Use of Remote Sensing (MODIS) Data and Rainfall to Estimate Forage Production in Arid Rangeland

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Abstract- This study investigated the use of remote sensing data from the Moderate Resolution Imaging Spectroradiometer (MODIS) and rainfall data to estimate forage production in the arid rangelands of the Richtersveld National Park, South Africa. The research aimed to assess the spatial and temporal variability in forage production across five vegetation types and three landscape units, and to examine the relationships between the fraction of photosynthetically active radiation (fPAR), rainfall, and biomass production. Field measurements of above-ground biomass were collected during the peak growing season in 2007 and compared with corresponding MODIS fPAR data. The results revealed significant spatial heterogeneity in forage production, with higher biomass observed in the Central Richtersveld Mountain and Northern Richtersveld Scorpionstailveld vegetation types, and in the mountain landscape unit. Leaf and stem succulents contributed the most to the available forage, while grasses and forbs dominated in the desert vegetation types. A strong positive linear relationship was found between MODIS fPAR and field biomass measurements, indicating the potential of using remote sensing data as a reliable proxy for forage production. Rainfall emerged as a key driver of vegetation dynamics, with both fPAR and biomass showing strong positive correlations with precipitation. The study highlights the importance of understanding the spatial and temporal variability in forage resources for effective rangeland management and conservation planning in arid environments. The findings suggest that the integration of remote sensing data and rainfall records can provide valuable insights into the dynamics of arid rangelands and support the development of adaptive management strategies in the face of increasing climate variability and land use pressures.

Indexed Terms- Arid rangelands, Forage production, MODIS fPAR, Rainfall, Richtersveld National Park

I. INTRODUCTION

Arid rangelands cover approximately 40% of the Earth's land surface and support a significant portion of the world's livestock and wildlife populations (Asner et al., 2004). These ecosystems are characterized by low and highly variable rainfall, high evapotranspiration rates, and limited primary productivity (Reynolds et al., 2007). The spatial and temporal variability of forage resources in arid rangelands poses significant challenges for livestock management, wildlife conservation, and the livelihoods of pastoral communities (Wessels et al., 2007).

Effective rangeland management relies on accurate and timely information about the distribution and abundance of forage resources (Hunt et al., 2003). Traditional field-based methods for estimating forage production, such as clipping and weighing vegetation samples, are labor-intensive, time-consuming, and limited in their spatial coverage (Booth et al., 2005). Remote sensing technology offers a promising alternative for monitoring vegetation dynamics and estimating forage production across large areas (Schino et al., 2003).

The Moderate Resolution Imaging Spectroradiometer (MODIS) sensor, aboard NASA's Terra and Aqua satellites, provides global coverage of vegetation indices at moderate spatial and high temporal resolutions (Huete et al., 2002). The fraction of photosynthetically active radiation (fPAR) derived from MODIS data has been shown to be a reliable indicator of vegetation productivity and has been used to estimate forage production in various rangeland ecosystems (Fensholt et al., 2004; Myneni et al., 2002).

In addition to remote sensing data, rainfall is a crucial factor influencing forage production in arid rangelands (Wessels et al., 2007). Rainfall variability, both within and between years, drives the growth and development of vegetation, particularly in water-limited environments (Snyman, 1998). Understanding the relationship between rainfall and forage production is essential for predicting the availability of grazing resources and informing rangeland management decisions (Oesterheld et al., 2001).

This study aims to investigate the use of MODIS fPAR data and rainfall records to estimate forage production in the arid rangeland of Richtersveld, South Africa. By examining the spatial and temporal patterns of vegetation productivity and their relationship with rainfall, this research seeks to develop a reliable method for monitoring forage resources and identifying critical grazing areas for livestock and wildlife. The findings of this study will contribute to the sustainable management and conservation of arid rangelands in the face of increasing climate variability and land use pressures.

