

Soil and vegetation changes under livestock production in the northern Kalahari, Namibia

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Abstract

The spatial scale and intensity of rangeland degradation under continuous grazing around water points in arid and semi-arid environments depend on the population density of livestock, the duration of water point use and the distance livestock travel from water points. We visually established a broadscale pattern of vegetation zonation along a grazing gradient on 28 settlements in the Kalahari to place five sampling points from artificial water points. We selected four settlements for a more intense study of vegetation and soil changes under livestock production. We tested the effect of livestock on species diversity of herbaceous and woody plants, structural parameters of woody plants, and soil moisture and nutrient contents. We found that the marked effect of livestock on vegetation was confined to the vicinity of the artificial water points. The diversity of herbaceous and woody species decreased under high livestock pressure, but the abundance of herbaceous species present near water points increased significantly. Soil parameters were not influenced significantly by livestock activities along the grazing gradient, however the upper soil layer had significantly higher organic carbon and total nitrogen, but lower soil moisture content. It appeared that marked livestock impact around artificial water points in the Kalahari was confined to the immediate areas of the water points. Alternatively, livestock impact may have resulted in relatively uniform vegetation and soil changes beyond the 200 m distance from the water points.

Key Words: arid environments, bush encroachment, dryland pastoralism, land degradation, soil hydrochemistry, range management.

Introduction

Arid and semi-arid environments are inherently variable, and largely driven by rainfall events (Ellis & Swift 1988, Ward *et al.* 1998, Illius & O'Connor 1999). To cope with this natural variability, pastoralists have been able to: 1) migrate to ephemeral water sources where forage

could be utilised during the wet seasons, while resting forage resources in areas with perennial water sources; 2) keep a variety of livestock to utilise both browse and grazing resources; and 3) utilise a wide land area to minimise localised negative impacts on resources (Ellis & Swift 1988). Much of Namibia is semi-arid to extremely arid (Van der Merwe 1983, Aharoni & Ward 1997), thus Namibian pastoralists have traditionally used the abovementioned flexible grazing system described by Ellis and Swift (1988) for the arid Turkana region of Kenya. However, this system of range and livestock management has changed in Namibia because current land tenure systems have confined pastoralists to specified land areas, and the provision of artificial permanent water sources has created permanent settlements. Elsewhere in arid and semi-arid Sub-Saharan Africa, the creation of permanent pastoral settlements, the high proportion of domestic grazers (cattle) to browsers (goats) and the decline of wild ungulate browsers in agricultural lands have tilted the balance between woody species and grasses into woody plant-dominated rangelands (Coppock 1993, Moleele 1998, Moleele *et al.* 2002). In addition, livestock pressure in the vicinity of water points reduces species diversity, increases the prevalence of invasive herbaceous species, reduces the abundance of palatable grass species, but favours unpalatable species (Tolsma *et al.* 1987, Strohbach 1992). The impacts on soils are multiple, but depend mainly on the soil type and the topography of the affected landscape (Behnke & Scoones 1993, Stafford-Smith & Pickup 1993). Excessive trampling and overgrazing can lead to soil erosion, compaction and reduced moisture infiltration on slopes (De Klerk 2004). However, sandy Kalahari soils are less affected (Dougill *et al.* 1999). Nonetheless, irrespective of soil type, the concentration of livestock around water points leads to increased nutrient accumulation in the soil as a result of urine and dung deposition (Tolsma *et al.* 1987).

A distinctive pattern of vegetation and soil changes develops around artificial water points under continuous grazing (Lange 1969, Jeltsch *et al.* 1997), of which the extent is determined by the age of the water point, livestock densities and the capacity of animals to forage away from the water points (Andrew 1988). Lange (1969) termed this unique ecological system centred around artificial permanent water points, 'piosphere' (derived from a Greek word: 'pios', meaning 'to drink'). The area closest to the water points experience severe pressures such that only few herbaceous plants can survive. This area is referred as the "sacrifice" zone (Graetz & Ludwig 1978). The sacrifice zone is characterised by extensive bare ground, particularly during the dry season, and is dominated by annual invasive herbs (Thrash 1998, Brits *et al.* 2002) that are mostly unpalatable to livestock (James *et al.* 1999, Ward 2004). Beyond the sacrifice area, is the second zone where the impact of large herbivores tapers off, until an upper asymptote is approximated (Thrash *et al.* 1993). The second zone is characterised by a rapidly-increasing total woody biomass, while the third has a relatively constant woody biomass (Thrash 1998). Thus, the impact of large herbivores on vegetation and soil parameters forms a sigmoid relationship with distance from water points (Thrash 1998, Britz *et al.* 2000). Thrash (1998) used a 2000 m transect to arrive at this sigmoid curve. Tolsma *et al.* (1987) reported thickets of *Acacia* spp. and *Dichrostachys cinerea* from 800 - 1 500 m of water points in a semi-arid district of eastern Botswana, and that these thickets were transitional to

a tree savannah at 3 000 m from the water points. Cattle in our study area were occasionally observed at about 7 000 m from water points (personal observations). Pickup (1994), using a model based on the Australian semi-arid rangelands, demonstrated that the effect of cattle on vegetation might extend beyond 7 000 m from water points.

