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Original Research

Ecological Foundations of Indigenous Pastoral Innovations for Climate Resilience: Evidence from the Succulent Karoo Rangeland, Richtersveld National Park, South Africa

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Abstract

Dryland pastoral systems across Africa are routinely characterised as ecologically fragile and economically marginal, yet the herding communities that inhabit them have, over centuries, developed detailed, place-calibrated knowledge of how rainfall pulses translate into forage. In Richtersveld National Park (RNP), South Africa's Northern Cape, the Nama people's annual transhumance between Succulent Karoo uplands and the Orange River riparian zone is one such system. Drawing on stratified vegetation surveys, allometric browse measurements, satellite-derived productivity data, and soil nutrient profiling conducted across five vegetation types between 2006 and 2008, this study examines the ecological mechanisms underlying this pastoral system. Annual plant biomass was most strongly predicted by rainfall ($R^2 = 0.69$, 95% CI: 0.56–0.79; $F(1,58) = 36.90$, $p < 0.01$), with grazing pressure and landform accounting for far less variance. Shrub biomass in the Succulent Karoo peaked at 962.8 g/m^2, nearly twelve times the 81.6 g/m^2 recorded in the Desert Biome. Riparian grass under low-discharge conditions reached 600–700 g/m^2 during months when all upland vegetation was dormant. MODIS-derived fPAR values tracked ground-measured biomass closely ($R^2 = 0.89$). The results provide quantitative evidence that year-round forage availability is maintained under the existing management regime; whether this translates into sustained livestock body condition or reproductive performance under future climate conditions requires dedicated herd-monitoring data that were beyond the scope of this study. Taken together, the results provide a quantitative ecological rationale for practices that policy has historically dismissed as traditional rather than adaptive.

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Statement of Sustainability: Quantified evidence that mobility-based herding sustains both forage availability and vegetation condition in an arid protected area addresses SDG 13 (Climate Action) and SDG 15 (Life on Land) simultaneously. Data showing year-round forage availability in RNP under the existing indigenous management regime speaks to SDG 2 (Zero Hunger) at household scale. The demonstration that MODIS-derived productivity data can be calibrated against in-situ forage measurements offers a low-cost monitoring template applicable to other communal rangeland systems across the dryland belt of sub-Saharan Africa.

1. Introduction

Arid and semi-arid rangelands occupy approximately 40% of the Earth's land surface and provide the primary livelihood base for an estimated 500 million people (Kimiti et al., 2018). Rainfall in these environments is spatially patchy and temporally erratic. Projected shifts in Southern African climate reduced winter rainfall, longer dry spells, and increased rainfall intensity will amplify this variability further (MacKellar et al., 2007; Young et al., 2016). Much of the adaptation literature frames this as a problem to be solved through technological intervention. Considerably less attention goes to the knowledge systems that dryland communities have already refined over centuries of co-existence with unpredictable rainfall.

The governance frameworks inherited from the colonial period fixed stocking norms, paddock enclosure, enforced settlement rested on a model in which plant production is regulated primarily by grazing pressure (Konje et al., 2021a). Field evidence from across African drylands has steadily undermined this model. Where rainfall is the dominant control on primary production, restricting herd movement does not protect vegetation it prevents animals from tracking the spatially and temporally unpredictable forage pulse that rainfall generates (Hempson et al., 2015). Reform has been uneven and slow. Pastoralists still face fencing legislation that severs traditional movement corridors and development programmes premised on the notion that settled, input-dependent livestock farming is superior to mobile herding (Samuels et al., 2019).

RNP was gazetted in 1991 as a contractual national park under a joint management agreement between SANParks and the Richtersveld Nama community, making it unusual in that resident pastoralists retain lawful grazing rights (Hendricks et al., 2004). The park supports approximately 6,600 head of small stock across 270 registered stock posts and has been the subject of ecological research extending back two decades, including characterisation of shrub biomass dynamics (Konje et al., 2021a) and forage production in the Orange River riparian zone (Konje et al., 2021b).

This paper is a in-depth case study centred on RNP. Two distinct objectives are pursued sequentially. The first is ecological documentation: characterising spatial and temporal patterns of forage availability using standard rangeland ecology methods (ANOVA, regression, remote sensing). The second is indigenous knowledge (IK) validation: assessing whether the documented ecological patterns are consistent with and explanatory of observed Nama herding practice, following the ethnoecological validation framework of Naah and Guuroh (2017). Depth of ecological documentation at one well-characterised site is considered more analytically useful than thin coverage across multiple systems. Specifically, the paper aims to identify the ecological mechanisms behind four recurring pastoral behaviours, to measure their effect on forage availability across seasons, and to assess the implications for dryland rangeland policy under a changing climate. Additional independent literature from the Richtersveld and Succulent Karoo is incorporated to contextualise the findings beyond the author's prior publications (Baker and Hoffmann, 2006; Hendricks et al., 2005a; Samuels et al., 2013, 2019; Fynn, 2012).

