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Understanding Rangeland Desertification at the Village Level: A Comparative Study with a Social-Ecological Systems Perspective in Namibia

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Abstract

Desertification poses significant environmental and socio-economic threats to pastoral systems within the drylands of sub-Saharan Africa. However, there remains a paucity of interdisciplinary studies delving into the anthropogenic drivers of desertification at the local level of social-ecological systems, resulting in an inadequate understanding of its human-induced causes. This research aims to bridge this gap by presenting three case studies from Namibia's eastern communal areas. Through an integrated approach drawing from rangeland ecology and anthropology, we offer a comparative analysis revealing nuanced differences among individual pastoral settlements, shaped by their distinct social contexts. Our findings elucidate the social determinants influencing varying degrees of desertification at the village level, highlighting local factors that mitigate the adverse impacts of grazing pressure and aridity on perennial grass populations. Notably, the study identifies the role of social institutions in managing critical environmental conditions and physical infrastructures, such as extensive pastures and cattle posts, which contribute to maintaining grassland resilience. Despite observable signs of desertification, the presence of perennial grasses both aboveground and in the soil seed bank across all settlements suggests that a tipping point has not yet been reached, emphasizing the window of opportunity for intervention. The discussion extends to the potential transferability of these findings to other Namibian communities within the existing socio-ecological framework, aiming to avert impending tipping points. Ultimately, the study challenges the notion of desertification in pastoral social-ecological systems as solely a tragedy of the commons, emphasizing the imperative of developing and implementing suitable social institutions within colonial and post-colonial contexts.

Keywords OvaHerero pastoralists · Communal rangelands · Desertification · Interdisciplinary approach · Namibia

Introduction

Drylands occupy 45% of the Earth's land surface and support 78% of the global grazing area (Asner et al., 2004). Livestock rearing is the primary land-use type in drylands, and many socially disadvantaged groups rely on natural forage resources to sustain their livelihoods (Godber & Wall, 2014; Reid et al., 2014). Concurrently, dryland ecosystems are particularly vulnerable to anthropogenic changes in climate and land use (Safriel, 2007; Maestre et al., 2022). They are under the accelerating threat of degradation (Berdugo et al., 2020; Huang et al., 2020), i.e., a reduction or loss in the capacity of the land to produce what the associated human society expects (Kassas, 1995). The type of land degradation characteristic of drylands is also known as desertification

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(UNCCD, 1994). As Becerril-Piña and Mastachi-Loza (2021) pointed out, desertification is also explicitly associated with a loss of ecosystem productivity (see D'Odorico et al., 2013; Kassas, 1995). Hence, desertification is "the persistent or irreversible reduction in the capacity of ecosystems to supply ecosystem services for several decades (soil, vegetation, and water) in drylands […] due to a variety of factors, particularly climatic variations and human activities" (Becerril-Piña & Mastachi-Loza, 2021). Already now, an estimated proportion of 10 to 20% of global drylands is considered desertified (Burrell et al., 2020), and a total area half of the size of the European Union is desertified annually, with Africa and Asia being the most affected (Cherlet et al., 2018). These processes and their effects on local livelihoods, rangeland ecosystems, and livestock constitute a serious socioeconomic and environmental concern (IPCC et al., 2019; Reynolds et al., 2007). This is especially true for Sub-Saharan Africa, where millions of humans rely on subsistence pastoral economies and the ecosystem service of forage provision for their livelihood (Robinson et al., 2011).

Desertification's main drivers include land-use changes resulting from socioeconomic pressures and climate change (i.e., aridification) (D'Odorico et al., 2013; Becerril-Piña & Mastachi-Loza, 2021). For rangelands, more intense and frequent droughts, high livestock densities, and non-adaptive herd management practices are particularly relevant (Ruppert et al., 2015; D'Odorico et al., 2013). Besides continued population growth (D'Odorico et al., 2013), the latter two are often the result of changes in the political economy, inadequate land management policies, and bad infrastructural planning (D'Odorico et al., 2019). These processes lead to overgrazing, soil exposure to wind erosion, and denitrification on the ground (Schlesinger et al., 1990). Thereby, rangelands might shift from a state with dense coverage of palatable, perennial grasses to bare soil, where the soil seed bank of these grasses also becomes depleted (Bestelmeyer et al., 2013; van Langevelde et al., 2016). This means that when resources are becoming sparse and land management is not adapted, the pressure on the dwindling natural resource base becomes even stronger, thus creating positive feedback between socio-economic and natural factors (D'Odorico et al., 2013). Such positive feedback loops are the basis for so-called tipping points (Kéfi et al., 2016), where the entire ecosystem tips over to a new state. When these 'desertification tipping points' are crossed, a natural re-establishment of productive rangeland vegetation is unlikely – at least on time scales relevant to human management (Linstädter & Baumann, 2013; Scheffer & Carpenter, 2003). Hence, social and environmental drivers are coupled and should thus be addressed simultaneously for studying desertification processes.

Given the unprecedented pressure on the planet's natural resources (Spinoni et al., 2021), it is unsurprising that multiple studies have examined the extent and environmental drivers of desertification. Usually, studies have used tools such as remote sensing (Omuto et al., 2014; Herrmann et al., 2020; Fadl et al., 2022; Rivera-Marin et al., 2022) or modelling (Lohmann et al., 2012; Reynolds et al., 2011; Oomen et al., 2016) for this purpose. Despite the overwhelmingly considerable importance of land-use change on desertification processes (Bestelmeyer et al., 2015), these studies rarely considered the socio-economic framework conditions of desertification. Moreover, rangelands are best conceptualized as social-ecological systems (SES), where humans are interconnected with local ecosystems and significant drivers of change (Linstädter et al., 2016; Roche, 2021; Hruska et al., 2017). This framework implies integrating study designs and results across natural and social sciences to integrate ecological assessments and socio-economic findings (Sander et al., 1998; Stringer & Reed, 2007). Ideally, equal emphasis is given to assessing the ecological and social subsystems to avoid oversimplifying either of these (Linstädter et al., 2016; Schlüter et al., 2014). This approach allows for a detailed assessment of degradation processes (e.g., losses of grass species) their direct linkages to local management practices and land-use histories (Reed et al., 2008; Tarrasón et al., 2016; Thomas & Twyman, 2004).

However, despite numerous advances in understanding the abiotic drivers of desertification in Sub-Saharan Africa (see D'Odorico et al., 2019), comparatively few studies have employed a truly integrated SES research design, putting equal weight to the assessment across natural and social sciences (McCabe, 1990; Bollig & Schulte, 1999; Boles et al., 2019; Coppock et al., 2022). This implies that the drivers of desertification in pastoral systems considering their spatial, temporal and socio-economic contexts are still not well understood (Darkoh, 1998; Geist & Lambin, 2004; Geist, 2005). This is also true for Namibia, where desertification processes in pastoral systems have, up to now, mainly been described without paying close attention to local social-ecological interactions and communal resource management dynamics (cf. Sullivan, 2000; Kahumba & Tefera, 2023; Ward et al., 1998; Menestrey Schwieger & Mbidzo, 2020; Coppock et al., 2022). Without this knowledge, the social drivers of desertification at the local level cannot be adequately addressed, and proactive management solutions to prevent desertification tipping points cannot be developed.

The natural sciences can establish causal relationships that lead to degradation through experimental studies of key factors, such as precipitation. In contrast, the social sciences investigate the links between environmental changes, political economy, local resource use, and behavioral factors in order to identify the causes of degradation (Little, 1994). Here, we apply an interdisciplinary approach integrating research findings across natural and social sciences to enhance the understanding of rangeland desertification at the village level in sub-Saharan Africa, particularly Namibia. Namibia is among the most arid countries in sub-Saharan Africa, where people's livelihoods in the country's communal areas (ca. 38% of the territory) largely depend on livestock farming (Mendelsohn et al., 2006). Simultaneously, land desertification has been extensively reported to impact various pastoral systems in these lands (Kahumba & Tefera, 2023; Inman et al., 2020; Kuiper & Meadows, 2002; Bollig & Schulte, 1999). Therefore, these circumstances present a critical and suitable case for studying desertification processes with an integrated SES approach.

The main research questions guiding our study were: (i) To what extent are rangelands in communal settlements degraded, and are there marked differences in the degradation state across these settlements? (ii) What social factors lead to different states of desertification (if any) at the village level? (iii) Are there local measures that help to control desertification better? (iv) Can these measures be adopted by other pastoral communities in the broader research region?

Materials and Methods

Study Area

We conducted our study in Namibia, the driest country in sub-Saharan Africa (Mendelsohn et al., 2002). Our study area is located in central Namibia, specifically in the Okakarara Constituency (Fig. 1), located approximately 250 km northeast of Namibia's capital, Windhoek. This part of Namibia is representative of dryland pastoral systems in the country (Mendelsohn & el Obeid, 2002) due to the socioeconomic and cultural importance of livestock farming (primarily Otjiherero-speaking pastoralists) and the characteristics of the land tenure system, which is communal.[1] Historically, this area was part of the so-called 'Native Reserve' in the Waterberg area, established by the South African colonial administration in the 1920s after defeating the former German colonial power in World War I. Later, this reserve became part of the larger Herero 'Homeland' in the 1960s as result of South Africa's apartheid policy until Namibia's independence in 1990 (Kakujaha-Matundu, 2003). These processes had different impacts on local communities, which we will show and discuss in detail below.