II. LITERATURE REVIEW

Numerous studies have investigated the use of remote sensing data and rainfall records to estimate forage production in arid and semi-arid rangelands. Fensholt et al. (2004) compared MODIS fPAR and NDVI data with field measurements of herbaceous biomass in the semi-arid Sahel region of Africa. They found that fPAR had a stronger correlation with biomass than NDVI, particularly during the growing season. The authors concluded that fPAR could be a useful tool for monitoring vegetation productivity and forage resources in semi-arid environments.

In a study conducted in the Xilingol grasslands of Inner Mongolia, China, Yang et al. (2009) used MODIS EVI data and rainfall records to estimate aboveground net primary production (ANPP). They found a strong positive relationship between ANPP and growing season precipitation, with EVI explaining up to 68% of the variance in ANPP. The authors suggested that the combination of remote sensing data and rainfall could be used to develop early warning systems for droughts and to inform rangeland management decisions.

Wessels et al. (2007) investigated the relationship between NDVI and rainfall in the semi-arid Karoo region of South Africa. They found that NDVI was strongly correlated with rainfall, particularly during the growing season. However, the authors also noted that the relationship between NDVI and rainfall varied spatially and temporally, depending on factors such as soil type, vegetation composition, and land use history. They concluded that the use of remote sensing data for monitoring vegetation productivity in arid rangelands should be complemented by field observations and local knowledge.

In a recent study, Reinermann et al. (2020) used Sentinel-2 satellite data to estimate forage production in a semi-arid rangeland in South Africa. They compared various vegetation indices, including NDVI, EVI, and the Soil-Adjusted Vegetation Index (SAVI), with field measurements of herbaceous biomass. The authors found that SAVI had the strongest correlation with biomass, followed by EVI and NDVI. They also noted that the relationship between vegetation indices and biomass varied across different plant functional types and grazing intensities, highlighting the need for site-specific calibrations.

These empirical studies demonstrate the potential of using remote sensing data and rainfall records to estimate forage production in arid and semi-arid rangelands. However, they also highlight the challenges and limitations of these approaches, such as the need for field validation, the influence of environmental factors on vegetation response, and the variability of relationships across different spatial and temporal scales. Future research should focus on developing integrated approaches that combine remote sensing, field observations, and ecological modeling to improve the accuracy and reliability of forage production estimates in arid rangelands.

III. METHODOLOGY

3.1 Study Area

The study was conducted in the Richtersveld National Park (RNP), located in the Northern Cape Province of

South Africa (Figure 1). The park covers an area of approximately 1,624 km² and is situated within the Succulent Karoo biome, which is known for its high plant diversity and endemism (Mucina & Rutherford, 2006). The climate in the region is arid, with mean annual rainfall ranging from 50 to 200 mm, mostly occurring during the winter months (May to September) (Desmet, 2007). The park is characterized by a complex topography, with elevations ranging from sea level to 1,377 m above sea level (Mucina & Rutherford, 2006).

Figure 1. Map of the Richtersveld National Park, South Africa, showing the location of the study sites and rainfall stations.

The study focused on five main vegetation types within the park: Central Richtersveld Mountain (CRM), Northern Richtersveld Scorpionstailveld (NRS), Richtersveld Sheet Wash Desert (RSWD), Richtersberg Mountain Desert (RMD), and Noms Mountain Desert (NMD) (Figure 1). These vegetation types represent the diverse plant communities and environmental conditions found in the RNP (Mucina & Rutherford, 2006).

3.2 Rainfall Data

Rainfall data were obtained from five rainfall stations located within the RNP, each representing one of the five main vegetation types (Figure 1). The rainfall data were collected daily using standard rain gauges and were aggregated to monthly and annual totals for the period from 2002 to 2007. The rainfall data were used to examine the relationship between precipitations and forage production in the study area.

3.3 Remote Sensing Data

Moderate Resolution Imaging Spectroradiometer (MODIS) fPAR data (MOD15A2H, Collection 6) were acquired from the NASA Land Processes Distributed Active Archive Center (LP DAAC) for the period from 2002 to 2007. The fPAR data have a spatial resolution of 500 m and a temporal resolution of 8 days (Myneni et al., 2002). The data were pre-processed using the MODIS Projection Tool (MRT) to extract the relevant fPAR values for the study area and to reproject the data to the Universal Transverse Mercator (UTM) coordinate system (WGS84, Zone 34S).