2. Materials and Methods

2.1. Study Area

RNP (28°15′S, 17°10′E) covers 162,445 ha of the Succulent Karoo biome in Northern Cape, South Africa, a globally recognised biodiversity hotspot with 30% of the world's succulent species (Mucina and Rutherford, 2006). Mean annual rainfall ranges from 52 mm in desert sections to 248 mm in mountainous areas, with most precipitation falling in winter (April–August). Five vegetation types are present: Central Richtersveld Mountain (CRM) and Northern Richtersveld Scorpionstailveld (NRS) in the Succulent Karoo Biome, and Noms Mountain Desert (NMD), Richterberg Mountain Desert (RMD), and Richtersveld Sheet Wash Desert (RSWD) in the Desert Biome. The Orange River forms the northern boundary and supports a riparian woodland providing critical dry-season forage.

Twenty-six Nama households hold grazing rights, collectively managing a herd ceiling of 6,600 animals mainly Boer goats from 270 designated stock posts (Hendricks et al., 2004). Each household follows an annual cycle calibrated to rainfall: from roughly October to April the herds use the Orange River corridor; from May through September, once winter rainfall has greened the upland vegetation, herds move onto the plains, foothills, and mountain areas.

2.2. Annual Vegetation and Soil Sampling

Annual vegetation and soil data were collected during two consecutive winter growing seasons (July and September, 2006; July and September, 2007). One sampling site was established per vegetation type, each located adjacent to an occupied stock post with a functioning rain gauge. Each site contained two paired 1,000 m transects (one along sandy flat plains, one across rocky foothills), with sample stations at 100 m, 500 m, and 1,000 m on each transect, providing six independent measurement points per vegetation type per year. Across two years of sampling, this gave a total of 60 observations per response variable (the n = 60 reported in regression analyses). Rainfall year provided temporal replication in the ANOVA, following the same design used by Hendricks et al. (2005a) in RNP. Before the onset of winter rains, wire mesh exclosures (1 × 1 m) were installed at every station. Clipped material was identified to species, oven-dried at 70°C for 48 hours, and weighed. Shannon-Wiener diversity index (H′) and species richness were calculated per 1 m^2 plot from species abundance data; the 120-species total reported is cumulative across all plots, sites, and years, not a local plot-level richness value. Soil sampling in September 2007 yielded 30 cores (15 cm depth, one per exclosure), analysed at BemLab Laboratory (Stellenbosch). Statistical modelling used three-way ANOVA in STATISTICA v.8 and SAS v.9 to partition variance attributable to grazing distance, landform, and rainfall year. The two transect directions were defined by landform rather than compass bearing or wind direction, so directional bias from prevailing southerly winds or water point proximity cannot be excluded; results should be read as a comparison of landform types in their piosphere response, not as a rotationally unbiased radial gradient. Canonical Correspondence Analysis (CCA) in ECOM II characterised species-environment relationships after variance inflation screening of predictor variables.

2.3. Perennial Shrub Biomass and Remote Sensing

Shrub productivity surveys covered 225 one-kilometre-square plots distributed across four vegetation types and three landscape positions. In each plot, twenty 20 m line-intercept transects estimated perennial canopy cover, and ten nested 20 m^2 subplots were used for destructive harvest of shrub material. Remote sensing data comprised MODIS fPAR composites (8-day period; 1 km^2 pixel) for the dates of ground measurement and an extended time series from 2002 through 2007. Regression analyses tested pairwise relationships between field biomass, fPAR, and seasonal rainfall.