The objective of this study was to investigate the extent of vegetation and soil changes in relatively homogenous flat landscapes of the northern Kalahari communal rangelands dominated by *Terminalia sericea*. We specifically tested the effects of livestock on species diversity, the structural parameters of woody plants, soil moisture and nutrients.

Materials and Methods

Site selection

We drove through 28 pastoral settlements and observed the pattern of vegetation distribution and abundance with increasing distance from artificial water points. We combined our observation with 30-year-old and current aerial photographs (1:60 000) to select four settlements with homogenous landscapes in all directions from the water points. All settlements located on calcrete outcrops and those dominated by *Acacia* species were excluded because of their limited distribution, and unusual vegetation composition to most of the northern Kalahari (Makhabu *et al.* 2002). All selected settlements had a flat landscape and were situated away from low-lying areas. The selection criteria met the requirement of our assumption that the impact of livestock on vegetation and soil is radial in relation to the locations of artificial water points in homogenous flat landscapes and that the impact is most intense at water points. This assumption is consistent with that adopted in related studies in arid and semi-arid environments (Lange 1969, Thrash 1998, Ward *et al.* 1998, Makhabu *et al.* 2002). In this study the distance between the selected and nearest neighbouring settlements ranged between 8 000 and 9 000 m. This distance was selected to minimize overlaps in livestock home ranges between the settlements and to allow for a maximum possible distance between settlements such that the full extent of livestock impacts could be determined around the water points. The age of the selected settlements ranged from 32-51 y, and with cattle production as the main form of land use (Table 1). The study sites were located between the Epukiro Omuramba (omuramba means dry drainage line) and Eiseb Omuramba in the Otjinene communal area (S21°E19°) (see Figure 1).

Table 1. Location of and date that water points were drilled and livestock numbers at the selected settlements. Figures of livestock numbers were obtained from village water point committees.

Settlement	Geographical coordinates	Borehole drilled (year)	Cattle no. (2002)	Goats no. (2002)	Sheep no. (2002)
Oukango	S21°16.509'; E19°04.904	1950	561	237	73
Otjirarua	S21°12.714'; E19°13.871'	(±1960)	916	356	135
Okatjana	S21°02.402'; E19°04.958'	1970	480	202	31
Ombujonjama	S21°00.421'; E19°08.987'	1970	734	157	48

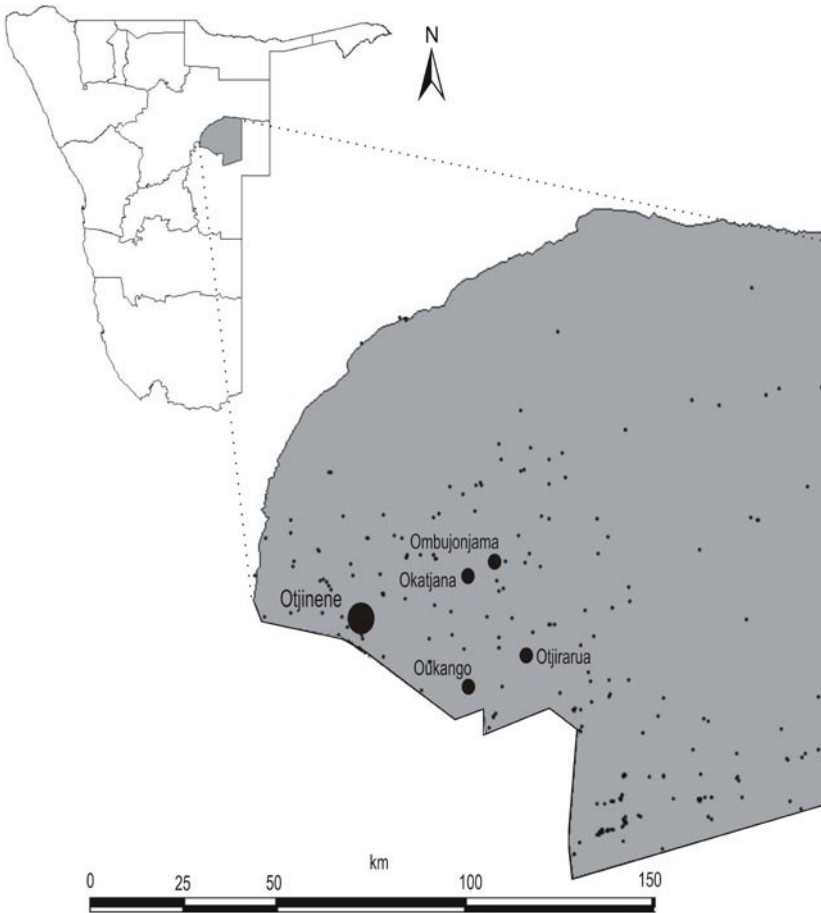


Figure 1: Otjinene constituency in the Omaheke region, indicating the Otjinene settlement, the four study sites and numerous artificial water points scattered in the constituency. The constituency falls within the northern Kalahari vegetation type.