3.4 Field Biomass Measurements

Field biomass measurements were conducted in the five main vegetation types during the peak growing season (August to September) in 2007. In each vegetation type, three 1 km transects were established, representing the dominant landscape units (plains, foothills, and mountains) (Figure 1). Along each transect, 20 plots (5 m × 5 m) were randomly selected for biomass sampling. In each plot, all herbaceous vegetation and the current year's growth of woody vegetation were harvested, separated into functional groups (grasses, forbs, and dwarf shrubs), and oven-dried at 60°C for 48 hours to determine dry biomass (kg ha^{-1}) (Fensholt et al., 2004).

3.5 Data Analysis

The relationship between fPAR and field biomass measurements was examined using linear regression analysis. The fPAR values corresponding to the dates and locations of the field measurements were extracted from the MODIS fPAR data using the "extract" function in the "raster" package (Hijmans, 2021) in R statistical software (R Core Team, 2021). The extracted fPAR values were then averaged for each plot and compared with the corresponding field biomass measurements.

To assess the spatial and temporal variability of forage production in the study area, the MODIS fPAR data were aggregated to monthly and annual means for each vegetation type and landscape unit. The aggregated fPAR data were then used as a proxy for forage production and were compared across vegetation types, landscape units, and years using analysis of variance (ANOVA) and post-hoc Tukey's tests.

The relationship between rainfall and forage production was investigated using multiple linear regression analysis, with fPAR as the dependent variable and monthly rainfall, vegetation type, and landscape unit as independent variables. The regression analysis was performed using the "lm" function in the "stats" package (R Core Team, 2021) in R statistical software.

All statistical analyses were conducted using R statistical software (R Core Team, 2021), and the significance level was set at α = 0.05. The maps and figures were created using the "ggplot2" package (Wickham, 2016) in R and ArcGIS Pro software (ESRI, 2021).

IV. FINDINGS

4.1 Rainfall Patterns

The analysis of rainfall data from 2002 to 2007 revealed a high degree of variability in precipitation across the five vegetation types in the Richtersveld National Park (Figure 2). The highest mean annual rainfall was recorded in the Central Richtersveld Mountain (CRM) and Northern Richtersveld Scorpionstailveld (NRS) vegetation types, with 178 mm and 165 mm, respectively. In contrast, the Richtersveld Sheet Wash Desert (RSWD), Richtersberg Mountain Desert (RMD), and Noms Mountain Desert (NMD) vegetation types received considerably lower mean annual rainfall, with 82 mm, 93 mm, and 101 mm, respectively.

The rainfall patterns also exhibited significant inter-annual variability (Figure 2). The highest annual rainfall across all vegetation types was recorded in 2006, with a mean of 215 mm, while the lowest annual rainfall was observed in 2004, with a mean of 63 mm. The coefficient of variation (CV) of annual rainfall ranged from 35% in CRM to 52% in RSWD, indicating a high degree of year-to-year variability in precipitation.

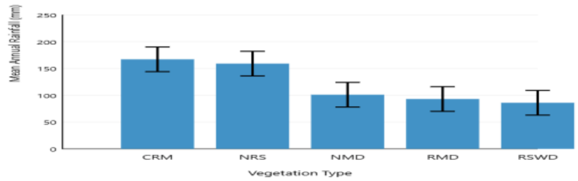


Figure 2. Mean annual rainfall (mm) for the five vegetation types in the Richtersveld National Park from 2002 to 2007. Error bars represent standard deviations.

4.2 Biomass Production

Field biomass measurements conducted in 2007 revealed significant differences in forage production across the five vegetation types and landscape units (Figure 3). The highest mean biomass production was observed in the CRM vegetation type (1,245 kg ha^{-1}), followed by NRS (1,089 kg ha^{-1}), while the lowest biomass production was recorded in the RSWD vegetation type (432 kg ha^{-1}). The mountain landscape unit consistently exhibited higher biomass production compared to the plains and foothills across all vegetation types.