Compared to its neighboring constituencies, Okakarara has the largest population (approximately 23,000 inhabitants; 4,800 households) and is the most densely populated (1.6 persons per square kilometer) (Republic of Namibia, 2014, 2015). The primary source of income is livestock farming, and most farmers[2] own between 10 and 50 head of cattle and an average of eight sheep and 25 goats (Mendelsohn & el Obeid, 2002). As few natural permanent water sources hold water year-round, most people and farm animals depend on underground water supplied by boreholes (ibid.). Households are typically grouped around these water sources and most communities practice continuous grazing unless they have access to a cattle post (Brinkmann et al., 2023).

The study area belongs to the western parts of the central Kalahari region, where nutrient-poor sands with low water retention dominate (Zimmer et al., 2024). Climate is arid (UNEP aridity index 0.14–0.16) with a mean annual precipitation of 325–350 mm, most of which falls between January and April (Mendelsohn & el Obeid, 2002). Vegetation belongs to the "Tree Savanna and Kalahari Woodland" types (Giess, 1998), where the xeric Southern Kalahari transitions into the woodlands of the Northern Kalahari (Strohbach, 2014). The tree layer in this flat landscape is dominated by *Senegalia mellifera* (black-thorn acacia) and *Terminalia sericea* (silver terminalia), while the grass layer of near-natural vegetation is composed of perennial grasses such as *Stipagrostis uniplumis* (silky Bushman-grass) and *Eragrostis rigidior* (curly-leaved love-grass). Ecosystems are generally susceptible to grazing-induced desertification processes due to soil characteristics and the occasional occurrence of severe droughts. Rangeland vegetation is typically heavily used by humans and livestock. Moreover, it is characterized by woody plant encroachment (Marquart et al., 2020), and annual grass species with low grazing value dominate the grass layer (Strohbach, 2014).

Case Studies

We selected the three neighbouring settlements of Ovitatu (west), Okomumbonde (center), and Ozongarangombe (east) for our study (Fig. 1). These comprised 38, 36, and 62 households, respectively. These settlements were selected for two primary reasons. Firstly, their close geographical proximity and their location within a flat landscape reduced variations in abiotic site conditions, such as rainfall, slope and physical soil characteristics (Zimmer et al., 2024), thus facilitating the comparison of any social factors across settlements without much confounding with environmental differences. Secondly, the settlements had the typical range of households comprising a village and sharing surrounding rangelands in the broader region (Kakujaha-Matundu,

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[1] Communal land tenure comprises 39% of the Namibian territory, while the other major system is freehold, which accounts for 43% (Werner, 2021).

[2] The terms "pastoralists" and "farmers" are used interchangeably in this study.

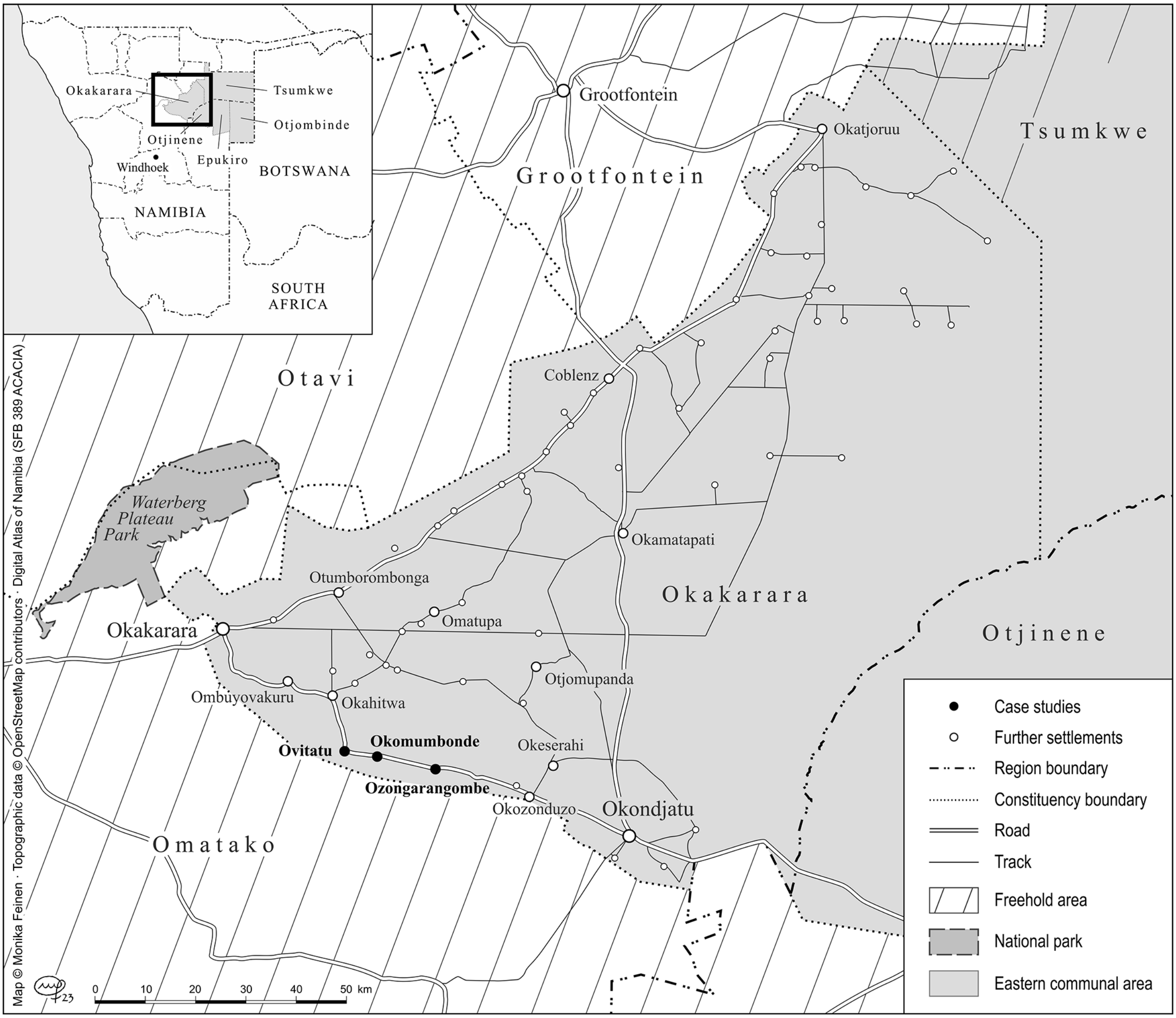

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Fig. 1 Study area and location of the three case studies of pastoral social-ecological systems where anthropological and ecological fieldwork was conducted. Source: see left margin of map

2003). More detailed information about the sizes of their communal rangeland, the location of farming infrastructure (e.g., boreholes, fences), livestock numbers, and rangeland management practices or dynamics were unavailable. These assessments – crucial to understanding the respective rangeland conditions – were part of our study. Initially, we assumed that socio-economic differences among settlements were small, but they were, in fact, significant and essential for explaining the varying degrees of desertification.

Acquisition of Ecological Data

To assess the desertification state of the communal rangelands, we focused on the population density of perennial grasses and the density and composition of soil seed banks. The former is a sensitive indicator of rangeland condition in dryland rangelands (Linstädter et al., 2014; Todd, 2006), while the latter is indicative of the resilience to grazing, i.e., the ability to recover after a major disturbance (van Langevelde et al., 2016). Ecological fieldwork was carried out using a grazing gradient approach. To this end, two transects were randomly demarcated per settlement, starting at local grazing hotspots – i.e., at the fenced edge of the households' camps – and stretching 2–3 km into communal land. Along each transect ($n=6$), nine 100 m² plots were set up (54 in total), with plot density increasing logarithmically with increasing distance from grazing hotspots to capture the non-linear decrease in grazing pressure away from the settlements (Manthey & Peper, 2010; Linstädter et al., 2014).

For the population density of perennial grasses, we selected five focal species that have been reported to occur in the study area's grass layer (Strohbach, 2014; Amputu et al., 2019): *Eragrostis lehmanniana; Eragrostis trichophora; Aristida congesta; Aristida stipitata;* and *Stipagrostis uniplumis*. The species differ in their grazing value for livestock and their indicative value for rangeland condition. *E. lehmanniana*, *E. trichophora*, and *A. congesta* have low grazing values (van Oudtshoorn, 2012) and indicate heavily grazed areas (Roodt, 2011). Likewise, *A. stipitata* also has a low grazing value (van Oudtshoorn, 2012). However, this species tend to change its ecological role with grazing intensity whereby it can either act as a pioneer under heavy grazing (Müller, 2007), or occur more frequently in lightly grazed areas (O'Connor, 1991). Finally, *S. uniplumis* is a comparatively productive grass with an average grazing value (van Oudtshoorn, 2012); in healthy savannas on sandy soils such as in our study area, it can dominate the grass layer (Strohbach, 2014; Zimmermann et al., 2015). Hence, the five species are indicative for different degrees of degradation.