Site Description

The long-term mean rainfall in the study area ranges from 250 - 400 mm per annum (Dealie *et al.* 1993). The coefficient of variation of the annual rainfall varies between 30 - 40% of the long-term mean rainfall (Mendelsohn *et al.* 2002). The general area consists of a large undulating landscape covered with sand dunes traversed by low-lying inter-dunal valleys (Köhler 1959). The sandy soils have low phosphorus and nitrogen contents (Mendelsohn *et al.* 2002). The vegetation of the area is classified as northern Kalahari bush savannah (Mendelsohn *et al.* 2002) and is characterised by dense stands of edible bush covering the dunes, of which *Croton grattissimus*, *Combretum apiculatum*, *Terminalia sericea* and *Philenoptera nelsii*, and shrubs such as *Bauhinia petersiana* and *Grewia* species are the most common (Rawlinson 1994). *Terminalia sericea* is regarded as the main bush encroaching species in the study area (De Klerk 2004).

Oukango and Otjirarua were the oldest of the four settlements (Table 1, Figure 1). According to Mr. Naftalie Mukungu, one of the first permanent residents of Oukango, the settlement water point was sunk at the end of 1951. The borehole at Otjirarua was drilled in 1960 (Mr. Alfeus Kauta, pers. comm. 2002). The water points at Okatjana and Ombujonjama were both drilled at the end of 1969. Prior to this date, only a few Khoi San families roamed the area (settlement elder, Chief Ben Hembapu, pers. comm. 2002). Free ranging cattle production was the main form of land use in all the settlements.

Data Collection

Observation of vegetation away from water points

A consistent vegetation zonation away from the artificial water points was observed during field reconnaissance and site selection exercise, across 28 settlements in June of 2001. We subdivided the observed vegetation pattern into five zones, on the basis of the abundance of *Sida cordifolia* (Malvaceae) which is a local invasive herb on degraded rangelands, clarity of browse line, shrub and bush density, and the proportion of tree and grass abundance (Table 2). Plant community structure differed across the distances from the water points. Nothing grew within about 30 m radius around the water points. Areas closest to the water points, but beyond 30 m, had the most sparse vegetation cover particularly woody plants, and the dominant tree *Terminalia sericea* rarely occurred in this zone. This zone (Zone I) extended to about 850 m from the water points. It was dominated by *Sida cordifolia*, and few scattered tall trees (mainly *Acacia erioloba* and *Combretum collium* subsp. *gazenze*) with a clear browse line. Homesteads and livestock pens were located in this zone - ranging from 300 - 600 m from the water points. A disappearing browse line and declining herbaceous-layer, but increasing shrub-layer characterized Zone II. This zone stretched from approximately 850 - 2 000 m from the water points. Beyond Zone II, the woody vegetation became denser and dominated by woody species such as *Terminalia sericea*, *Grewia flava*, *Bauhinia petersiana*, *Acacia fleckii* and *Acacia mellifera*. This we classified as Zone III, which extended approximately

3 000 m from the water points. This appeared to be the bush proliferation zone. Zone IV, 3 000 - 4 000 m was more of a transitional zone showing varying features of Zone III at some sites, and also becoming more of a savannah vegetation type (sparse trees interspersed with herbage) at other sites. Zone V, from 4 000-5 000 m from water points, was more open with shrubs, trees and a grassy layer. Overgrazing by livestock made identification of the grass component difficult at the time of the field reconnaissance.

Table 2. Observed vegetation zonation along a livestock pressure gradient. Zone I experienced the greatest pressure at the water point, while Zone V suffered the least pressure on soils and vegetation. This pattern is based on field observations of 28 settlements in the northern Kalahari.

Zone	I	II	III	IV	V
Distance	30 - 850 m from water points (WPs).	± 850 - 2 000 m from WPs.	± 2 000 - 3 000 m from WPs.	± 3 000 - 4 000 m from WPs.	+ 4000-5000 m from WPs.
Vegetation	Mainly invasive herbs – i.e. <i>Sida cordifolia</i> and <i>Acanthospermum hispidum</i> ; few big trees: <i>A. erioloba</i> , <i>Combretum collium</i> subsp. <i>gazenze</i> , and shrubby <i>A. hebaclada</i> .	Increasing shrub layer; greater tree abundance and lesser invasive herbs compared to Zone I.	Dense woody plants dominated by <i>T. sericea</i> ; <i>A. flecki</i> , <i>A. mellifera</i> , <i>G. flava</i> and <i>Bauhinia petersiana</i> seemed to occur frequently.	This seem to be a transitional zone between zone III and V, at some sites it was becoming less dense, while at others is was more of a savannah dominated by <i>T. sericea</i> and tall perennial grass cover.	Woody species interspersed with grass layer.

