Soil water movement and nutrient cycling in semi-arid rangeland: vegetation change and system resilience

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Abstract:

Recent decades have seen rapid intensification of cattle production in semi-arid savannah ecosystems, increasingly on formalized ranch blocks. As a result, vegetation community changes have occurred, notably bush encroachment (increased bush dominance) in intensively grazed areas. The exact causes of this vegetation change remain widely debated. Previous studies have suggested: (i) increased leaching of water and nutrients into the subsoil in intensively grazed areas provides deeper rooting bush species with a competitive advantage for soil water and nutrients, and (ii) nutrient leaching may be exacerbated by nutrient inputs from cattle dung and urine. Our research in the Eastern Kalahari showed that in infertile sandy soils both the magnitude of soil water and concentration of soil nutrients leached into the subsoil is largely unaffected by the ecological and biochemical effects of increased cattle use. We found that despite the high soil hydraulic conductivity (>12 cm h^{-1}), relatively high subsoil moisture contents and the restriction of water movement to matrix flow pathways prevent leaching losses beyond the rooting zone of savannah grass species. No significant differences in patterns of soil water redistribution were noted between bush dominant and grass dominant sites. We also found that the low nutrient status of Kalahari soils and leachate movement as matrix flow combine to allow nutrient adsorption on to soil particles. Nutrient adsorption ensures that nitrogen and phosphorus cycling remains topsoil dominated even following the removal of vegetation and direct nutrient inputs in cattle dung and urine. This conclusion refutes environmental change models that portray increases in the leaching of soil water and available nitrogen as a major factor causing bush encroachment. This provides a possible explanation for the now widely cited, but hitherto unexplained, resilience of dryland soils. We suggest that infertile sandy soils appear **resilient** to changes in soil water distribution and nutrient availability caused by increased cattle use. Hence, soil characteristics contribute to the resilience to permanent ecological change that is increasingly recognized as an attribute of semi-arid rangelands. © 1998 John Wiley & Sons, Ltd.

KEY WORDS   bush encroachment; soil water; cattle ranching; ecological resilience; nitrogen; phosphorus; savannah

INTRODUCTION

Intensification of pastoral agriculture in semi-arid savannahs has typically been associated with bush encroachment in intensively grazed areas (Warren and Agnew, 1988; Scholes and Walker, 1993). Bush encroachment describes the transition from a grass-dominated vegetation community to one dominated by woody species. Whilst these ecological changes have been clearly linked to the intensity of grazing (Perkins and Thomas, 1993a,b), identification of the specific physical factors that determine the temporal and spatial nature of changes in vegetation communities has been problematic. Recent ecological reviews (e.g. Frost

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et al., 1986; Walker, 1987; Skarpe, 1990; Behnke *et al.*, 1993; Scholes and Walker, 1993; Belsky, 1994) have consistently stressed the importance of soil hydrochemical characteristics, notably water and nutrient availability, in determining the nature of ecosystem structure changes, including bush encroachment. However, there are few studies that directly examine the links between soils, increased livestock intensities and patterns of vegetation change. Explanations of bush encroachment have largely been based on the 'two-layer model' (Walter, 1971; Walker and Noy-Meir, 1982). This model proposes that the removal of herbaceous vegetation by intensive grazing results in increased leaching of rainfall into the subsoil (classed as below 50 cm depth in sandy soils, since no direct evaporative losses occur from this depth; Tsoar and Møller, 1986; Vossen, 1990). In addition, dung and urine inputs are thought to increase net nutrient mineralization rates, increasing water-soluble nutrient concentrations (notably NO_3-N), leading to increased rates of nutrient leaching into the subsoil (Ruess, 1987). The two-layer model assumes that these two factors combine to increase water and nutrient availability in the subsoil. Bush encroachment results because bush roots are competitively dominant over grasses in the subsoil zone (Cole and Brown, 1976; Rutherford, 1982).