At the peak of the growing season (April 2021), we employed a nested plot design to record perennial grasses' population densities. This approach is particularly well-suited to the patchy, disturbance-prone character of dryland vegetation (Kindermann et al., 2022), as it keeps sampling efforts within reasonable limits. To this end, we subdivided plots into four subplots of 25 m² labeled as subplots A, B, C, and D. Starting with subplot A, a minimum target of 25 individuals per species was recorded. If the minimum target number was not reached in that subplot, we moved on to the next one until all the four subplots were surveyed. In cases were the minimum target of 25 individuals was not reached in the entire 100m^2 plot, the exact number of individuals counted (0–24) in that plot was recorded. If densities were exceptionally high, we recorded individuals of the five perennial grasses only on 4–9 quadrats of 1 m² within the four 25 m² subplot (Elzinga et al., 1998). Accordingly, the sampling area per plot ranged from 4 m² to 100 m² as an increase in sampling area was done if individual species were sparse and the minimum number was not reached (ibid.).

For the soil seed bank, topsoil cores (9.8 cm diameter, 5 cm depth) were collected per plot from September to October 2020. Sampling was stratified into a plot's intercanopy and subcanopy habitats to account for these two cardinal habitat types in savanna ecosystems (Sandhage-Hofmann et al., 2021). To better capture the patchy character of vegetation, the intercanopy samples were collected from bare patches and where possible, supplemented with samples of patches with established perennial grasses (see Zimmer et al., 2024). We took three replicates per habitat type (6–9 samples per plot; 341 samples in total). Soil samples were added to a 12 cm x 12 cm pot half-filled with sterile soil and placed in a net-house. Throughout the rainy season, i.e. from December 2020 to May 2021, pots were regularly watered to maintain moisture content. Emerging herbaceous plant seedlings were assigned to a species and counted weekly. Specimens of all unidentified species were air-dried, mounted and taken to the Namibia Botanical Research Institute (NBRI) for identification.

Analysis of Ecological Data

To assess the desertification state of rangelands, data for rangeland health proxies (population density of perennial grasses, and density and composition of soil seed banks) were analysed via Generalised Linear Mixed Models (GLMMs), using the R package 'lme4' (Bates et al., 2015) in R version 4.1.1 (R Core Team, 2022). All statistical models included a random intercept variable 'Transect' to account for covariance among transect plots. Plots were allocated to a fixed categorical variable, reflecting distance to the grazing hotspot and, thus, grazing pressure. We distinguished three distance classes ('Distance category') with three plots per transect and class, i.e. 'Near' (closest to the grazing hotspot); 'Intermediate'; and 'Far' (furthest from the grazing hotspot). We also included the categorical variable 'Village' to assess differences in rangeland health between the three settlements ('Ovitatu'; 'Okomumbonde, and 'Ozongarangombe'). Depending on the response variable, other fixed variables were included in the full model as appropriate (for details, see below). Each model was then assessed using model comparison by dropping terms that accounted for the least variance sequentially until the best model was found based on the Akaike Information Criterion (AIC). Post-hoc analysis was used to assess differences in individual categories, using Estimated Marginal Means (EMMs), with Tukey correction for multiple comparisons (performed in R package 'emmeans' (Lenth, 2022).

For the densities of perennial grass populations, we upscaled plant counts to population densities per 100 m^2 where necessary. GLMMs were used to assess differences in densities, with a Negative Binomial distribution and log link-function. Models failed to converge when all data was included, so separate GLMMs were run per species (to compare settlements) or per settlement (to compare species responses within settlements). 'Distance category' was included as a fixed factor within all models, with either 'Village' or 'Species' and their interaction term with 'Distance category' as appropriate. All models only included values for species or settlement where present, e.g., for *S. uniplumis* (absent in all plots of Ovitatu), only Okomumbonde (center) and Ozongarangombe (east) were included.

For the soil seed bank, we summed the number of emerging seedlings for the 6–9 soil samples per plot intospecies, functional group (‘Perennial grasses’, ‘Annual grasses’, ‘Other species’) or across all species (‘Total’). Seedling densities were upscaled to comparable densities (seedlings per 1 m² for functional groups and for the total seed bank, and 100 m² for perennial grass species). For each functional group and for the whole seed bank, we used GLMMs with a Negative Binomial distribution and log-link function to test for differences in seed bank densities (number of seedlings per 1 m²) between villages and distance category. Accordingly, the four full models contained the two fixed categorical variables ‘Distance Category’ and ‘Village’ and their interaction. Finally, the relative abundances of functional groups (proportion of seedlings) in the soil seed bank were compared between all transects separately via GLMMs with a Binomial distribution and logit link-function.

Ethnographic data Acquisition and Analysis

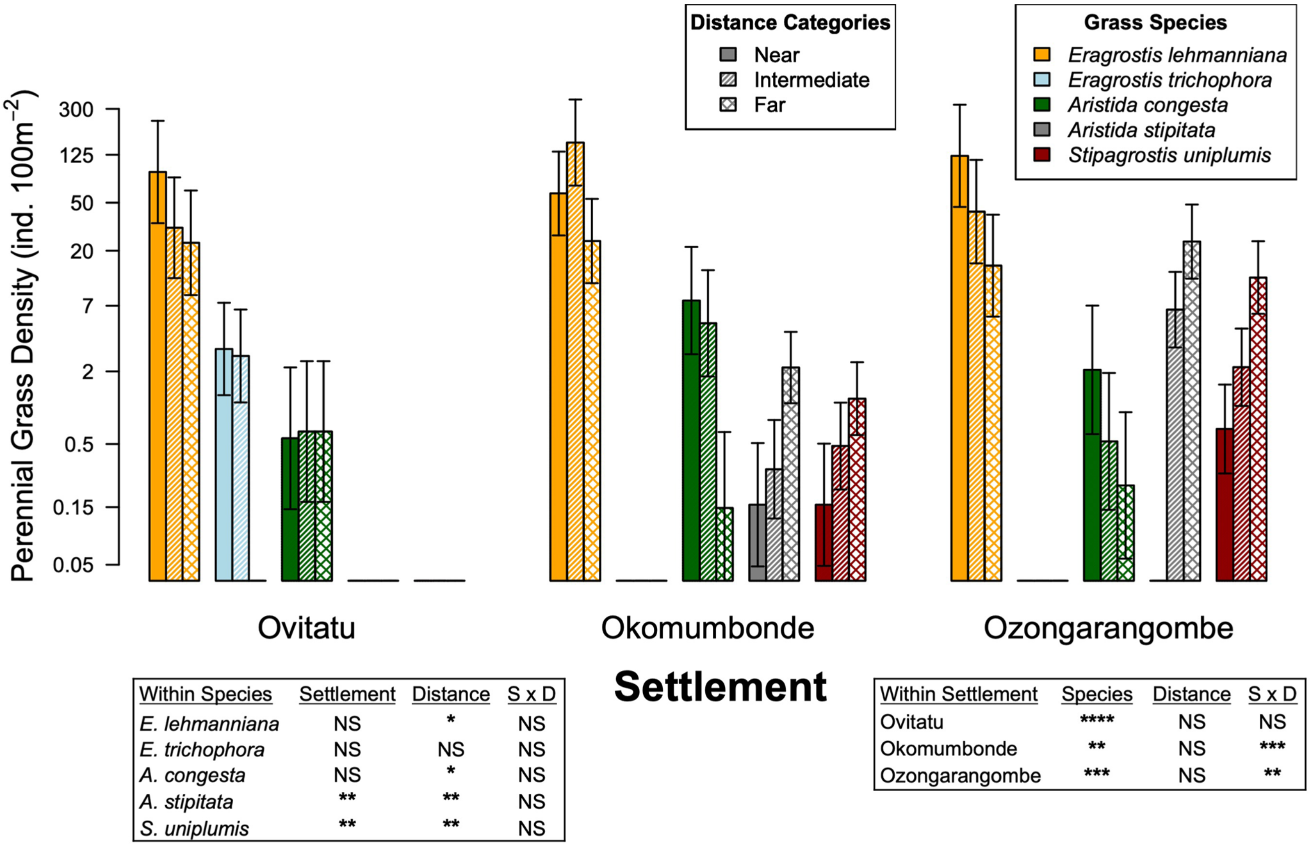
Ethnographic data collection occurred during long-term fieldwork, evenly distributed across the three settlements between October 2019 and October 2020. We followed the Event Ecology approach from Walters and Vayda (2009) for this study. This approach aims to generate plausible explanations for specific environmental changes by reconstructing the causal chains of interrelated social-ecological events and actions that produced such changes. To this end, we utilized a mixed-method strategy (Creswell, 2003) to gather data on the historical settlement processes, land-use dynamics, and infrastructure developments in all three locations. First, we created detailed maps of each settlement and its surroundings by georeferencing the positions of households and farming infrastructures, such as boreholes, fences, and grazing areas. Using these maps, we conducted in-depth interviews with oral historians and knowledgeable farmers to reconstruct the historical emergence of these dwelling and farming infrastructures, including grazing practices and rangeland management institutions. Additionally, we conducted literature research to situate the interview data within broader socio-political and historical processes. We then organized all the data using the software MAXQDA. We applied thematic coding to identify critical events (e.g., the introduction of boreholes) and their linkages to sustained changes in local social-ecological processes (e.g., decisive shifts in grazing management) over time. By comparing the chronology of events with the ecological findings, we developed a plausible explanation for the primary social drivers of rangeland states in each settlement. This included the measures that helped to control desertification processes. Finally, we compared the synthesized findings regarding the principles that helped most to keep desertification at bay with available information about the broader region. This allowed us to discuss if the principles could be applied elsewhere.