Other observations	Clear browse line. <i>Combretum collium subsp. gizenze</i> was more abundant than <i>A. erioloba</i> .	Diminishing browse line. <i>Terminalia sericea</i> started to be more abundant in this zone.	Bush proliferation zone.	It is possible that the age of the water points and cattle density may play a defining role in this zone. (older sites = more dense woody plants in this zone, meaning expansion of piosphere on older WPs).	This zone could not clearly be established as only few villages had inter-village distance exceeding 10 km.
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Quantitative analysis of vegetation and soil parameters along a grazing gradient

We sampled woody vegetation, herbs and soil parameters at 200, 600, 1 200, 2 500 and 4 000 m along two random transects from the artificial water points. These sampling distances were selected as such to match and test the observed vegetation zonation. No sampling was done in the sacrificial zone.

Woody Vegetation Sampling

We recorded woody species richness, basal circumference, height and canopy diameter in 50 m x 10 m plots at each sampling point along the two grazing gradients from water points. Canopy diameters were measured in two perpendicular directions, that is the longest and the shortest diameters of the canopy. Average canopy diameter was then obtained for each tree measured and then the area of the canopy cover was calculated, assuming a circular spread. Basal area was measured above the buttress swelling, and in the case of multi-stemmed trees, where the stems are separated at the ground level; each was measured separately, but summed to give the total stem basal for the tree. In the majority of cases, plant height was measured directly with a tape, but in a limited number of cases where trees were too high, a clinometer was used to calculate tree height (Brower and Zar 1984). Only one observer was consistently used throughout this exercise. The density of woody species was estimated by the *T*-square method (Greenwood 1996). The *T*-square sampling method is based on the point-to-object and

nearest neighbour methods. Twenty (20) random points at each sampling distance were sampled. These random points were more than the 10 recommended by Greenwood (1996).

Herbaceous-layer Sampling

Herbaceous species were recorded in 24 restricted random quadrats (1 m²) along a 50 m tape at 0, 10, 20, 30, 40 and 50 m intervals at each sampling distance away from water points (Figure 2). Species abundance by counts was recorded. Sampling was carried out at the beginning of April 2002 during the growing season when herbaceous species were easily identifiable. Species that could not be identified in the field were identified at the National Botanical Research Institute in Windhoek.

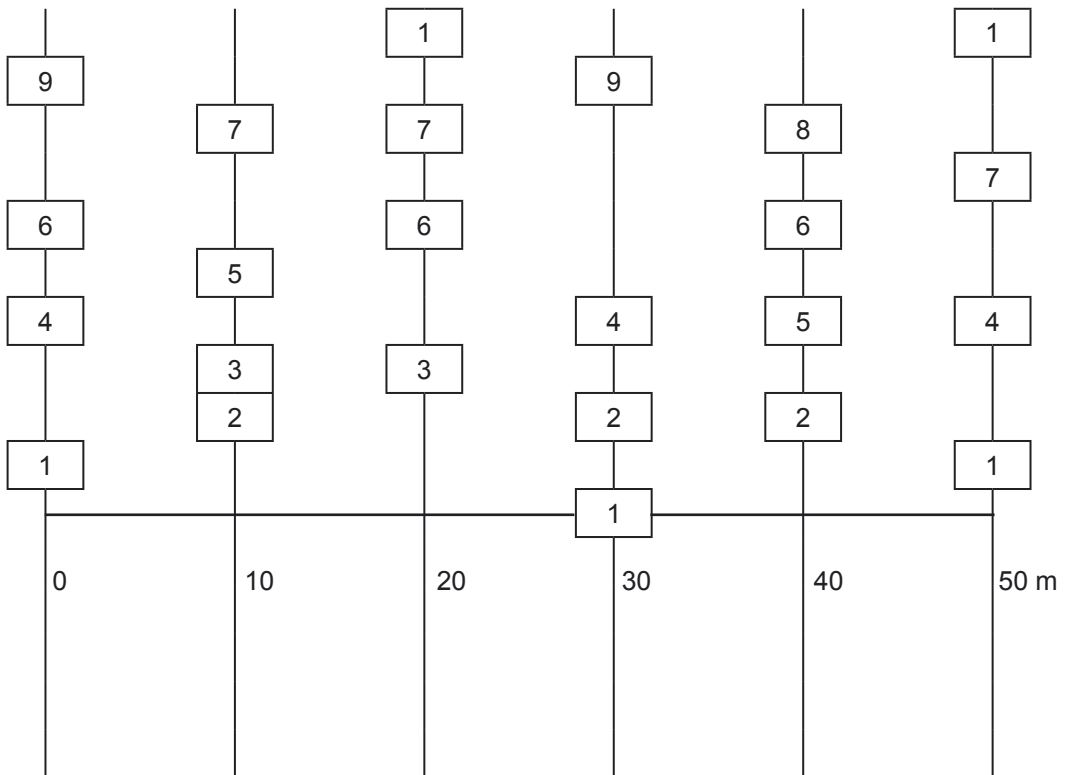


Figure 2: General layout of 24 restricted random sampling quadrats, for herbaceous species abundance, placed at 10 m interval along a 50 m tape. At each interval four samples were collected at any random distance from 1 to 10 m perpendicular from the tape.