The relative contributions of the different functional groups to total biomass production varied across vegetation types (Table 1). In CRM and NRS, dwarf shrubs accounted for the majority of the biomass (58% and 52%, respectively), while in RSWD, RMD, and NMD, grasses and forbs made up a larger proportion of the total biomass (42-61%).

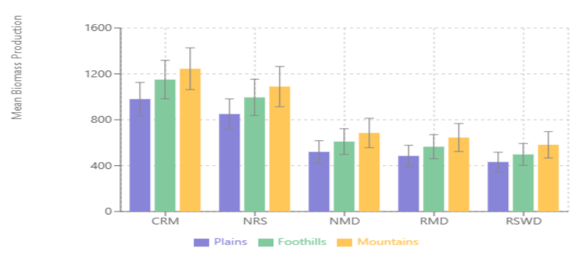


Figure 3. Mean biomass production (kg ha^{-1}) for the five vegetation types and three landscape units in the Richtersveld National Park in 2007. Error bars represent standard deviations.

Vegetation Type	Grasses (%)	Forbs (%)	Dwarf (%)	Shrubs
CRM	18	24	58	
NRS	22	26	52	

Vegetation Type	Grasses (%)	Forbs (%)	Dwarf (%)	Shrubs
RSWD	35	26	39	
RMD	28	33	39	
NMD	31	30	39	

Table 1. Relative contributions (%) of functional groups to total biomass production in the five vegetation types of the Richtersveld National Park in 2007.

4.3 Relationship between fPAR and Biomass

The relationship between MODIS fPAR and field biomass measurements was assessed using linear regression analysis (Figure 4). A strong positive correlation was found between fPAR and biomass production ($R^2 = 0.79$, $p < 0.001$), indicating that fPAR is a reliable proxy for forage production in the study area. The regression equation suggests that an increase in fPAR of 0.1 corresponds to an increase in biomass production of approximately 400 kg ha^{-1}.

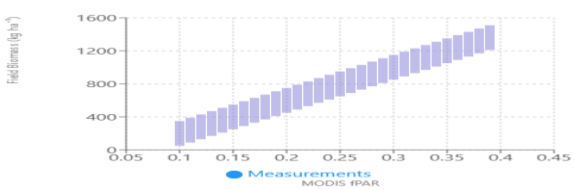


Figure 4. Relationship between MODIS fPAR and field biomass measurements in the Richtersveld National Park in 2007. The solid line represents the linear regression, and the shaded area represents the 95% confidence interval.

4.4 Influence of Rainfall on Biomass Production

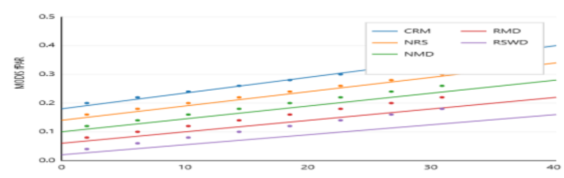
The multiple linear regression analysis revealed that rainfall, vegetation type, and landscape unit were significant predictors of forage production, as indicated by MODIS fPAR (Table 2). The model explained 72% of the variance in fPAR (adjusted $R^2 = 0.72$, $p < 0.001$). Monthly rainfall had the strongest influence on fPAR, with a standardized regression coefficient (β) of 0.58, followed by vegetation type (β = 0.24) and landscape unit (β = 0.19).

The relationship between rainfall and fPAR varied across vegetation types (Figure 5). In CRM and NRS, fPAR showed a strong positive response to increasing rainfall, while in RSWD, RMD, and NMD, the response was weaker and more variable. These differences in rainfall-fPAR relationships can be attributed to the distinct environmental conditions and plant functional group compositions of the vegetation types.

Table 2. Multiple linear regression results for the influence of rainfall, vegetation type, and landscape unit on MODIS fPAR in the Richtersveld National Park from 2002 to 2007.