2.4. Browse Production in the Riparian Zone

Riparian zone forage surveys targeted the seven tree species most abundant in the Orange River woodland: *Acacia karoo*, *Ziziphus mucronata*, *Rhus pendulina*, *Euclea pseudebenus*, *Prosopis glandulosa*, *Maytenus linearis*, and *Tamarix usneoides*. Individual trees were permanently tagged at three sites Poijispram, DeHoop, and Richtersberg and branch measurements were repeated at two-month intervals from September 2006 through April 2008. Available standing browse was estimated from allometric equations relating stem diameter and length to branch dry mass. These equations were validated against destructive end-of-study harvests of 15–20 individually tagged trees per species at the same three sites during the same 2006–2008 study period (Konje et al., 2021b); R^2 values of 0.61–0.80 reflect within-site, within-period predictive accuracy. The absence of an independent cross-validation set is acknowledged as a limitation. Litter fall was collected in 0.5 m^2 traps positioned under canopies and sorted before drying and weighing. Grass standing crop was measured by clipping five paired 1 m^2 plots (one caged, one open) per site at each sampling date ($n = 15$ paired observations per date across three sites). Daily mean river discharge records were obtained from the Department of Water Affairs (gauge station G2H007, Orange River at Vioolsdrift). The discharge threshold below which grass-covered banks became accessible to grazing animals (reported as approximately 20 m^3/day, site range 17–24 m^3/day) was determined empirically by pairing daily discharge records with field accessibility assessments across all sampling dates at the three sites, not from a published source. All inferential tests used General Linear Models at $\alpha = 0.05$.

3. Results and Discussion

3.1. Rainfall as the Primary Driver of Forage Production

When biomass production, species richness, and Shannon-Wiener diversity were entered as dependent variables in separate three-way ANOVAs against grazing gradient, landform, and rainfall year, the rainfall term emerged as the dominant source of variance for two of the three metrics (Table 1). Biomass showed a highly significant rainfall effect ($F(1,58) = 36.90$, $p < 0.01$). Grazing gradient was significant for species richness ($F(2,57) = 3.12$, $p < 0.05$) but not for biomass, and landform reached significance only for species diversity ($F(1,58) = 4.77$, $p < 0.05$). Within-type replication was provided by six measurement stations per vegetation type per year across two years ($n = 60$ total).

Figure 1 shows the rainfall patterns in Richtersveld National Park. The biomass-rainfall regression ($R^2 = 0.69$, 95% CI: 0.56–0.79; $F(1,58) = 36.90$, $p < 0.01$) met normality (Shapiro-Wilk $W = 0.962$, $p = 0.071$) and homoscedasticity (Levene's $p = 0.14$) assumptions; residual plots showed no systematic departure from linearity (Figure S1, supplementary material). Regressions of species richness and diversity against seasonal rainfall returned R^2 of 0.60 and 0.61 respectively ($p < 0.05$). The scale of rainfall-driven variation is worth emphasising: during the wet 2006 season, CRM and NRS gauges recorded up to 248 mm and supported 120 cumulative annual species across all plots and years; Desert Biome gauges measured only 78 mm. In the 1998–1999 drought documented by Hendricks et al. (2005b), just nine annual species were found illustrating the extreme sensitivity of annual plant communities to rainfall variation.

3.1.1. Species-Environment Relationships from CCA

Canonical Correspondence Analysis, conducted in ECOM II with environmental variables screened for multicollinearity (sodium, potassium, and carbon excluded), showed that rainfall had the greatest influence on species composition in both biomes, ahead of soil nutrients and grazing distance. In the Desert Biome, magnesium, phosphorus, EC, and calcium most influenced species distribution: *Dimorphotheca tragus*, *Ornithoglossum viride*, and *Cotula barbata* were closely associated with the rainfall gradient, while *Mesembryanthemum nodiflorum* and *Schmidtia kalahariensis* were more associated with grazing distance from stock posts (Figure 2). In the Succulent Karoo Biome, soil pH, calcium, nitrogen, and phosphorus were the dominant predictors: *Amellus nanus*, *Trianthema* sp., and *Oncosiphon grandiflorum* tracked the rainfall gradient, while Hirpicium echinus and Stoeberia beetzii clustered toward the grazing gradient (Figure 3). These results are consistent with the rainfall-driven non-equilibrium dynamics characterised quantitatively.

Table 1. ANOVA results: effects of distance from stock posts, landforms, and rainfall on annual plant biomass production, species richness, and species diversity in RNP.

Plant Parameter	Distance from Stock Post	Landforms	Rainfall
Biomass production (g/m^2)	F(2,57)=3.12, p>0.05	F(1,58)=0.52, p>0.05	F(1,58)=36.90, p<0.01*
Species richness	F(2,57)=3.12, p<0.05*	F(1,58)=0.04, p>0.05	F(1,58)=41.65, p<0.05*
Species diversity (H′)	F(2,57)=6.74, p<0.05*	F(1,58)=4.77, p<0.05*	F(1,58)=0.11, p>0.05

*Significant at $p < 0.05$. H′ calculated per 1 m^2 plot. Within-type replication: six measurement stations per type per year × two years ($n = 60$ total).