Soil Parameters

The top loose-sandy soil containing litter was removed and samples were taken from three depths: 10-20, 50-60 and 90-100 cm during May 2002. A total of 120 samples were collected, air-dried and delivered to the Agricultural Laboratories of the Ministry of Agriculture, Water and Forestry (Government of Namibia) in Windhoek. The samples were further dried at 65°C for 48 hours and passed through 2 mm sieve. Available phosphorus was extracted following the Olsen method— measured with a UV/VIS spectrophotometer (Olsen *et al.* 1954), organic carbon by the Walkley-Black method (Walkley 1947) and total nitrogen by the Kjeldahl digestion method (Cohen 1910).

Data Analyses

Vegetation community analyses

We used detrended correspondence analysis (DECORANA) for the analysis of differences in woody and herbaceous plant communities, using total counts of each species encountered at the 40 sampling localities along a decreasing livestock pressure gradient from the water points. DECORANA groups vegetation into one or more composite dimensions (axes) on the basis of floristic similarities that generally correspond to major influencing factors in the environment (Ward & Olsvig-Whittaker 1993). It is an improved multivariate eigenvector technique based on reciprocal averaging (also called correspondence analyses) but correcting its main faults (Hill & Gauch 1980). The ordination was performed on the 40 sampling localities and 31 woody or 65 herbaceous species. The data were log transformed and rare species were downweighted. Pearson product-moment correlations were used to determine correlations between Shannon-species diversity index values and eigenvalues of species abundance for axis 1 (DC1) and axis 2 (DC2) across the distance from water points.

Furthermore, a two-factorial mixed model ANOVA was performed to compare differences in woody plant species diversity, basal area, density, height and canopy area, using distance from water points as a fixed factor and sites as a random factor. Basal area, canopy area and height data were log-transformed. A three-factorial mixed model ANOVA was used to compare soil parameters (organic carbon, total nitrogen, available phosphorus and soil moisture), using soil depth and distance from water points as fixed factors and site as a random factor. Best-fit arcsine and square-root transformation equations were fitted to organic carbon and total nitrogen data respectively to normalize the data. Soil moisture was also arcsine-transformed, while available phosphorus remained untransformed. Degrees of freedom and mean square errors were computed using Satterthwaite method. Transects from water points were treated as replicates. A Scheffe *post hoc* test ($\alpha = 0.05$) was carried out to determine where significant differences occurred when the treatment effects were significant in ANOVA; means were listed with standard errors in tables, but 95% confidence limits were plotted in Figure 3.

