands, 1260 kg/ha from protected areas and 1052 kg/ha from private ranches. The overall average AGB was 907 kg/ha from this zone. The standard deviation (SD) of AGB in the region was 1882 kg which is very high in terms of the general AGB production capacity of the region. There was a significant difference in the level of AGB production among the three study sites [$F(2,57)=71.39;P<0.001$] (Table 3). However, no significant difference was detected between the private and protected areas in terms of AGB production.

Medium rainfall zones

AGB production level in the medium rainfall zone is presented in Table 3. In the medium rainfall zone, AGB average production were 794 kg/ha from the communal lands, 1909 kg/ha from protected areas and 3742 kg/ha from private ranches. The overall average AGB was 2115 kg/ha. The SD of the AGB production of the region was 1381 kg. There

Source of Variation	SS	Df	MS	F	P-value	F crit
Between groups	129835.76	2.00	64917.88	85.20	0.00	3.05
Within groups	137158.38	176.00	761.99			
Total	266994.14	178.00				

Table 2: Analysis of variance for the rangeland management systems and AGB productivity.

Source of variation	SS	Df	MS	F	P-value	F crit
Between groups	19530.59	2.00	9765.30	71.39	0.00	3.16
Within groups	7797.40	57.00	136.80			
Total	27327.99	59.00				

Table 3: Analysis of variance for the low rainfall zones and AGB productivity.

Source of variation	SS	Df	MS	F	P-value	F crit
Between groups	65238.00	2.00	32619.00	40.70	0.00	3.16
Within groups	45680.61	53.00	801.41			
Total	110918.61	55.00				

Table 4: Analysis of variance for the medium rainfall zones and AGB productivity.

Source of variation	SS	Df	MS	F	P-value	F crit
Between groups	51114.29	2.00	25557.14	34.15	0.00	3.16
Within groups	42657.12	57.00	748.37			
Total	93771.41	59.00				

Table 5: Analysis of variance for the high rainfall zones and AGB productivity.

was a significant difference in the level of AGB production between the three rangeland management regimes [$F(2,57)=40.7; P<0.001$] (Table 4).

High rainfall zones

AGB production level in the high rainfall zone is presented in Table 3. In the high rainfall zones, the average AGB production was 1135 kg/ha in the communal rangelands, protected areas 2543 kg/ha and private ranch 4023 kg/ha. The overall average AGB was 2647 kg/ha. The SD of the AGB in the region was 1946 kg. There was a significant difference in terms of AGB production among the rangeland regimes [($F(0.05,2,57)=34.15; P<0.001$] (Table 5).

Results from this study showed that the AGB production measured from the three land tenure systems differed statistically [$F(0.05,2,177)=85.20; P<0.001$] (Table 2). AGB production from communal lands were overall ranging from 402 kg/ha in the low rainfall zone to 1150 kg/ha in the high rainfall zone. The private ranch AGB production was the highest ranging from 1080 kg/ha in the low rainfall zone to 9990 kg/ha in the high rainfall zone. This study hypothesized that the variation of the rangelands in terms of AGB production in different rainfall zones of the study area were due to differences in managerial activities and spatial variations. Low AGB was recorded from all study sites of the communal areas where most of these rangelands were described [33] as areas of high proportion of bare ground, low quantity of palatable grasses and soil erosion. These factors are considered as indicators of rangeland degradation that can result into low AGB production [19]. Generally, communal areas are characterised by high human population and livestock density, over utilization of rangeland resources [46] and bush encroachment particularly in the low rainfall regions [33]. These phenomena subject the communal rangelands to overgrazing and over cultivation [15,46]. Heavy grazing pressure can cause compositional changes and local extinction of some grass species following drought [35]. Considering the erratic nature of rainfall in South Africa, particularly in the North West Province, over utilization of these rangelands can lead to an ecological decline having a profound effect on the overall productivity of these resources.

Conclusion

In this study, average temperature and rainfall, AGB and data on rangeland management systems were collected. The results suggested that AGB productivity was affected by spatial distribution of rainfall and temperature. The low rainfall zone produced the lowest AGB, while the high rainfall zones had the highest AGB. As such, low rainfall coupled with high temperature negatively affected the productivity of the rangelands. Rangeland management strategy was also identified as one of the factors that determine the productivity of these rangelands. Generally, communal rangelands were the lowest productive units due to the high number of population and over exploitation of rangeland resources, whereas the private ranches were highly productive due to proper maintenance and management. Despite the short time period of this study, the results are in agreement with the available literature that low rainfall conditions limit AGB production of rangelands. In the case of rangeland management regimes in South Africa, communal areas are less productive than the surrounding private ranches and protected areas although, in some cases, comparison with the previous studies were very difficult because of different locations of the study sites, criteria and methodologies applied. However, it was clear that the less quantity in the AGB production in communal areas as compared to the private ranches and protected areas was caused by differences in managerial systems and combined effects of human activities and climate variations. However, the magnitude of the impacts of these phenomena is not clear hence the need for further studies to ascertain the amount is important.

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