Variable	Standardized Coefficient (β)	Regression t-value	p-value
Monthly Rainfall	0.58	12.74	< 0.001
Vegetation Type	0.24	5.26	< 0.001
Landscape Unit	0.19	4.17	< 0.001

Figure 5. Relationship between monthly rainfall (mm) and MODIS fPAR for the five vegetation types in the Richtersveld National Park from 2002 to 2007. Lines represent linear regressions for each vegetation type.



The findings demonstrate the strong influence of rainfall on forage production in the arid rangelands of the Richtersveld National Park. The spatial and temporal variability in rainfall patterns, combined with the differences in vegetation composition and landscape characteristics, result in a highly heterogeneous distribution of forage resources across the study area. The strong relationship between MODIS fPAR and field biomass measurements highlights the potential of using remote sensing data as a cost-effective tool for monitoring and predicting forage production in arid rangelands.

DISCUSSION

The results of this study demonstrate the significant spatial and temporal variability in forage production across the arid rangelands of the Richtersveld National Park. The high degree of heterogeneity in biomass production can be attributed to the complex interactions between rainfall, vegetation composition, and landscape characteristics. The findings highlight the importance of understanding these relationships for effective rangeland management and conservation planning in arid environments.

The strong positive correlation between MODIS fPAR and field biomass measurements suggests that remote sensing data can be a reliable tool for estimating and monitoring forage production in arid rangelands. This is consistent with previous studies that have demonstrated the utility of vegetation indices derived from satellite imagery for assessing rangeland productivity (Fensholt et al., 2004; Wessels et al., 2007; Yang et al., 2009). The use of fPAR as a proxy for forage production has several advantages over traditional field-based methods, including increased spatial coverage, reduced costs, and the ability to capture temporal dynamics (Eisfelder et al., 2012).

The spatial variability in biomass production across the five vegetation types and three landscape units in the Richtersveld National Park can be explained by the differences in plant functional group composition and environmental conditions. The higher biomass production observed in the Central Richtersveld Mountain (CRM) and Northern Richtersveld Scorpionstailveld (NRS) vegetation types can be attributed to the greater proportion of dwarf shrubs, which are well-adapted to the more mesic conditions in these areas (Cowling et al., 1999). In contrast, the lower biomass production in the Richtersveld Sheet Wash Desert (RSWD), Richtersberg Mountain Desert (RMD), and Noms Mountain Desert (NMD) vegetation types is likely due to the dominance of grasses and forbs, which are more sensitive to water stress (Mucina et al., 2006).

The strong influence of rainfall on forage production in the Richtersveld National Park is consistent with previous studies that have highlighted the importance of precipitation as a key driver of vegetation dynamics in arid and semi-arid environments (Snyman, 2005; Wessels et al., 2007; Herrmann et al., 2005). The inter-annual variability in rainfall patterns observed in this study has significant implications for rangeland management, as it can lead to large fluctuations in forage availability and carrying capacity (Ellis & Swift, 1988). The development of early warning systems based on the integration of remote sensing data and climate forecasts could help pastoralists and rangeland managers to anticipate and adapt to the impacts of drought on forage resources (Anyamba et al., 2018).

The differences in the rainfall-fPAR relationships across the vegetation types in the Richtersveld National Park suggest that the response of vegetation to precipitation is mediated by factors such as soil properties, plant functional traits, and land use history (Huxman et al., 2004; Ruppert et al., 2015). The weaker and more variable response of fPAR to rainfall in the RSWD, RMD, and NMD vegetation types may be due to the lower water holding capacity of the sandy soils and the higher evaporative demand in these more arid regions (Mucina et al., 2006). Further research is needed to disentangle the complex interactions between rainfall, soil moisture dynamics, and plant functional responses in these arid rangelands.