Research in semi-arid rangelands has focused on soil erosion (Parr *et al.*, 1990; Pimentel, 1993) and total nutrient concentrations of soils (Botkin *et al.*, 1981; Tolsma *et al.*, 1987). Such research has not provided data to test the two-layer model. This paper presents the results of a series of investigations that specifically set out to test the two-layer model. The research reported here covers two main areas: (i) *hydrological studies* designed to measure the effect of herbaceous vegetation removal on soil water redistribution, and (ii) *nutrient studies* investigating the effect of herbaceous vegetation removal and cattle dung and urine inputs on soil nitrogen (N) and phosphorus (P) availability. The importance of these two nutrients in limiting vegetation growth in semi-arid rangelands has been widely recognized (Penning deVries *et al.*, 1980; Medina, 1987; Scholes and Walker, 1993). Here we sought to assess: (i) the rate of mineralization of nutrients added to the soil surface in organic form; (ii) the rate of leaching of nutrients from cattle dung and urine inputs; and (iii) the effect of a reduction in herbaceous biomass cover on nutrient cycling within soils.

STUDY AREA

The location of Uwe Aboo Ranch in the Makoba Ranch Blocks of Central District, Botswana, is shown in Figure 1. The site was chosen because ecological data were available from previous work on the spatial variation of vegetation communities in relation to patterns of grazing intensity (Perkins and Thomas, 1993a,b). Characteristic of large areas of the Kalahari, cattle grazing on this ranch is centred around a borehole tapping deep groundwater reserves. Uwe Aboo presently supports a herd of over 300 cattle and 50 goats on the 6400 ha ranch block. Two further boreholes have recently been installed in the south of the ranch block where cattle production is now more intensive. The work reported here was restricted to the north of the original Uwe Aboo borehole (Figure 2), which has been grazed continuously since 1973. The major ecological change on the ranch, as elsewhere in Botswana (van Vegten, 1983; Tolsma *et al.*, 1987; Ringrose *et al.*, 1990; Skarpe, 1990), is bush encroachment. Vegetation changes reflect the replacement of mixed grass and broad-leaved bush savanna communities with fine-leaved bush species. In particular, increases in the cover of *Acacia* spp. and *Dichrostachys cinerea* are seen in areas close to the borehole, which have experienced intensive grazing for over 20 years.