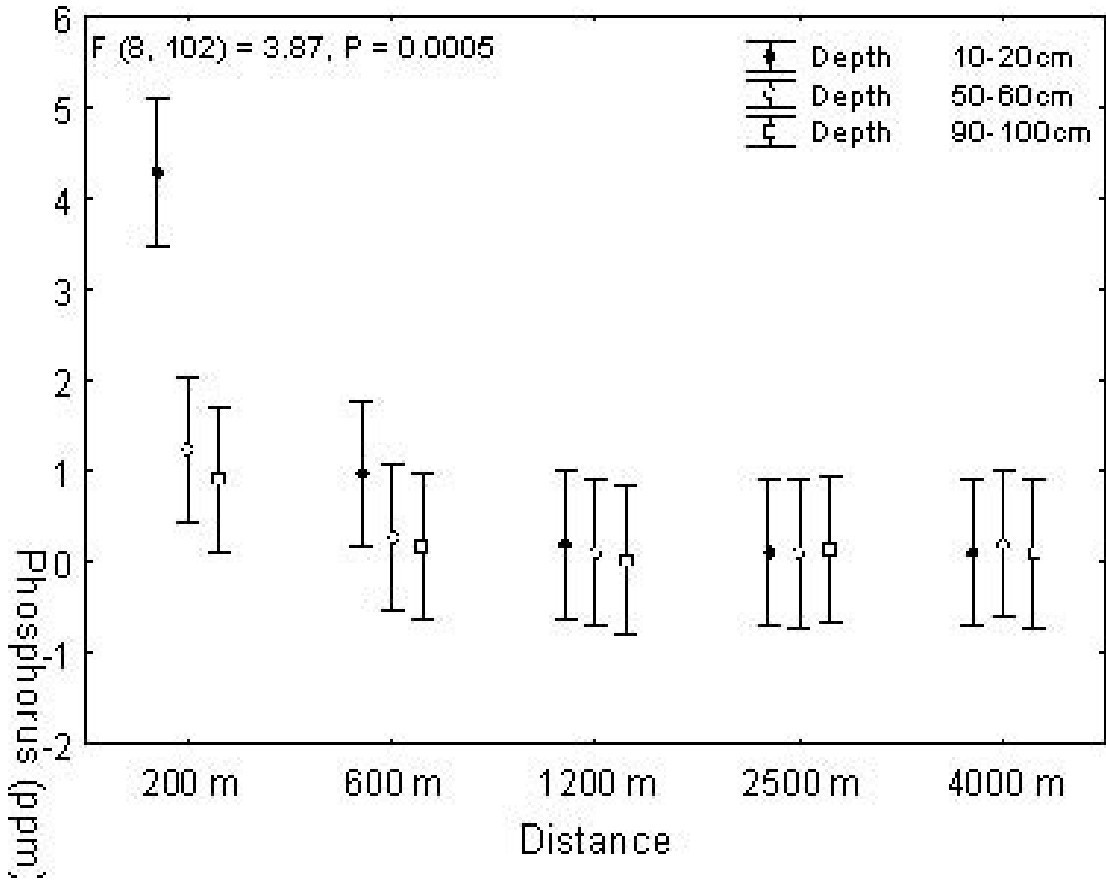


Figure 3. Interaction effect of distance and soil depth on available phosphorus content. Error bars denote 95 % confidence limits.

Results

Quantitative analysis of vegetation structure at distances from water points

Species composition

Distance from water points affected woody species diversity significantly ($F = 13.46, P < 0.001, d.f. = 4, 12$). Scheffé *post hoc* test showed that mean woody species diversity was significantly lower at 200 m ($P < 0.05$), compared to further away from the water points (Table 3). There were no significant differences among woody species diversity further away from water points ($P > 0.05$). The pattern of herbaceous species diversity resembled that of woody plants ($F = 7.61, P < 0.05, d.f. = 4, 12$). Mean herbaceous species diversity was significantly lower at 200 m than further away from the water points ($P < 0.05$, Table 3). No significant differences existed in herbaceous species diversity at the remaining distance from water points (Table 3).

Table 3. Mean±SE woody and herbaceous species diversity at distances from water points. The Shannon-Wiener index was used to express species diversity. Different letters indicate significant differences in mean values at $P < 0.05$.

Distance (m)	Woody species diversity (H')	Herbaceous species diversity (H')	Woody plants DC 1 values	Herbaceous plants DC 1 values
200	0.219 ± 0.0805 a	0.448 ± 0.4844 a	0.375 ± 0.4678 a	4.079 ± 0.3643 a
600	0.726 ± 0.1022 b	0.758 ± 0.0576 b	2.073 ± 0.5723 b	2.678 ± 0.1443 b
1200	0.813 ± 0.0496 b	0.858 ± 0.0731 b	2.814 ± 0.2849 bc	0.824 ± 0.5013 c
2500	0.723 ± 0.0428 b	0.839 ± 0.0596 b	3.441 ± 0.2722 bc	0.244 ± 0.2624 c
4000	0.731 ± 0.0426 b	0.785 ± 0.0346 b	3.644 ± 0.3357 c	0.655 ± 0.1729 c

We used DECORANA to compare woody vegetation parameters sampled at 40 localities from water points. The percentage of variance in woody plant species abundance explained by the first two axes in the DECORANA was low (DC1 = 20.6%, DC2 = 10.5%). There was a positive significant correlation between DC1 values of species abundance and woody species diversity along the livestock pressure gradient ($r = 0.42$, $P = 0.0068$, $n = 40$), the correlation between DC2 values and woody species diversity was non-significant ($r = 0.05$, $P = 0.7646$, $n = 40$). We found a highly significant difference in DC1 values between sampling distances from the water points ($F = 17.65$, $P < 0.0001$, d.f. = 4, 12). DC1 values at 200 were significantly lower than at any other distance from the water points, but generally increased with distance from the water points ($P < 0.05$, Table 3). There were no significant differences in DC2 values ($F = 0.53$, $P = 0.7160$, d.f. = 4, 12). These results indicate that the most important axis in the ordination of woody species was the livestock pressure gradient around the artificial water points.

The percentage of variance in herbaceous plant species abundance explained by the first two axes in the DECORANA was low (DC1 = 21.3%, DC2 = 7.5%). There was a negative significant correlation between DC1 values and herbaceous species diversity along the grazing gradient ($r = -0.66$, $P < 0.0001$, $n = 40$), however, the correlation between DC2 values and herbaceous species diversity was non-significant ($r = 0.002$, $P = 0.9882$, $n = 40$). We found highly significant differences in DC1 values between sampling distances from the water points ($F = 35.06$, $P < 0.0001$, d.f. = 4, 12). DC1 values at 200 and 600 m were significantly higher than those at the remaining distances ($P < 0.05$, Table 3), while values at 200 m were significantly higher than at 600 m. There was no significant difference in DC2 values between sampling points from water points ($F = 0.60$, $P = 0.6666$, d.f. = 4, 12). Again, these results indicate that the most important axis in the ordination of herbs (DC1) is primarily a grazing intensity axis, and that herbaceous abundance increased with declining diversity towards the water points. The secondary and tertiary axes indicated significant differences that existed in herbaceous abundance between the settlements.

Basal area

Basal area of woody plants varied significantly along a distance from water points ($F = 13.89$, $P < 0.001$, d.f. = 4, 12). Mean basal area declined with distance from water points (Table 4). Trees at 200 m had the biggest mean basal area, while there were no further significant differences among the remaining distances from the water points (Scheffe test, $P > 0.05$).