Desertification State of Rangelands

State of Grass Populations

In terms of the population densities of perennial grasses, we found clear differences between the three settlements, hinting to different desertification states of their rangelands (Fig. 2). Specifically, our results suggest that the western settlement Ovitatu had the most degraded communal rangelands, while the eastern settlement Ozongarangombe had the least degraded ones. This was already observable with respect to the presence and absence of grass species. Of the five focal species, only three occurred in Ovitatu, the western settlement (*E. lehmanniana*, *E. trichophora*, *and A. congesta*). All three species are indicators of poor rangeland condition. In the central and eastern settlements (Okomumbonde and Ozongarangombe), *A. stipitata* and *S. uniplumis* – indicators of healthier rangeland – were additionally found (Fig. 2). These two grazing-sensitive species were also recorded in particular high densities in the eastern settlement of Ozongarangombe (GLMM; Negative Binomial; “*A. stipitata*”: D.F. = 1,2; Chi-sq = 5.28; $p < 0.05$; “*S. uniplumis*”: D.F. = 1,2; Chi-sq. = 6.06; $p < 0.05$) (Fig. 2).

We also found significant main effects of the factor ‘Distance Category’ for *E. lehmanniana* (D.F. = 2,46; Chi-sq = 7.42; $p < 0.05$), *A. congesta* (D.F. = 2,46; Chi-sq = 6.09; $p < 0.05$), *A. stipitata* (D.F. = 2,30; Chi-sq = 11.70; $p < 0.01$) and *S. uniplumis* (D.F. = 2,30; Chi-sq = 8.60; $p < 0.05$) (GLMM; Negative Bionmial), and a significant interaction between Distance Category and Species in Ozongarangombe, the eastern settlement (D.F. = 6,59; Chi-sq = 17.23; $p < 0.01$). In general, the ‘poor’ rangeland species were recorded at higher densities close to the settlement edges (distance category ‘Near’), where grazing was assumed to be of higher intensity, e.g., *E. lehmanniana* (EMM: “Far versus Near”: z-ratio = -2.36; $p < 0.05$) (Fig. 2). In contrast, the indicator species for ‘good’ rangeland condition were generally found further away from the settlement, where grazing was assumed to be less intense, e.g., *A. stipitata* had higher densities at Far and Intermediate distances compared to Near (EMM: “Inter v Near”: z-ratio = 2.41; $p < 0.05$; “Far v Near”: z-ratio = 3.51; $p < 0.01$) (Fig. 2).



Within Species	Settlement	Distance	S x D
E. lehmanniana	NS	*	NS
E. trichophora	NS	NS	NS
A. congesta	NS	*	NS
A. stipitata	**	**	NS
S. uniplumis	**	**	NS

Within Settlement	Species	Distance	S x D
Ovitatu	****	NS	NS
Okomumbonde	**	NS	***
Ozongarangombe	***	NS	**

Fig. 2 Population densities of five focal perennial grass species in communal rangelands of the three settlements. Grasses are ordered according to their indicative value for rangeland state, from "poor" (*E. lehmanniana*) to "good" (*S. uniplumis*). Bars show the mean population density per plot along two transects along grazing gradients per village ($n = 18$). Distance categories indicate the distance of plots to the settlement edge ($n = 6$) with associated Standard Errors. Statistical results are shown within species or within settlement models, indicating p-values of * <0.05 ** <0.01 *** <0.001 **** <0.0001

Soil Seed Bank Characteristics

Eight perennial grass species emerged during the germination experiment (Fig. 3a). All these species were present in the eastern settlement of Ozongarangombe, with the number of species decreasing towards the west (Fig. 3a). Accordingly, the western settlement Ovitatu had the lowest perennial grass species richness with only two germinated species (*E. trichophora* and *A. congesta*), both indicators of poor rangeland condition. *E. trichophora* accounted for 97% of all perennial grass seedlings here, and the two species combined accounted for 100%. While in the central settlement Okomumbonde, *E. trichophora* accounted for 61% (with this species together *with A. congesta* accounting for 97%), in the eastern settlement Ozongarangombe, these values were 81% and 83%, respectively.

Total numbers of emerging seedlings from the seedbanks were significantly different among settlements (GLMM; Negative Binomial; "Village"; D.F. = 2,49; Chi-sq. = 9.97; $p < 0.01$) (Fig. 3b). In contrast to our other findings for perennial grass population, the eastern settlement of Ozongarangombe was found to be the least desertified, with a smaller soil seed bank than both settlements more to the west (Fig. 3b). This result can be related to the functional group composition of seedling communities. Here, total seed densities were mainly related to the number of annual grass species. The eastern settlement of Ozongarangombe had less germinating annual grass seeds than either settlement to the west Okomumbonde (z-ratio = 3.674; $p < 0.001$) or Ovitatu (z-ratio = 2.385; $p < 0.05$) (EMM). In contrast, there were no statistical differences between settlements, both for perennial grass seedling densities and for the seedlings of other species ($p > 0.05$). For total seedling densities and seedling densities of functional groups, 'Distance' never had a significant effect (neither as an interaction nor as a main effect), or improved the model when used as a random variable, so it was excluded from final models.

Results for the relative abundances of functional groups were confounded by differences between transects. In the western settlement Ovitatu, the two transects were significantly different, with one transect having the lowest relative abundance of perennial grasses among all six transects

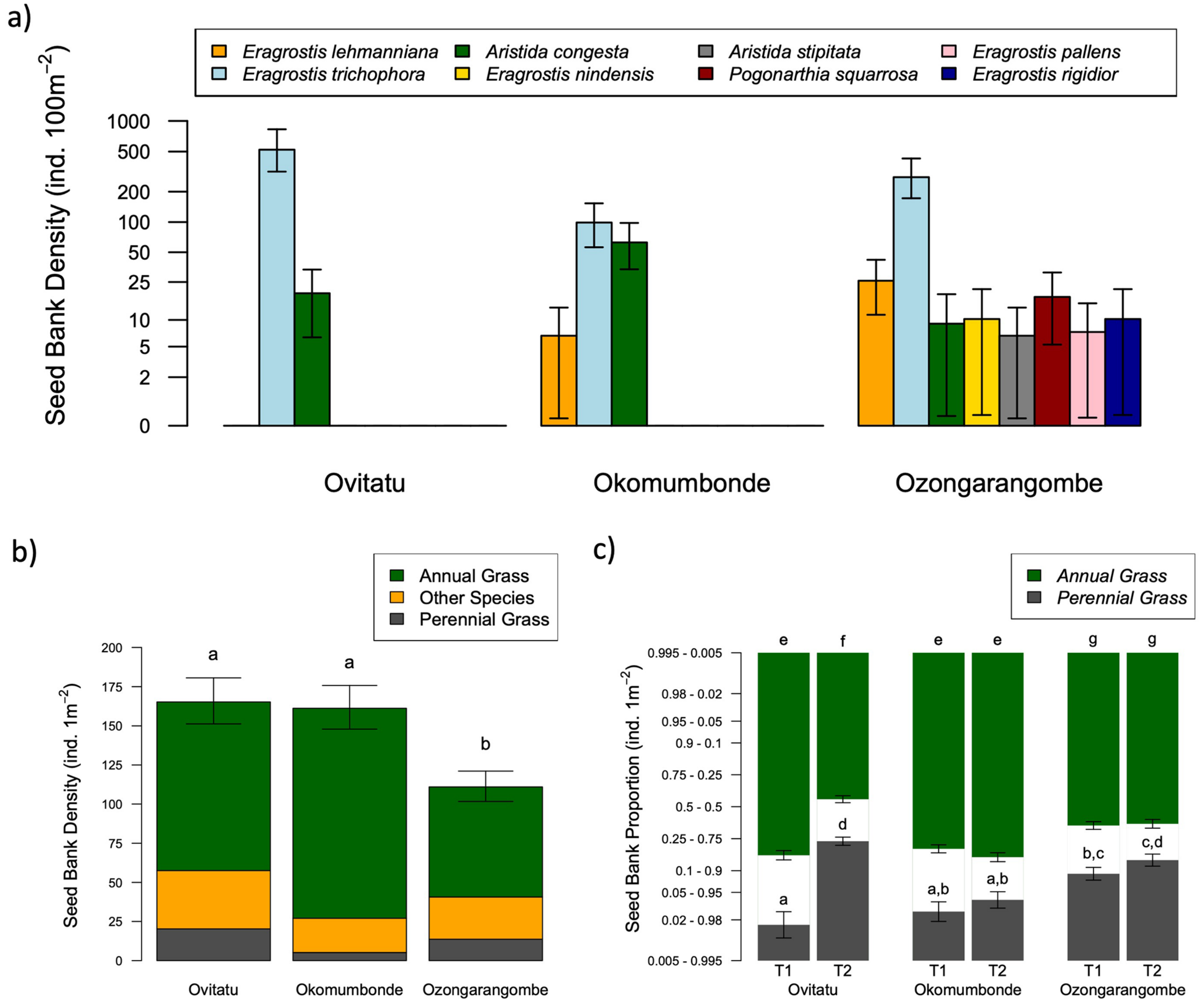


Fig. 3 Soil seed bank density and composition in the communal rangelands of the three settlements (Ovitatu; Okomumbonde; Ozongarangombe). (**a**) Mean perennial grass species abundance; (**b**) Total seedling abundance and functional group composition, with standard error bars and statistical similarity given for total abundance; (**c**) Relative abundances of perennial and annual grasses in the soil seed bank, subdivided into transects, with statistical similarity across transects given within functional groups