The Kalahari sand soils of the study ranch are extremely infertile and contain a high proportion of fine sand particles. General soil hydrochemical characteristics are summarized in Table I. Note should be taken of the high infiltration capacity, which limits erosion losses from surface runoff. Erosion is further limited by the maintenance of vegetation cover over 40%, even in bush-encroached areas (Perkins and Thomas, 1993b). The soils found here are similar to those covering larger areas of semi-arid regions in not only Africa, but also Australia (Buckley *et al.*, 1987a,b; Paton *et al.*, 1995) and parts of the Middle East (Batanouny, 1990). Consequently, although the research reported here focuses on a single site, the implications may have wider environmental significance.
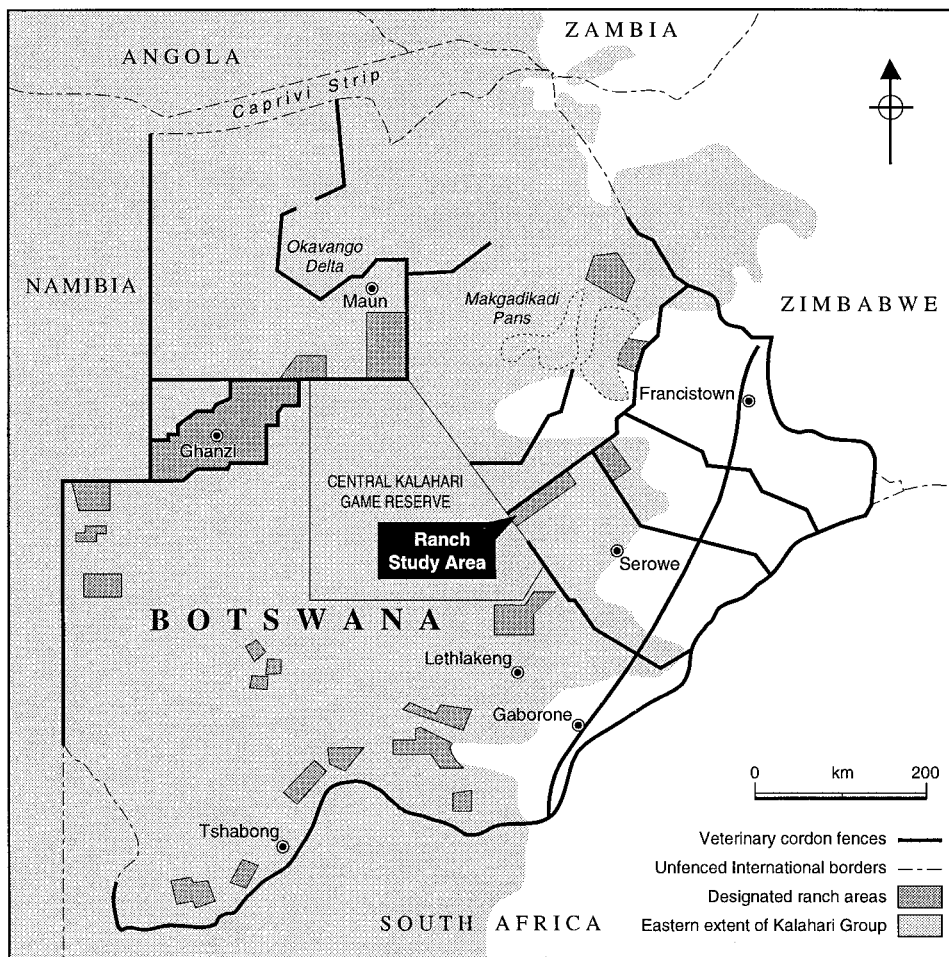
Figure 1. Location of Uwe Aboo Ranch, Eastern Kalahari, Botswana

MATERIALS AND METHODS

Three integrated scales of analysis were used. At the micro-scale, soil column experiments under controlled conditions were used to: (i) investigate the pathways of soil water redistribution and the rate of soil water movement; (ii) examine the net nutrient mineralization rates and nutrient concentrations in leachate; and (iii) investigate the effect of cattle dung and urine inputs on nutrient cycling. At the field plot scale (Figure 2), a comparison of bush dominant and grass dominant sites using 2 m × 1 m unbounded areas was undertaken to assess the effect of vegetation community changes on soil water and nutrient distribution. Cattle dung and urine were artificially added to the plots to evaluate their effect on soil water and nutrient availability. At the ranch scale, we attempted to quantify the spatial variation in water and nutrient availability along a 3 km transect radiating from the borehole. Results of these ranch-scale studies have been reported previously by Dougill and Cox (1995) and are not considered in detail here.