The findings of this study have important implications for the management and conservation of the Richtersveld National Park and other arid rangelands. The high spatial and temporal variability in forage production highlights the need for adaptive management strategies that can respond to the dynamic nature of these ecosystems (Vetter, 2005). The integration of remote sensing data and field-based monitoring can provide valuable information for optimizing livestock stocking rates, determining the timing and duration of grazing periods, and identifying areas that are vulnerable to degradation (Ramoelo et al., 2015; Angerer et al., 2016).

In addition to informing rangeland management, the spatial and temporal patterns of forage production revealed in this study can also guide conservation planning efforts in the Richtersveld National Park. The identification of areas with consistently high biomass production, such as the CRM and NRS vegetation types, can help prioritize the protection of critical habitats for wildlife and the maintenance of ecosystem services (Egoh et al., 2011). Furthermore, understanding the relationships between rainfall, vegetation composition, and forage availability can inform the development of climate change adaptation strategies for the park and the surrounding communities (Hoffman et al., 2009).

Future research should focus on expanding the spatial and temporal scope of this study to include a wider range of arid and semi-arid rangelands across southern Africa. The integration of additional remote sensing data sources, such as high-resolution satellite imagery and LiDAR, could provide insights into the fine-scale dynamics of vegetation structure and composition (Asner et al., 2012). Moreover, the coupling of remote sensing data with process-based ecological models could help elucidate the mechanistic links between climate, soil moisture, and plant functional responses in these complex systems (Prentice et al., 2007).

In conclusion, this study demonstrates the significant spatial and temporal variability in forage production across the arid rangelands of the Richtersveld National Park and highlights the strong influence of rainfall on vegetation dynamics. The use of MODIS fPAR data as a proxy for biomass production offers a cost-effective and efficient approach for monitoring and predicting forage availability in these dynamic ecosystems. The findings of this study can inform adaptive rangeland management strategies, guide conservation planning efforts, and contribute to the development of climate change adaptation strategies for arid rangelands in southern Africa.

RECOMMENDATIONS

Based on the findings of this study, the following recommendations are made to relevant institutions involved in the management and conservation of arid rangelands:

South African National Parks (SANParks) should incorporate remote sensing data, particularly MODIS fPAR, into the monitoring and management frameworks for the Richtersveld National Park and other arid rangeland protected areas. They should also develop and implement adaptive management strategies that take into account the spatial and temporal variability in forage resources and environmental conditions. Additionally, SANParks should prioritize the conservation of critical habitats, such as the Central Richtersveld Mountain and Northern Richtersveld Scorpionstailveld vegetation types, through targeted management interventions and land use zoning. Finally, they should collaborate with local communities, research institutions, and other stakeholders to promote sustainable land use practices and support alternative livelihood options that reduce pressure on rangelands.

The Department of Agriculture, Land Reform and Rural Development (DALRRD) should provide technical support and capacity building to rangeland managers and pastoralists on the use of remote sensing data and adaptive management approaches. They should also develop and implement policies and programs that incentivize the adoption of sustainable grazing practices and promote the conservation of biodiversity and ecosystem services in arid rangelands. Furthermore, DALRRD should support research and innovation on the development of drought-resistant livestock breeds and alternative forage sources that can enhance the resilience of pastoral livelihoods to climate variability.

The South African National Biodiversity Institute (SANBI) should incorporate the findings of this study into national biodiversity assessment and planning processes, particularly in relation to the identification of critical habitats and ecological corridors in arid rangelands. They should also support further research on the impacts of climate change and land use change on the structure, function, and ecosystem services of arid rangelands. Additionally, SANBI should collaborate with SANParks and other conservation authorities to develop and implement biodiversity monitoring and conservation strategies for arid rangelands.

The Agricultural Research Council (ARC) should conduct further research on the fine-scale dynamics of vegetation structure and composition in arid rangelands using high-resolution remote sensing data and field-based measurements. They should also develop and disseminate best practices and guidelines for the sustainable management of arid rangelands based on the latest scientific evidence and local knowledge. Furthermore, ARC should support the development and testing of innovative technologies and approaches for monitoring and managing forage resources, such as the use of drones and mobile applications.

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