Woody Plant height

Plant heights differed significantly with distance from water points ($F = 5.88$, $P < 0.05$, d.f. = 4, 12). Trees at 200 m were significantly taller (mean \pm SE, 2.43 ± 0.107 cm), while those further away from water points did not differ significantly in height (Scheffe test, $P > 0.05$) (Table 4).

Canopy area

Mean canopy area differed significantly along the grazing gradient ($F = 25.38$, $P < 0.0001$, d.f. = 4, 12). Trees in the vicinity of water points (200 m) had significantly the biggest canopy area (Table 4). Canopy area at 600 m and further away did not differ significantly (Scheffe test, $P > 0.05$).

Table 4. Mean \pm SE woody plant basal area, height, canopy area and density at distances from water points. Different letters indicate significant differences in mean values at $P < 0.05$. Data were log-transformed.

Distance (m)	Basal area (cm ²)	Plant height (cm)	Canopy area (cm ²)	Woody density (m ⁻²)
200	2.59 \pm 0.125 a	2.43 \pm 0.107 a	5.1 \pm 0.16 a	0.01 \pm 0.005 a
600	1.90 \pm 0.141 b	2.08 \pm 0.053 b	4.5 \pm 0.11 b	0.06 \pm 0.017 ab
1200	1.65 \pm 0.075 b	2.07 \pm 0.043 b	4.2 \pm 0.05 b	0.11 \pm 0.014 b
2500	1.64 \pm 0.121 b	2.09 \pm 0.030 b	4.2 \pm 0.07 b	0.15 \pm 0.033 b
4000	1.75 \pm 0.126 b	0.02 \pm 0.046 b	4.2 \pm 0.07 b	0.15 \pm 0.024 b

Woody plant density

Livestock activities around water points affected plant density significantly ($F = 10.92$, $P < 0.001$, d.f. = 4, 12). Plants were sparsely distributed around 200 to 600 m off the water points, but increased gradually in density with increasing distance. Mean tree densities at 200 and 600 m (Table 4) did not differ significantly ($P > 0.05$), however only woody density at 200 m was significantly lower than at 1200, 2500 and 4000 m ($P < 0.05$). Thus mean tree density did not differ significantly at 600, 1200, 2500 and 4000 m from water points.

Soil organic carbon

Soil organic carbon did not differ significantly across the distance from water points ($F = 1.98$, $P = 0.1621$, d.f. = 4, 12). Mean organic carbon differed significantly across the soil profile ($F = 42.97$, $P < 0.001$, d.f. = 2, 6). Organic carbon content was significantly higher in the 10-20 cm depth (Scheffe test, $P < 0.05$), while no significant differences existed between the 50-60 cm and 90-100 cm depth (Table 5) (Scheffe test, $P > 0.05$).

Total nitrogen

Total nitrogen in the soil did not differ across the distance from water points ($F = 1.041$, $P = 0.4264$, d.f. = 4, 12). However, mean total nitrogen differed significantly across the soil profile ($F = 29.66$, $P < 0.001$, d.f. = 2, 6). Mean total nitrogen was significantly higher in the 10-20 cm layer than down the soil profile (Table 5). No significant differences existed between the 50 – 60 cm and 90 – 100 cm soil depths (Scheffe test, $P > 0.05$).

Available phosphorus

The individual effects of distance and depth on soil phosphorus content were not significant ($P > 0.05$). However, their interaction effect was significant ($F = 4.80$, $P = 0.0013$, d.f. = 8, 24). A Scheffe *post hoc* test revealed that the 10-20 cm layer at 200 m from the water points contained significantly higher phosphorus content, than at any other depth and distance from water points (Figure 3). Phosphorus content away from the water points and at 50-60 cm and 90-100 cm depths at 200 m did not differ significantly (Scheffe test, $P > 0.05$).

Soil moisture

Soil moisture did not differ significantly across the distance from water points ($F = 1.84$, $P = 0.1859$, d.f. = 4, 12). However, it differed significantly across the soil profile ($F = 11.65$, $P = 0.0086$, d.f. = 2, 6). The 10-20 cm soil layer contained significantly lower moisture content than at 50-60 cm and 90-100 cm depths (Scheffe test, $P < 0.05$), and no significant differences existed between the latter depths (Table 5).

Table 5. Mean±SE soil organic carbon, total nitrogen and soil moisture across the soil profile. Different letters indicate significant difference in mean values at $p < 0.05$.

Distance (cm)	Soil organic carbon (%)	Total nitrogen (ppm)	Soil moisture (%)
10-20	0.228±0.0197 a	13.177±0.5281 a	0.308±0.0094 a
50-60	0.146±0.0093 b	10.708±0.6235 b	0.400±0.0238 b
90-100	0.112±0.0070 b	9.406±0.6091 b	0.436±0.0332 b

Discussion

Vegetation and soil changes along a grazing gradient

Sinking boreholes to tap groundwater resources facilitated all-year round livestock production in the semi-arid Kalahari, and high livestock pressure around artificial water points often leads to undesirable vegetation and soil changes (Andrew 1988, Thrash 1998). We found that livestock activities near the water points had significant impacts on vegetation and soils. The status of vegetation and soil around the water points reflected the situation of continuous livestock pressure on relatively homogenous dune fields of the northern Kalahari after 32 to 51 years of livestock production.