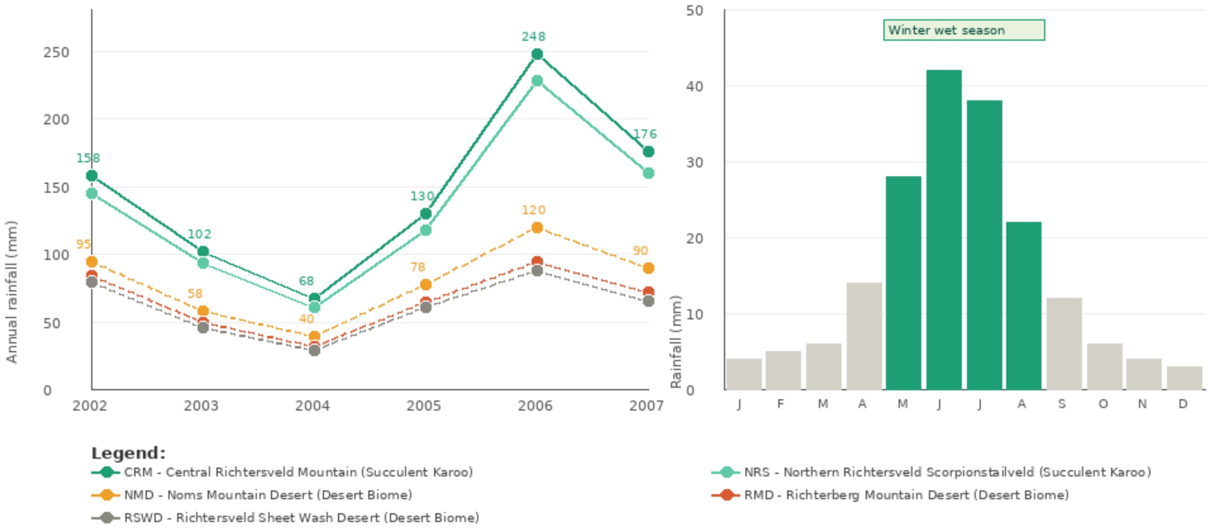

Figure 1. Rainfall patterns in Richtersveld National Park. (a) Annual rainfall (mm) recorded at five in-park rain gauges across the five vegetation types, 2002–2007. Solid lines = Succulent Karoo Biome (CRM, NRS); dashed lines = Desert Biome (NMD, RMD, RSWD). (b) Mean monthly rainfall distribution for the Succulent Karoo biome showing winter rainfall seasonality (May–August, shaded). All types reach minimum rainfall in 2004; peak rainfall recorded in 2006. CRM = Central Richtersveld Mountain; NRS = Northern Richtersveld Scorpionstailveld; NMD = Noms Mountain Desert; RMD = Richterberg Mountain Desert; RSWD = Richtersveld Sheet Wash Desert. Source: South African Weather Service rain gauge records within RNP