Soil column experiments

Soil water. Methylene blue dye (6.6 litres, equivalent to 40 mm rainfall) was used as a tracer to evaluate flow pathways in the upper soil layers. The dye solution was applied within an infiltration ring of 29 cm internal
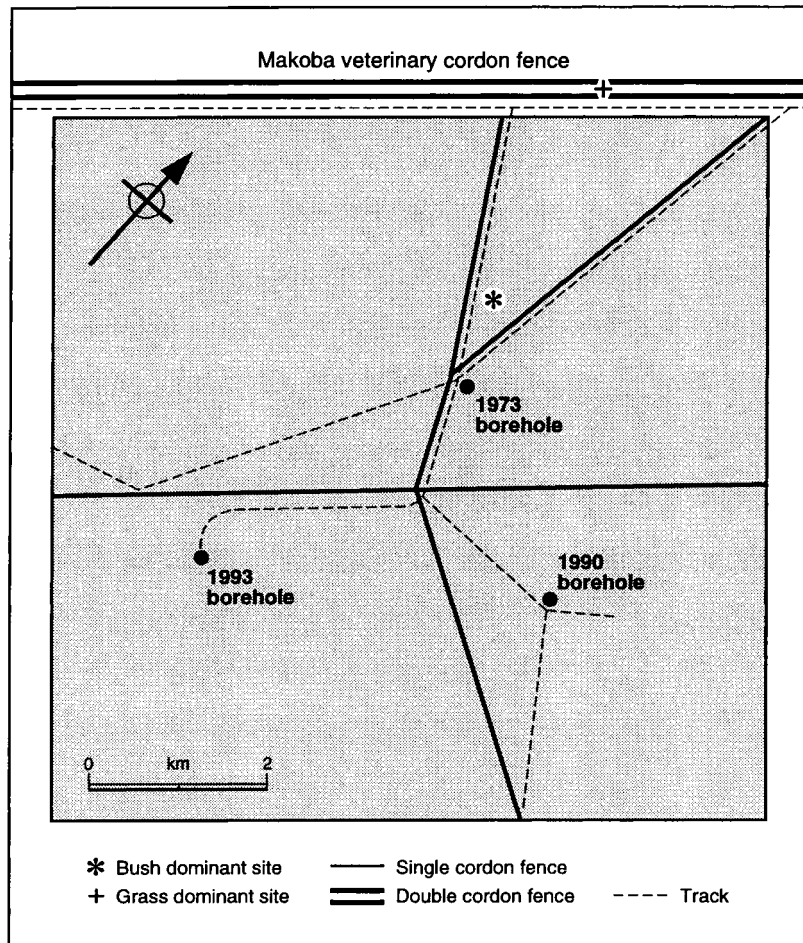
Figure 2. Layout of Uwe Aboo ranch in 1993 showing principal study sites

diameter and at a concentration of 10 g l^{-1}. Eight replicate applications were conducted at both grass dominant and bush dominant sites at the end of the dry season in September 1993. Three hours following application, the dye staining down the face of the wetted soil profile was exposed and water flow pathways recorded in order to quantify the uniformity and depth of wetting front penetration. This was achieved by measuring the modal depth of penetration of moisture staining (Pd_{mod}) and the maximum penetration depth (Pd_{max}). The uniformity of water movement was quantified as a percentage [equation (1)]. The rate of wetting front movement (Pd_{mod}/time) was used to compare the hydraulic conductivity at bush dominant and grass dominant sites.

$$\text{Uniformity (\%)} = \frac{Pd_{max} - Pd_{mod}}{Pd_{mod}} \times 100 \qquad (1)$$

Nutrient mineralization. Net N and P mineralization rates were evaluated using soil column experiments based on the field incubation method of Raison *et al.* (1987; amended by Anderson and Ingram, 1993). Eighteen undisturbed soil columns were taken from the bush dominant site (Figure 2) by driving plastic soil

Table I. Summary of characteristics at Uwe Aboo Ranch. All results based on soils analyses using standard methods outlined in Anderson and Ingram (1993) and Allen (1989). All measurements based on analysis of 30 topsoil samples (20 cm depth). Infiltration capacity assessed from 30 infiltration ring (internal diameter 29 cm) experiments. Details of hydraulic conductivity measurement methods given in text