and the other having the highest (Fig. 3c). When Ovitatu was removed from the analyses, relative abundances of functional groups indicated clear differences between the remaining two villages. Overall, the eastern settlement Ozongarangombe had the highest relative abundance of perennial grasses in its soil seed bank, and the lowest relative abundance of annual grasses, while the central settlement Okomumbonde had the lowest relative abundance of perennial grasses, and highest annual grass relative abundance (EMMeans: “Perennial” z-ratio = -5.070; $p<0.001$; “Annual” z-ratio = 6.746; $p<0.001$).

For relative abundances, there were also Distance x Village and overall Distance effects for both Perennial and Annual grass proportions (results not shown) (Perennial DxV: Chi-sq = 17.513, $p<0.01$; Perennial D: Chi-sq = 27.302, $p<0.0001$; Annual DxV: Chi-sq = 12.573, $p<0.05$; Annual D: Chi-sq = 17.401, $p<0.001$). Unexpectedly, the general patterns were for perennial grasses to have a higher proportion in local soil seed banks near the settlement edge, while annual grasses showed an opposite trend.

The Chains of Socio-Historical Events Influencing Local Rangeland Conditions

In this section, we aim to link our ecological findings on rangeland condition (see above) to a reconstruction of socio-historical events. For this purpose, we will recurrently refer to the map of the three pastoral settlements (Fig. 4), indicating the location and establishment year of infrastructures related to livestock farming. Note that the camps, fences, and boreholes shown on this map did not exist 100 years ago; it depicts the landscape features assessed during our ethnographic fieldwork between 2019 and 2020.

First Residents, First Boreholes and Incoming Herders

Grazing histories of the area could be traced to the years preceding German colonialism (1884–1915), when all infrastructures shown in Fig. 4. did not exist yet. During this time, the study area was utilized by OvaHerero pastoralists from the Waterberg to establish summer cattle-grazing outposts that were regularly relocated through a network of waterholes, access to which was regulated through kinship. These practices aided to keep degradation processes at bay (Mossolow, 1992; Henrichsen, 2011). The only people living on a more permanent basis in the area were '*ovatjimba*' (impoverished OvaHerero), relying on perennial wells (*ozondjombo*) in Okahitwa at the Omatako river (Lindholm, 2006).

It was only after the South African colonial authorities created the Waterberg 'native reserve' in 1924 that Ovitatu, Okomumbonde and Ozongarangombe began to take on their present form. In this context, the colonial administration relocated many OvaHerero communities residing in central Namibia – in districts exclusively designated for white settler farming – to the recently established reserve to control them politically and economically (Werner, 1998). However, water sources in this delimited territory were scarce, and the few places with boreholes rapidly became overcrowded (Kakujaha-Matundu, 2003:168f). Therefore, the first permanent inhabitants of the area were a handful of pastoralists who came from other parts of the reserve (such as Ombujovakuru and Omaihi) in search of better areas to live. In the late 1920s, they succeeded in digging wells (*ozondjombo*) in productive spots and settled permanently.[3]

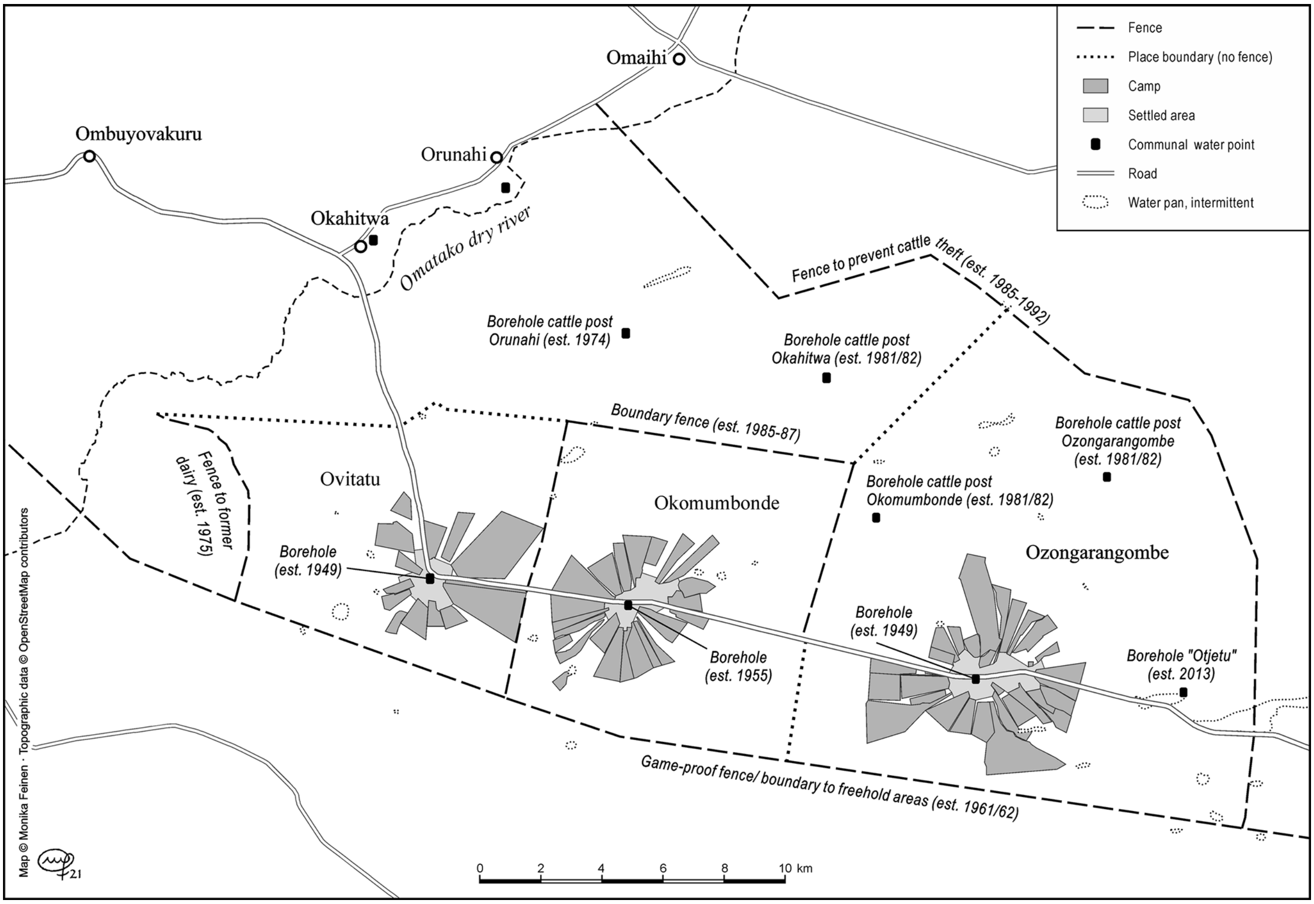


Fig. 4 Map of the three pastoral social-ecological systems studied in this paper (Ovitatu, Okomumbonde and Ozongarangombe), with a special emphasis on infrastructures related to livestock farming (camps, fences, boreholes in settlements, and boreholes in cattle posts). Where possible, the year of establishment is given

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[3] Interview with Uahumua Hei, Okondjatu, 16.06.2020.

With the completion of these wells, Ovitatu, Okomumbonde and Ozongarangombe emerged as 'socially constructed' settlement names, i.e., local communities attached meaning to them (Aucoin, 2017). In each of these cases, the names were closely linked to the construction of permanent wells, signifying that these events enabled people to establish permanent settlements at these locations. The name Ovitatu is derived from the Otjiherero word for "barks", which refers to the tree bark that the first inhabitants used as makeshift drinking troughs for their animals at the newly dug wells. Okomumbonde originates from the phrase *ondjombo okomumbonde*, meaning "the well at the omumbonde tree (*Vachellia erioloba*)", alluding to the exact spot of the first well. Similarly, Ozongarangombe takes its name from *otjikango tjozongarangombe* – "the place of the eland", indicating that the first well was dug where a large herd of these animals used to drink.