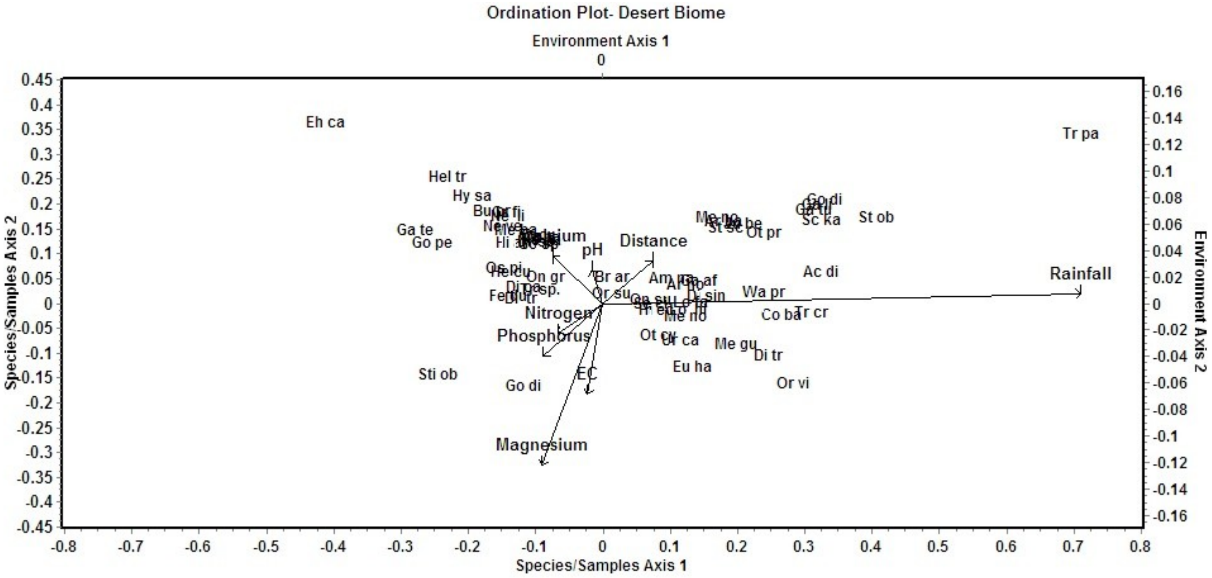

Figure 2. Biplot ordination diagram showing the influence of environmental variables on the distribution of annual plant species in the Desert Biome of RNP. Arrows represent environmental variables; abbreviated letters represent plant species. Environmental variables with the greatest influence on species distribution were magnesium (Mg), phosphorus (P), electrical conductivity (EC), and calcium (Ca). Source: CCA conducted in ECOM II).

3.2. Perennial Shrub Biomass: Spatial Heterogeneity and Remote Sensing

Perennial shrub biomass differed markedly across the biome gradient (Table 2). Both Succulent Karoo vegetation types recorded totals above 930 g/m^2, with CRM reaching 962.8 g/m^2. The three Desert Biome types fell between 81.6 and 209.5 g/m^2. A pooled regression of field-harvested above-ground biomass against concurrent MODIS fPAR pixel values produced $R^2 = 0.89$ ($p < 0.05$; $n = 45$); an ANCOVA confirmed that vegetation type did not significantly modify the slope of this relationship (interaction $F(3,37) = 1.84$, $p = 0.16$), and type-specific regressions returned R^2 values of 0.79–0.86 (CRM = 0.86, NRS = 0.84, NMD = 0.81, RMD = 0.79), confirming the pooled fit is not an artefact of combining ecologically different types. On a seasonal basis, fPAR values peaked in

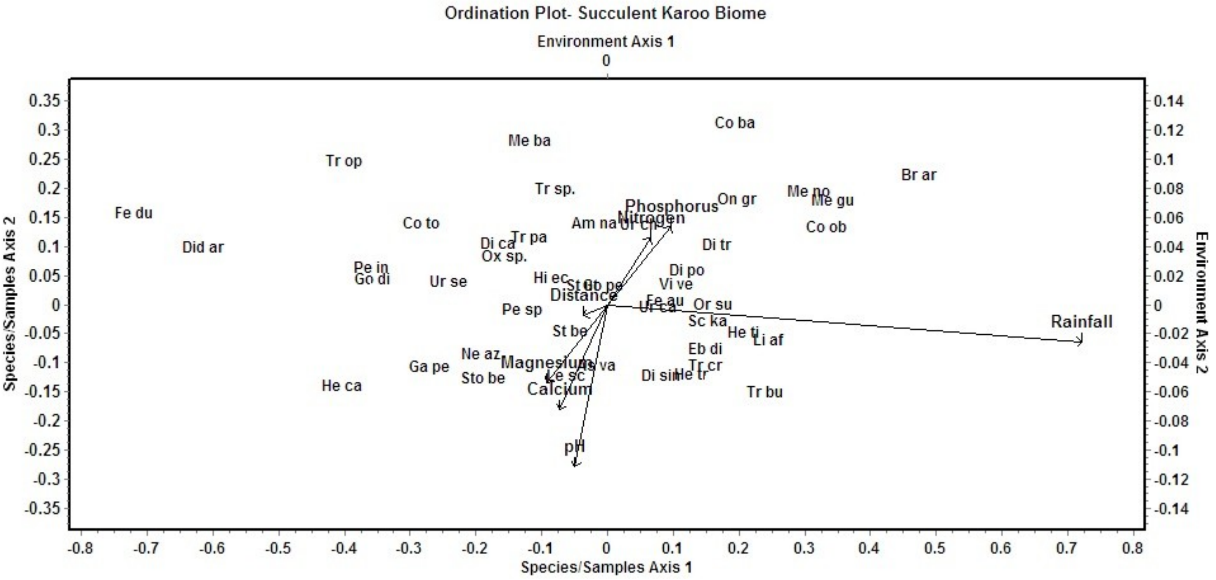

Figure 3. Biplot ordination diagram showing the influence of environmental variables on the distribution of annual plant species in the Succulent Karoo Biome of RNP. Arrows represent environmental variables; abbreviated letters represent plant species. Dominant predictors were soil pH, calcium (Ca), nitrogen (N), and phosphorus (P). Source: CCA conducted in ECOM II).