Fewer, but taller trees with broader canopy areas grew near the water points. Tree density declined with 91 %, while their height and canopy area increased with about 96 % and 16 % respectively around 200 m from the water points in comparison with farther distances (Table 4). It appears that reduced competition for soil nutrients and moisture among the sparsely distributed trees, and increased phosphorous fertilisation from dung may have been responsible for increased plant growth. Soil moisture, organic carbon and nitrogen did not differ across the distance from water points, but because of fewer trees near water points more resources could have been available for the individual trees. Livestock trampling may have reduced soil moisture in the upper layer of the soil, whilst scattered woody distribution in the vicinity of water points may reduce evapotranspiration resulting in the higher moisture down the profile (Dougill & Cox 1995). The predominant matrix flow of water movement in the Kalahari allows nutrient adsorption onto soil particles (Dougill *et al.* 1998). Hence, Dougill *et al.* (1998) suggested that high nitrogen and phosphorus would remain in the upper soil layer because of the low mineralization and adsorption onto soil particles. We found higher organic carbon and nitrogen content at 10 – 20 cm depth than at lower depths despite higher soil moisture down the soil profile. Available phosphorus in the upper soil layer was only high at 200 m from water points, and may have resulted from dung deposition by cattle supplemented with phosphorous licks. Phosphorus is generally very low in the Kalahari environment (Mendelsohn *et al.* 2002).

Herbaceous abundance increased with proximity to the water points. These results suggest that disturbance decreased species diversity, but increased the population size of herb species in the vicinity of water points. Graminoid species such as *Setaria verticillata*, *Cynodon dactylon* and herb species such as *Sida cordifolia*, *Acanthospermum hispidum*, *Tribulus terrestris*, *Amaranthus thunbergii* and *Indigofera* species were most abundant (Katjiua & Ward, unpublished data) and may be indicators of land degradation. The combination of high soil fertility, especially phosphorous out of those measured in the upper soil layer and reduced tree density may have increased the intensity of the above-ground herb interspecific competition which resulted in fewer species, but with high abundances (Wilson & Tilman 1991). In this system, selective herbivory may have altered community structure by enhancing the abundance of unpalatable species. Disturbance and low tree density favours the production of herbaceous species (Barker *et al.* 1990, James *et al.* 1999), while livestock activities may reduce the establishment of perennial species (Britz *et al.* 2002).

Spatial and temporal vegetation change under grazing

This study showed that the current pattern of vegetation was significantly altered near the water points. However this result does not confirm with certainty that livestock impact is only confined to the areas near the water points. Livestock in the study area had unrestricted movement on the rangeland and normally returned to the water point every other day. The non-significant differences away from water points may be a reflection of small sample size, given the clear differences observed during field reconnaissance and elaborated on in the descriptions of the different zones. The absence of long-term data is a limitation; hence we cannot ascertain the nature of change. However, long-term observations by pastoralists revealed that the structure of plant community has changed substantially from an open savannah to a more closed savannah ecosystem all over the rangelands since the commencement of sedentary settlements around the artificial permanent water points some 32 to 51 years ago (Katjiua & Ward unpublished data). The effects of grazing on the structure of plant communities depend on the distance livestock travel from water points (Jeltsch *et al.* 1997) and temporal scale (Ward *et al.* 1998). Simulation data for the arid and semi-arid environments, southern Kalahari (Jeltsch *et al.* 1997) and northern Australia (Pickup 1994), showed that the effects of cattle grazing on vegetation can indeed extend beyond 7 000 m from artificial water points, which is further than what this study could possibly assess given the high density of pastoral settlements in the study area. Historically livestock production has significant impact on the structure of plant communities in Namibia, even if current local-scale data suggest that the impact is confined to the areas near water points. Grass production in Namibia has decreased by approximately 100% between 1939 and 1997 (Ward *et al.* 2004), while woody plants have increased in density over much of Namibia's rangelands over the past 40 to 50 years (De Klerk 2004).

However, a distance of more than 10 000 m between water points would potentially minimise the expansion of negative impacts on range resources under continuous grazing production systems, and ensure grazing reserves mid-way between settlements (Walker *et al.* 1987). Thus such distance may prevent starvation-induced mortality during droughts (Owen-Smith 1996). The 7 000 m distance applied by the Ministry of Agriculture, Water and Forestry for spacing water points between pastoral settlements may intensify land degradation and increase drought vulnerability under continuous grazing production systems. In addition, the current uncontrolled fencing and subdivisions of communal rangelands by some pastoralists may confine livestock foraging activities, thereby causing excessive livestock pressure which may lead to potentially undesirable vegetation change. The development of community-based rangeland management institutions is a potential avenue for introducing controlled stocking density and rotational grazing at village level.

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