In these conditions, during the rainy season, the new residents shared the larger grazing area with Okathiwa and Orunahi pastoralists as long as water was available in small land pans (*omarindi*) and/or small, shallow wells (*ozombu*) in the fields. These incoming herders did not source water from the *ozondjombo* used by their fellows living on-site because these were already used to their full capacity,[4] although they might have possessed less than 15 heads of cattle each (Werner, 1998:187ff).

These circumstances changed with the introduction of high-yield pump boreholes equipped with wind or diesel pumps in the area. This was the case for Ovitatu (west) and Ozongarangombe (east) in 1949 and Okomumbonde (center) in 1955.[5] These installations coincided with the demands of OvaHerero leaders, including local headman Ludgwig Ndinda from Okahitwa, to address the detrimental water situation in the reserve (Castro, 2015). The new, more powerful infrastructure significantly increased water availability for livestock in the area. As result, herders from the crowded Omatako dry river area began relocating to these newly established settlements, leading to a rapid population increase.[6] When government ethnologist Orwin Köhler visited the region in December 1956, he did not find the mere handful of herders who had initially settled permanently a few years earlier (see above), but a substantial number of residents. By then, the settlements were home to 119, 56, and 102 men, women, and children in Ovitatu, Okomumbonde, and Ozongarangombe, respectively (Köhler, 1959:42ff).

Game-Proof Fences, Re-Settlement and Further Population Increase

Two events additionally affected the land-use in our case studies from the 1960s onwards: first, the 1961/62 foot-and-mouth pandemic; and second, the consolidation of the eastern reserves into the larger Herero 'homeland' in 1964 as part of the South African Apartheid policies (Kakujaha-Matundu, 2003). Concerning the foot-and-mouth outbreak, significant portions of the predominantly white farming areas were severely affected by 1961. The colonial administration responded by constructing game-proof fences to prevent the disease from spreading to the northern and eastern regions of the country (Miescher, 2012:168ff). In the study area, the fence materialized the boundary between the settler farming area and all the native reserves in the region (Waterberg, Otjituo and Epukiro). This had significant implications for the inhabitants of all three settlements. Located adjacent to the margin of the newly erected fence and the reserve, grazing land towards the south was excised:

> "[Previously] *there was no fence, only poles in the landscape marking where the lands started or ended. The people from those places* [Ovitatu, Okomumbonde, and Ozongarangombe] *used these areas for grazing* […]. *They could go even nine kilometers south from where the fence is now. It was open.*"[7]

Moreover, when the reserves were consolidated into Herero 'homeland' – a territory that stretched up to the Botswanan border – OvaHerero residing in the Rehoboth sub-reserves in southern Namibia and Windhoek's district were relocated to the newly established homeland (Kakujaha-Matundu, 2003:114f). Reportedly, a portion of these new-comers were relocated in Ovitatu, Okomumbonde, and Ozongarangombe as well.[8] Likewise, the area around Omatako became more intensively used, which prompted the residents of Orunahi to request the colonial administration to install a borehole halfway eastwards to Okomumbonde to use it as a cattle post. This borehole was constructed in 1974, thanks to the intervention of headman, Ndinda.[9]

Camps

From the 1970s onwards, livestock owners within the homeland – including the three settlements – started constructing camps (*ozokamba*) (Stahl, 2009; Werner, 2009). These fenced-off pieces of land were (and still are) built behind the

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[4] Interview with Gustaf Veuserua and Erastus Tjivau, Okahitwa, 15.06.2020.

[5] Before this, Ovitatu and Okomumbonde had low-yield hand pumps installed in the 1930s, which strongly limited the water supply.

[6] Interview with Erastus Tjivau, Okahitwa, 15.06.2020.

[7] Interview with Uahumua Hei, Okondjatu, 16.06.2020.

[8] Interview with Gustaf Veuserua and Erastus Tjivau, Okahitwa, 15.06.2020.

[9] Interview with Philipus Tjiteere, Okahitwa, 01.02.2021.

owner's homestead, and they fulfill different purposes, such as: to keep the old, sick, weak, and pregnant cattle more easily under guard; to keep the bull separate from other peoples' herds, and to protect livestock from being stolen. The proliferation of these enclosures has been linked to the progressive outmigration of young men (i.e., those household members typically taking care of cattle) searching for wage labor due to the colonial structural causes of poverty and the necessity of securing grazing in the context of human population increase (Stahl, 2009), which also applied to our communities.

Since the introduction of these infrastructures, the general rule in all three places has been that each camp should not exceed 1km^2. In this context, affluent livestock owners tended to fence off larger tracts of land at the expense of impoverished livestock farmers who could not afford fencing (or only for smaller camps). In practice, it has been challenging to sanction these actions, as recorded for Ozongarangombe:

> *"There have been a lot of meetings about reducing the size of some camps. However, those with big camps claim they can't make them smaller. Some say they will make them smaller, but don't follow through. These issues are only revisited after a long time, but then they are dropped again."*[10]

The construction of these infrastructures has resulted in a reduction of communal rangeland availability (see below) and has posed greater challenges for cattle seeking fodder. Animals have to traverse through the corridors left by these enclosures to access the open veld beyond. Currently, cattle feed mainly behind the fences during rainy seasons. However, as these pastures are depleted, the cattle move further away, extending the grazing area into the orbits of settlements during the dry seasons. Despite grazing far from homesteads, cattle must walk back to communal boreholes for water. This significantly increases their energy costs and intensifies grazing pressure in the area closer to the boreholes.

Drought and Additional Boreholes

These land-use and grazing practices continue to exist in Ovitatu, Okomumbonde, and Ozongarangombe. However, the main difference is that the residents of the last two places now have the opportunity to take their animals to cattle posts (see Fig. 4) whenever the grazing situation around their own areas demands it. This is not the case for Ovitatu: there are no alternative animal grazing areas even in adverse rangeland conditions. In times of drought, Ovitatu's people depend on the surrounding communities or places elsewhere in the broader region for permission to access grazing lands.

These cattle posts emerged after the severe drought of 1981/82. While suffering heavy livestock losses, the communities of Okahitwa, Ovitatu, Okomumbonde, and Ozongarangombe requested the Herero Ethnic Authority to install additional water points to access nearby grazing land (Kakujaha-Matundu, 2003, p. 173).[11] The requests were approved, but the responsibility to determine the placement of water points was given to the communities. They were instructed to negotiate with each other since their grazing areas were interconnected.

After the deliberations, only Ovitatu did not receive a cattle post. The cattle from Ovitatu and Okahitwa were already meeting halfway for grazing, therefore, an additional water point between the two settlements would have increased grazing pressure along the stretch between them. Similarly, due to limited space and harsher grazing conditions around the dry river, Okahitwa was granted a borehole north of Okomumbonde. The areas east of the Omatako and/or north of Orunahi were out of question since other communities already used these rangelands. The area north of Ozongarangombe, in contrast, was open and therefore suitable for introducing a new water point, which was accomplished. But then again, there were no available areas for serving Okomumbonde's cattle. This place became a cattle post thanks to the concession made by neighbors in Ozongarangombe who conceded the actual drilling spot (which is closer to Ozongarangombe) since Okomumbonde's cattle did not have anywhere to go in times of drought.

Border Fences

The construction of three different border fences further impacted the local land-use practices in the area and continues to do so. The three fences are sited as follows: (i) one fence runs north from Orunahi up to the game-proof fence at Ozongarangombe in the east; (ii) a quadratic fence surrounds Okomumbonde, and (iii) the border fence running west from Ovitatu (see Fig. 4).

The fence construction, spanning from Orunahi to Ozongarangombe, commenced in the mid-1980s but only reached completion circa 1991/92 due to difficulties to organize funds and workers for its construction. The residents of all five enclosed territories contributed money and labor to build it to combat cattle loss and theft, particularly in the northern parts of the area. Long and difficult negotiations with neighboring communities in the north and east were necessary to determine its precise location. Allegedly, more

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[10] Interview carried out with Vehonga Kahuure, Ozongarangombe, 05.03.2020.

[11] Interview with Ngeriuo Kamuingona in Ozongarangombe on the 26.11.2020.

than a hundred heads of cattle went astray before the people finally decided to construct it.[12] Upon completion, the new barrier successfully prevented cattle from straying. However, due to the patchy rainfall in the area, it also impeded the opportunistic use of nearby pastures, such as relocating animals from Ovitatu to Ohamuheke (a settlement located north of the fence) during times of low rainfall in Ovitatu. Therefore, while the fence resolved the problem of theft and unwanted herd movement, it also increased the herds' susceptibility to drought and led to a rise in permanent grazing pressure.