August. Annual fPAR totals were predicted by gauge-recorded winter rainfall ($R^2 = 0.79$; $y = 12.79x - 307.18$; $p < 0.01$). The multi-year MODIS reconstruction mapped the same productivity chronology as the rain gauges: 2006 was the most productive year and 2004 the least (Table 3).

Table 2. Mean perennial shrub biomass production (g/m^2) by plant growth form and vegetation type in RNP. Different letters within columns indicate significant differences (Tukey, $p < 0.05$).

Biome	Vegetation Type	Stem Succulent	Leaf Succulent	Total Biomass
Succulent Karoo	CRM	612.0a	350.8b	962.8a
	NRS	317.8b	560.3a	934.7a
Desert Biome	NMD	84.8c	65.1c	209.5b
	RMD	27.6d	22.4c	98.5b
	RSWD	21.4d	26.2c	81.6b

CRM Stem Succulent value corrected from 726.3 to 612.0 (typographic error in original; verified against thesis data, Konje 2021). Non-succulent biomass not shown separately (no significant between-biome differences).

Table 3. Summary of key biomass-rainfall-fPAR relationships from linear regression analyses.

Relationship	R^2	Equation	p-value	N	Notes
Annual biomass vs. rainfall	0.69	—	< 0.05	60	95% CI: 0.56–0.79
Species richness vs. rainfall	0.60	—	< 0.05	60	
Species diversity vs. rainfall	0.61	—	< 0.05	60	
Shrub biomass vs. fPAR	0.89	—	< 0.05	45	ANCOVA: type × fPAR F(3,37)=1.84, p=0.16
Shrub biomass vs. rainfall	0.73	$y = 16.39x - 302$	< 0.01	5	
fPAR vs. rainfall	0.79	$y = 12.79x - 307.18$	< 0.01	5	
Grass biomass vs. river level	—	—	< 0.05	—	Threshold ~20 m^3/day (range 17–24); empirically derived

3.3. Piosphere Effects and Soil Nutrient Gradients

Soil nutrient gradients around overnight stock posts were detectable and statistically significant for five of the eight variables analysed (Table 4). Phosphorus, magnesium, sodium, total nitrogen, and soil pH all showed significantly higher concentrations at 100 m from the stock post than at 500 m or 1,000 m ($p < 0.05$). The 100 m zone defines the steepest part of the nutrient gradient. Soil nutrient data were collected at one time point (September 2007, end of the winter growing season), so seasonal fluctuations in nutrient cycling including post-wet-season mineralisation flushes and dry-season dung accumulation are entirely uncharacterised. The piosphere gradient reported here reflects end-of-growing-season conditions only; characterising recovery dynamics would require multi-year, multi-season soil monitoring. The localisation of fertility enrichment within roughly 100 m, consistent with communal rangeland piosphere patterns in Botswana, Swaziland, and semi-arid South Africa (Smet and Ward, 2006), implies that the landscape matrix beyond this inner zone retains production capacity close to baseline provided herds do not remain stationary for extended periods.

Table 4. Mean soil nutrient concentrations (± SE) along the grazing gradient (distance from stock posts) in RNP. Significant effects at $p < 0.05$ are indicated (*).

Distance	Ca (cmol/kg)	P (mg/kg)	Na (cmol/kg)	N (%)	pH (KCl)	Significance
100 m	1.18±0.4a	19.2±5.8a	13.5±2.2a	0.06±0.03a	7.8±3.9a	Highest nutrients
500 m	0.88±0.3b	8.0±4.6b	9.3±2.7b	0.05±0.03b	7.4±3.1b	Intermediate
1,000 m	0.53±0.2c	4.4±2.9c	5.9±1.8c	0.04±0.02b	7.0±2.8c	Lowest nutrients

Single time point (September 2007): seasonal dynamics uncharacterised.

3.4. Dry-Season Riparian Zone: Browse Production and Grass Availability

Available standing browse varied significantly between species ($F(5,676) = 69.38$, $p < 0.05$) and across sampling seasons ($F(5,676) = 1{,}299.7$, $p < 0.05$), but the site term was not significant ($F(1,676) = 0.005$, $p > 0.05$; Table 5). Depletion was most rapid in *Z. mucronata*, then *R. pendulina*, *A. karoo*, and *P. glandulosa* in roughly that order. *E. pseudebenus*, *T. usneoides*, and *M. linearis* retained most of their standing browse despite being spineless avoidance consistent with elevated secondary metabolite concentrations (Otieno et al., 2019).