The enclosure around Okomumbonde was constructed parallel to the elaborate structure described earlier. The decision was driven by two pivotal reasons: To prevent animals from surrounding communities from encroaching upon the grassland around the settlement; and to keep Okomumbonde's cattle within the village to avoid any possible loss. Negotiations with individuals from all the surrounding areas preceded the fence's installation, and its location was determined based on mutual agreement. Nevertheless, the fence structure was never fully completed in the southeast to allow mobility for the cattle:

> *"We realized that if we fence off the whole place, in times of drought, the animals will be only inside the fence, and others will not come inside either.* [...] *therefore, we stopped the construction of the fence."*[13]

The fence to the west of Ovitatu was built in the mid-1970s for a different reason. It was built by a wealthy cattle owner from Ombuyovakuru (a settlement 20 km to the northwest) to run a dairy. He obtained permission from the colonial administration to build a fence to better control his dairy cows.[14] By then, it was not exceptional that these enterprises – once strictly controlled by the administration – were now run independently by OvaHerero individuals (Wagner, 1952; Werner, 1998). The location of the fence was agreed upon between the dairy owner and Ovitatu residents. Although the dairy no longer exists today, the fence still stands, and the owner's descendants rent the grazing land within it to residents of neighboring areas during droughts.

Table 1 Rangeland sizes of our three case studies

Community	Size of area (total)	Thereof camps	Net area
Ovitatu (west)	81.173 km^2	12.813 km^2	68.360 km^2
Okomumbonde (center)	98.287 km^2	14.188 km^2	84.099 km^2
Ozongarangombe (east)	202.095 km^2	20.970 km^2	181.125 km^2

Stocking Rates

Border fences and grazing boundaries have defined the size of Ovitatu's, Okomumbonde's and Ozongarangombe's rangelands. Presently, Ovitatu (west) has the smallest area, while Ozongarangombe (east) has the largest (see Table 1). The net areas have remained stable for the past decade as no new camps have been built during this period.

Livestock numbers have been increasing in all three locations due to population growth and breeding, according to local reports. Detailed statistics are unavailable for our case studies, but records for the homeland and constituencies following independence between 1970 and 1999 demonstrate an overall increase (Kakujaha-Matundu, 2003). Besides, people with off-farm employment began receiving better salaries after independence and invested in cattle, several of them becoming 'weekend farmers', paying family members or workers to take care of their animals. In our case studies, we identified six of these farmers. Thanks to the local water-point committees, concrete livestock numbers have been obtainable for the last three to nine years. Although these figures are not entirely precise, they provide an idea of the pressure exerted on each settlement's grazing land in recent years (Table 2).[15]

Considering the carrying capacity of 18 ha/LSU for the broader Okakarara region (Stehn, 2011:24), we can infer that the values estimated for both Ovitatu and Okomumbonde had exceeded the stocking rate several times up until 2019 – when many animals in the region perished due to severe drought (Menestrey Schwieger, 2023). However, this was not the case for Ozongarangombe: its stocking rates were consistently above the limit, except for 2018, the year preceding the drought.

Villagers recognize that fewer livestock would keep rangelands in better condition, but state that developing and enforcing a rule limiting the number of animals owned per household would be impracticable. The question of who should own how much and why would be complicated to resolve fairly. Moreover, some livestock owners perceive such measures as reminiscent of colonial practices of oppression and as an impediment to self-determination and improving their livelihoods.[16] These practices consisted of a graded system of grazing fees (the more animals, the higher

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[12] Interview with Gerson Tjihuiko, Okahitwa, 13.07.2020.

[13] Interview with Gerson Ngetume, Ombooronde, 05.06.2020.

[14] Interview with Philipus Tjiteere, Okahitwa, 23.11.2020.

[15] The local water committees count the animals of all homesteads using the communal borehole to calculate the annual water fees for diesel and repairs to be paid per head of livestock per household. Incomplete data (e.g. small livestock in Ovitatu) and gaps in specific years (e.g. Okomumbonde) are attributed to unavailable records.

[16] Interview with Gerson Ngetume, 05.06.2020, Okahitwa.

Table 2 Numbers of livestock and stocking rates in the three pastoral social-ecological systems studied in this paper

Settlement	No. of cattle	No. of small stock (goats and sheep)	Stocking rate
Ovitatu (west)	436 (Jun. 2020)	477 (January 2020)	19.37 ha/LSU
-	266 (Aug. 2019)	- not available -	36.71 ha/LSU
-	795 (Jun. 2018)	- not available -	12.28 ha/LSU*
-	801 (May 2017)	- not available -	12.19 ha/LSU*
Okomumbonde (center)	256 (Jan. 2020)	168 (January 2020)	42.9 ha/LSU
-	470 (Jan. 2019)	356 (Jan. 2019)	23.06 ha/LSU
-	793 (Sept. 2014)	663 (Feb. 2014)	13.53 ha/LSU*
-	1066 (Jan. 2013)	889 (Jun. 2013)	10.07 ha/LSU*
-	1045 (Aug. 2012)	1150 (Apr. 2012)	9.93 ha/LSU*
-	853 (Jul. 2011)	1331 (Oct. 2011)	11.51 ha/LSU*
Ozongarangombe (east)	778 (Aug. 2020)	449 (August 2020)	30.72 ha/LSU
-	1331 (Aug. 2019)	399 (Aug. 2019)	18.64 ha/LSU
-	1357 (Jul. 2018)	577 (Jul. 2018)	17.97 ha/LSU*
-	935 (Sept. 2016)	406 (Sept. 2016)	26.05 ha/LSU
-	503 (Sept. 2015)	317 (Sept. 2015)	47.27 ha/LSU
-	782 (Mar. 2014)	417 (Mar. 2014)	30.74 ha/LSU

[a] Factor 0.7 and 0.1 for cattle and small stock units, respectively

* Values exceeding the carrying capacity of 18 ha/LSU

the tax) and a maximum limit on livestock ownership (max. 100 head of cattle and 300 small stock) per family (Wagner, 1952). Instead, since the early 2000s, the residents of all three pastoral communities have agreed on two basic rules: (i) no newcomers would be allowed to settle permanently in their villages, and (ii) no new households (including camps) would be allowed to be built behind existing ones. The rules were established based on the perception that the settlements had reached their maximum capacity, and over-exploitation had to be prevented.

Exercising Resource Boundaries

Apart from differences in rangeland sizes and stocking rates, we found clear differences in how the rangeland boundaries are managed and enforced across the three settlements. For example, we discovered that cattle from Okahitwa frequently entered Ovitatu's designated grazing areas, exacerbating the already high pressure on local rangelands. Due to the close proximity of Okahitwa and Ovitatu, and because grasses on the Omatako River's hard clay soils deplete quickly after rainfall, unattended animals from Okahitwa often wander into Ovitatu's area in search of food, typically reaching the communal water point. Ovitatu's residents view these 'spill overs' a long-standing issue that has worsened in recent years.[17] Preventing these animals from crossing over is often problematic, as the boundary between Okahitwa and Ovitatu spans at least 10.5 kilometers, and animals often enter at night. Chasing them out has proven ineffective, and herding them back is labour-intensive. Although a fence between the two settlements has been discussed, it was never constructed because some Ovitatu residents opposed the project, arguing that such a barrier would complicate the movement of animals outside the area during droughts.

Conversely, Okomumbonde's fence effectively prevents cattle from other places from entering their grazing areas, including animals from Okahitwa and Orunahi when they use the cattle post north of the settlement (Fig. 4.). Only some cattle from Ozongarangombe occasionally enter Okomumbonde's area from the east, where there is no fence, during the dry seasons, but this is considered a minor issue. To prevent cattle and their owners from using the cattle post when this area should not be used, Okomumbonde's water-point committee removed the borehole's diesel pump.

The same is true in Ozongarangombe. An eight-member 'cattle-post committee' (*okomiti yohambo*) guarantees that livestock owners do not use or stay in their cattle post without authorization. If the area should not be used, they also take away the pump. When there are violations, the community is alerted, and measures are implemented. We could record cases of visitors who were expelled from the area after using the cattle post unlawfully and/or not paying the water fees for the diesel pump. Also, herders entering Ozongarangombe's grazing lands to the east via the main road have been stopped on several occasions; one of these encounters almost escalated into physical violence and the police intervened. To protect the east boundary in the long-term, the Ozongarangombe community mobilized the regional government to install a borehole in the area, which was finally done in 2013. Since then, four households have settled near the borehole and residents monitor the boundary of the settlements' grazing territory.

Discussion and Conclusion

With our ecological assessment of rangeland state, we found that overall rangeland condition in all three pastoral

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[17] Interview with Gottlieb Murangi, Ovitatu, 09.10.2019.

settlements was poor compared to a desired condition, characterized by a dominance of palatable perennial grasses (van Oudtshoorn, 2012). In all three cases, perennial grass populations were small, and grazing-tolerant species with low grazing value, such as *E. lehmanniana*, *E. trichophora*, and *A. congesta*, were found to dominate both aboveground and in the soil seed bank. This finding supports earlier studies indicating that undesirable grass species, such as unpalatable perennial grasses, annual grasses and forbs dominate communal areas in eastern and southern Africa as a result of overgrazing (Tessema et al., 2012; Solomon et al., 2006). Conversely, ethnographic accounts from the region also indicate that key perennial palatable grasses for grazing are becoming rare, some of them already since the 1980s (Menestrey Schwieger, 2022). The comparatively poor rangeland condition in our case studies is likely due to a combination of multiple human interventions with detrimental effects on rangeland state; similar interventions have been found in other communal rangelands in sub-Saharan Africa (Bollig & Schulte, 1999; Kiage, 2013; Linstädter et al., 2014). These include a long history of intensive livestock grazing, recent population growth, a reduction of rangeland areas and mobility through the introduction of camps and border fences, and limited opportunities for rangeland recovery due to the lack (or abandonment) of rotational grazing or other forms of sustainable rangeland management, such as deferred grazing, which involves delaying grazing during critical plant growth periods (Teague & Barnes, 2017). This strategy is known to have been used by OvaHimba pastoralists (Sander et al., 1998; Müller et al., 2007), an ethnical group in Namibia which is closely related to the OvaHerero pastoralists in our study area (Bollig & Gewald, 2009).