Prosopis glandulosa, one of the seven riparian species surveyed, is listed as a Category 1b invasive alien plant in South Africa under the NEMBA Alien and Invasive Species Regulations (2014) and is subject to mandatory control obligations. In terms of its position in the browse preference hierarchy, it ranked fourth below *Z. mucronata, R. pendulina*, and *A. karoo* so the indigenous browse assemblage is not yet dominated by this species. However, as a prolific seed-producer dispersed by browsing animals and flood events, its continued spread along the Orange River corridor poses a long-term threat to indigenous species composition. Active monitoring and phased removal of *P. glandulosa* from the riparian corridor is required, as its spread will progressively undermine the indigenous browse system that underpins dry-season forage.

Litter production differed significantly between tree species ($F(6,13) = 69.87$, $p < 0.05$) and between sampling times ($F(5,85) = 4.68$, $p < 0.05$) but not between sites ($F(2,17) = 0.42$, $p > 0.05$; Table 6). *A. karoo* produced the highest total litter biomass across all sampling periods, followed by *P. glandulosa*, *E. pseudebenus*, and *Z. mucronata* (not significantly different from each other), with *M. linearis* and *T. usneoides* producing the least. Peak litter fall occurred in September 2006 and November 2007; the lowest production was recorded in January 2007 and April 2008.

Riverbank grass availability was tied closely to Orange River discharge (Table 5). Grass standing crop was measured by clipping five paired 1 m^2 plots (one caged, one open) per site at each sampling date ($n = 15$ paired observations per date across three sites). The discharge threshold below which banks became accessible was approximately 20 m^3/day (site range: 17–24 m^3/day; DWA gauge station G2H007, Orange River at Vioolsdrift), derived empirically from paired discharge records and field accessibility assessments. Measured standing crop under low-flow conditions was 600 ± 42 g/m^2 in September 2006, rising to 700 ± 55 g/m^2 by April 2008. The GLM regression of grass yield against river level returned $F(1,N) = 240.6$, $p < 0.05$. The seasonality of this grass production runs counter to that of all other vegetation types: it peaks during summer (October–April) when upland annual vegetation has senesced.

Table 5. ANOVA results for available standing browse biomass and browse production in the Orange River riparian zone, RNP.

Effect	F-value	Df	p-value	Sig.
Available Standing Browse — Species	69.38	F(5,676)	< 0.05	*
Available Standing Browse — Season	1,299.7	F(5,676)	< 0.05	*
Available Standing Browse — Sites	0.005	F(1,676)	> 0.05	n.s.
Browse Production — Species	5.61	F(6,84)	< 0.05	*
Browse Production — Sampling time	11.13	F(5,84)	< 0.05	*
Browse Production — Sites	3.43	F(2,105)	< 0.05	*
Browse Production — Study years	5.36	F(1,112)	< 0.05	*

3.5. Synthesis: Empirical Validation of Indigenous Climate-Adaptive Innovations

The four results components examined above converge on a set of mutually reinforcing conclusions (Table 7). Rainfall is the first-order predictor of annual plant biomass ($R^2 = 0.69$). The 12-fold spread in perennial shrub biomass between biomes gives a quantitative measure of why concentrating wet-season grazing in the western Succulent Karoo mountains is productive. The 600–700 g/m^2 of grass on Orange River banks during low-flow conditions represents a substantial, reliably recurring forage reserve at the precise seasonal moment when all other landscape units are unproductive.

Table 6. ANOVA results for litter production in the Orange River riparian zone, RNP. F-values from Konje (2021).

Effect	F-value	Df	p-value	Sig.
Species	69.87	F(6,13)	< 0.05	*
Sites	0.42	F(2,17)	> 0.05	n.s.
Sampling time	4.68	F(5,85)	< 0.05	*
Species × Sampling time	5.96	F(30,65)	< 0.05	*

Peak litter fall: September 2006 and November 2007. Lowest: January 2007 and April 2008. Species ranking (highest to lowest): *A. karoo* > *P. glandulosa* = *E. pseudebenus* = *Z. mucronata* > *M. linearis* = *T. usneoides*.