Although we found clear signs of desertification processes in all three pastoral settlements, such as the near depletion of palatable perennial grasses, the fact that some perennial grasses were still present both aboveground and in the soil seed bank indicates that a desertification tipping point may not have been crossed yet. In other words, the rangelands have not yet shifted to a state of bare soil, where the soil seed bank is fully depleted (Bestelmeyer et al., 2013). However, we noted that perennial grass species with low grazing value showed comparatively higher population densities in transect sections with more intense grazing pressure, especially closer to the water points. This can be explained by the concentration of households and their livestock around the communal boreholes (James et al., 1999; Todd, 2006). *E. lehmanniana*, for instance, tends to establish itself in areas near water points, where it is able to replace grazing-susceptible grasses due to its high resilience to frequent grazing (Cable, 1971; Williamson et al., 1986; Angell & McClaran, 2001). Likewise, the increasing densities of *A. congesta* towards the water point in Okomumbonde implies a desertification processes, as this fast-growing grass species usually thrives in areas with a long history of overgrazing (du Toit et al., 2018; Müller, 2007).

Despite the prevailing poor rangeland condition across all pastoral settlements, we also identified a clear trend, reflected both in the population densities of perennial grasses and in the composition of soil seed banks: The level of rangeland desertification decreased from west to east. Accordingly, the settlement Ozongarangombe – located most to the east – exhibited a comparatively high diversity of perennial grass species and a low density of annual grass species in the soil seed bank, implying a better rangeland condition (Rothauge, 2007). In contrast, the westernmost settlement (Ovitatu) displayed the most advanced state of desertification. This was illustrated by a complete absence of grazing-sensitive perennial grass species both aboveground and in the soil seed bank, as well as by a low richness of perennial grass species in the soil seed bank and a high abundance of annual grass seeds, indicating degradation (O’Connor, 1995; Joubert et al., 2008; Tessema et al., 2012; Dreber et al., 2011; Kassahun et al., 2008).

These differences can be linked to divergent historical processes among the three pastoral settlements. Notably, this is not the age of the initial permanent boreholes, as found in other pastoral areas (Perkins & Thomas, 1993). All three settlement boreholes were drilled almost simultaneously (from 1949 to 1955). Specifically, the eastern settlement (Ozongarangombe) with its better grazing conditions seems to have benefited from two particular historical events: The installation of an additional borehole after the 1981/82 drought, and the construction of a large fence to prevent cattle theft. The first event led to the creation of a cattle post north of the settlement that allowed for the seasonal movement of cattle, giving rangelands close to the settlement time to recover during the time window at the beginning of the rainy season when perennial grasses are most sensitive to overgrazing (Müller et al., 2007; O’Connor & Everson, 1998). The second event led to the expansion of the surrounding rangelands as the fence was constructed using the cattle post borehole as a reference, thus improving the ability of herdsmen to implement a spatio-temporal adaptive movement of their herds (Jakoby et al., 2015; Martin et al., 2014). The larger rangeland area probably also allowed for (implicit) rest periods in years with sufficient rainfall, which are known to be crucial for the regeneration of perennial grass populations (Müller et al., 2007). Both events together have created a specific infrastructural set-up of this pastoral settlement, and helped to reduce the negative synergistic effect of grazing pressure and aridity on perennial grass populations (Oñatibia et al., 2020). In contrast, the western settlement (Ovitatu) with its worst rangeland condition has the smallest grazing area and no cattle post.

Intermediate conditions (i.e. a slightly larger grazing area and a cattle post nearby) characterize the central settlement (Okomumbonde) with its intermediate rangeland state.

In addition, it is important to note that while all three communities have implemented measures through social institutions to limit livestock numbers in their settlements since the 2000s, our findings suggest that the rules were introduced when stocking rates were higher in Ovitatu (west) and Okomumbonde (center) than in Ozongarangombe (east). These measures contributed to limiting livestock numbers in the eastern settlement earlier than in the other two. Furthermore, the impoverished rangeland conditions in Ovitatu could also be attributed to the influx of cattle from nearby Okahitwa, which the residents have been unable to prevent. On the contrary, Okomumbonde has been able to mitigate this problem through the installation of a perimeter fence. In Ozongarangombe (east), the northern fence and community actions have successfully controlled the use and access to local grasslands.

Against this background, it can be deduced that the creation and effective social regulation of environmental conditions and key physical infrastructures (i.e. cattle post and extensive pastures) – as is the case in Ozongarangombe (east) – are essential prerequisites for keeping desertification processes at bay. While this finding may not be surprising from an ecological perspective, since livestock mobility, along with regulations that prevent 'open access' situations, are crucial to ensuring rangeland sustainability (e.g., McCabe, 1990; Niamir-Fuller & Turner, 1999), it is remarkable that local communities have been able to create these conditions despite the multiple influences of colonialism (e.g., forced resettlement, territorial encapsulation, economic oppression) and the difficulties associated with farming in a communal land tenure system (Menestrey Schwieger & Mbidzo, 2020).

In this context, it is important to emphasize that the main purpose of the reserves and later the homelands was not to help communities become successful pastoralists, but to keep them impoverished and ensure the "legislative obliteration of the black pastoral economy" (Silvester, 1998, p. 98), while at the same time providing labor for the farms in the freehold areas (Werner, 1998). By extension, pre-colonial rangeland management practices, which were characterized by the ability to maintain a high degree of mobility, were severely affected by colonial land use policies and are very difficult to apply today. Consequently, the lasting effects of colonial interventions, particularly in terms of land distribution and resettlement, and mobility restrictions can be seen as the primary cause of the region's current land degradation problems, which are very difficult to address (for a more detailed discussion on the impacts of colonialism on Herero pastoralism in the region, see Menestrey Schwieger & Mbidzo, 2020).

With that said, we argue that desertification in pastoral systems of sub-Saharan Africa is not necessarily a 'tragedy of the commons', but rather a problem intrinsically linked to past colonial policies and the development and implementation of social institutions that effectively promote collective action in colonial and post-colonial contexts (Darkoh, 1989; Kiage, 2013).

The question is whether other communities in the region can adopt and use the principles that we identified in our research, which are not exhaustive or conclusive, within the current socio-ecological framework in which they live and farm, to prevent further loss of rangeland productivity. Given the current conditions in Okakarara constituency, there are challenges to consider. Firstly, the feasibility of introducing more cattle posts with additional boreholes in this densely populated semi-arid region is uncertain, ecologically and geographically. In certain cases, such as Ovitatu (west), there may not be adequate space nearby for another borehole to be introduced. Thus, careful planning and community consultations are crucial for avoiding further rangeland over-utilization. Besides, if new cattle posts are created, local communities should be supported in keeping these areas for seasonal use only since this can be socially costly, even if these areas are fenced (e.g., Ozongarangombe, east). Furthermore, fencing as such involves difficult negotiations between communities and could not always be feasible, as in the case of Ovitatu (West).

To provide context, out of 129 settlements in the Okakarara constituency, only 8 currently have their own cattle post according to records from the regional Office of Rural Water Supply. At least one-third of these 129 were once cattle posts that became permanently settled over time. The reasons for this could be attributed to colonial re-settlement measures, population pressure, and local residents being unable to keep the places vacant.[18] Therefore, besides supporting local institutions, structural changes would be needed too. Initiatives such as the Programme for Communal Land Development and ongoing land reform in Namibia are already important steps in the right direction. Such programs effectively promote and strengthen infrastructural development, access to land, and tenure security, including group rights. Likewise, climate change predictions and their potential social-ecological impacts, need to be taken into consideration. In any case, local communities should not be left alone to deal with the problems of desertification in their areas considering its links to past state interventions and colonial practices. The solution to these problems may also require a multi-dimensional approach, including

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addressing some of the structural causes mentioned above (e.g., inequitable land distribution) by expanding communal areas through land reform and making pastures accessible through new boreholes, along with programs to support and implement feasible and sustainable rangeland restoration measures that fit current socio-economic conditions and capabilities. Otherwise, socio-environmental tipping points may be difficult to avoid in the future if no action is taken.

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Author Contributions D.A.M.S., A.L., K.T., W.C.N., and M.Bollig were responsible for the study's conception and design. D.A.M.S., F.M.C., N.H., M.Bilton, and A.L. performed material preparation, data collection, and analysis. D.A.M.S., F.M.C., and N.H. authored the initial manuscript. The remaining authors provided feedback on subsequent versions of the text. All authors read and approved the final manuscript.

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Declarations

Competing Interests The authors declare no competing interests.

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