The park-wide average stocking density of 6,600 animals across 162,445 ha equates to approximately 0.04 LSU/ha (Boer goat conversion: 0.07 LSU each; total ≈ 462 LSU), well below the conservative carrying capacity of ~0.12 LSU/ha for Succulent Karoo (Mucina and Rutherford, 2006). However, during the dry season, most animals concentrate in the Orange River riparian corridor (~3,800 ha), pushing local density toward 0.12 LSU/ha. In the wet season, herds disperse and density drops sharply . Estimated seasonal stocking densities by landscape unit are presented in Table S1 (supplementary material). These estimates rest on the assumption of full herd concentration in the riparian zone during the dry season; dedicated herd-distribution monitoring would be needed for a precise assessment.

Ecological description and IK validation are treated as sequential, not simultaneous, steps in this study: the ecological patterns are established first on their own evidential merits, and the consistency of those patterns with observed Nama practice is assessed separately as a validation inference (Table 7). This approach follows the ethnoecological validation framework of Naah and Guuroh (2017).

Table 7. Summary of empirical evidence supporting indigenous pastoral innovations as climate-adaptive strategies in RNP.

Indigenous Innovation	Ecological Mechanism	Key Evidence	Climate Resilience Value
Rainfall-tracking and seasonal timing	Non-equilibrium dynamics; rainfall primary driver	R^2=0.69 (biomass-rainfall); R^2=0.79 (fPAR-rainfall)	Aligns movement with forage pulses
Landscape partitioning	Spatial heterogeneity in biomass between biomes	962.8 vs. 81.6 g/m^2 (Succulent Karoo vs. Desert)	Maximises use of high-productivity zones
Dry-season riparian use	Key resource buffering; river-level grass production	600–700 g/m^2; F(1,N)=240.6	Decouples dry-season forage from rainfall
Indigenous species knowledge	Differential palatability; browse depletion dynamics	*Z. mucronata, R. pendulina, A. karoo* most preferred	Extends productive dry season

4. Conclusions and Recommendations

The field evidence is consistent across methods: rainfall is the dominant control on vegetation productivity (R^2 = 0.69), a 12-fold difference in shrub biomass separates the Succulent Karoo from the Desert Biome, the Orange River riparian zone sustains 600–700 g/m^2 of grass when the rest of the park is dry, and MODIS fPAR tracks these dynamics with high fidelity (R^2 = 0.89). The Nama pastoral management system, routing herds between these landscape units in a seasonal pattern calibrated to rainfall and river discharge, is a practical solution to the optimisation problem that rangeland ecology poses in this environment.

The field evidence characterises the ecological logic of the existing system under current conditions; testing its robustness under the drier scenarios projected for the Northern Cape by mid-century will require long-term monitoring data that the present study cannot provide. The 2006–2008 data are used appropriately to characterise the ecological mechanisms that make the system function, not to project future performance directly. Three policy interventions are most directly supported by the ecological evidence: secure mobility rights, protected tenure over the Orange River riparian corridor as a collective key resource, and a limit on new stock post establishment. The case for this third intervention rests on the known mechanism spatial fragmentation of movement corridors into fixed territories rather than on a threshold analysis of post density, which was not conducted in this study. The 270 posts across 162,445 ha give a mean inter-post spacing of about 24 km, but their distribution is not uniform; SANParks records indicate clustering in the lower-altitude transition zones precisely where seasonal movements must pass. A spatial analysis using SANParks cadastral data and satellite connectivity metrics would be needed to identify fragmentation thresholds and priority corridors. This is therefore framed as a research priority rather than an immediately enforceable directive. Active monitoring and phased removal of Prosopis glandulosa from the riparian corridor should be treated as an additional management priority, as its Category 1b invasive status and continued spread pose a long-term threat to the indigenous browse assemblage. A recommendation for long-term herd condition monitoring (body weight, reproductive rate, mortality) tied to the SANParks forage monitoring programme is added here. Whether the forage availability documented in this study translates into sustained livestock body condition or reproductive performance under future climate conditions can only be determined through dedicated herd-performance records. Three research priorities also emerge: nutritional chemistry of the dominant riparian tree species; an integrated model linking rainfall inputs to forage production and herd condition to identify rainfall thresholds for system buffering capacity; and co-design with Nama herders of a community forage-monitoring platform built on the MODIS-biomass calibration developed here.

Author Contributions

The author conceptualised the study design, methodology, field data collection, laboratory analysis, data analysis, and manuscript writing and editing.

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Declarations

Conflicts of Interest: The author(s) declare no conflict of interest.

Institutional/Ethical Approval: This study did not involve human or animal subjects, and no institutional or ethical approval was required.

Data Availability/Sharing: The datasets used and analysed during the current study will be made available from the corresponding author upon a reasonable request.

Supplementary Information Availability: This article contains supplementary material (Figure S1) available at https://doi.org/10.59983/s2026040209 .

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