Soil characteristic	Mean value	Implications
Physical characteristics		
Particle size distribution	97.6 ± 1.4 fine sand	Physical characteristics and hydrology dominated by sand content.
Bulk density (g cm^{-3})	1.36 ± 0.02	Unstructured soil. No compaction problems.
Infiltration capacity (cm h^{-1})	>30	All rainfall infiltrated rapidly. No surface water flow.
Hydraulic conductivity (cm h^{-1})	12.6 ± 5.1	Very rapid (as classed by Landon, 1991) movement of water through topsoil.
Chemical characteristics		
pH	5.8 ± 0.9	Moderate pH value should not greatly affect plant growth.
Organic matter content	$0.70 \pm 0.09\%$ dry soil weight	Naturally very low. Limited capability for binding soils and for water and nutrient retention.
Cation exchange capacity (me 100 g^{-1})	2.2 ± 1.4	Very low CEC value indicative of low soil fertility.
Inorganic N concentration (mg N 100 g^{-1})	6.7 ± 2.7	Inorganic nitrogen availability low and could limit plant growth.
Total N concentration (mg N 100 g^{-1})	521 ± 292	Large organic N pool implying that net N mineralization limits nitrogen availability.
Inorganic P concentration (mg P 100 g^{-1})	1.2 ± 0.7	Inorganic phosphorus availability low and could limit plant growth.
Total P concentration (mg P 100 g^{-1})	123 ± 69	Large organic P pool implying that net P mineralization limits phosphorus availability.
Ca concentration (me 100 g^{-1})	2.5 ± 0.8	Moderate concentration (Landon, 1991). May adsorb PO_4-P.
Fe concentration (me 100 g^{-1})	5.4 ± 3.2	Moderate concentration (Landon, 1991). May adsorb PO_4-P.

columns (35 cm height, 78 mm internal diameter) into the ground and extracting them by digging around the columns and inserting a vilene^{TM} base to hold the 'undisturbed' soil sample in place. Sampling took place after major rainfall events in November 1993, thus ensuring that low soil moisture contents did not limit mineralization. Six columns were returned to the laboratory and immediately analysed for inorganic N (NO_3-N + NH_4-N), inorganic P (PO_4-P), total N and total P. The 12 remaining columns were covered with plastic sheeting to prevent leaching losses and replaced *in situ* for a four-week period. This four-week period is the maximum suggested for field incubation experiments by Scholes and Scholes (1989) and was chosen to minimize the problems caused by the low nutrient concentrations of Kalahari soils. The potential 'mineralizable pool' of organic N and P was enhanced in six of the twelve columns by surface addition of 5 g of fresh cattle dung. Net mineralization rates were assessed by difference, from the increase in inorganic nutrient concentrations during the incubation period.

Nutrient leaching. Leachate nutrient concentrations were measured to assess the solubility of nutrient inputs from cattle dung and urine. Twelve soil columns (7·8 cm diameter × 35 cm length) were removed from the bush-dominated site (Figure 2) and used in controlled leaching column experiments. Rain-water, equivalent to a 100 mm storm event, was added to the soil surface of all 12 soil columns over a 30-minute period. This amount of 'rainfall' was designed to ensure that sufficient leachate output was collected at the base of the columns for subsequent analysis of inorganic N and P. Rainfall events of this magnitude have been recorded in Botswana (Bhalotra, 1987); however, these occur only approximately every 50 years and so experiments

represent a worst-case scenario of leaching under intense rainfall and negligible plant uptake. To investigate the effect of cattle dung and urine additions on leachate concentrations the 12 columns were assigned to three groups of four replicate columns. To one group, 5 g of fresh cattle dung was added to the soil surface 24 hours prior to rain-water addition; to the second, 40 ml of artificial cattle urine (Day and Detling, 1990) was added 24 hours prior to rain-water addition; and, finally, four columns experienced no additional surface inputs and acted as controls representing natural field conditions.

Plot-scale studies

At both bush dominant and grass dominant sites further measurements of water flow pathways and the rate of wetting front movement were made by applying 16 litres of water to the surface of two unbounded 4 m^2 plots. The water input was equivalent to a high-magnitude rainfall event of 40 mm, typical of intense storms in the region (Bhalotra, 1987). Following application, the plots were covered with white plastic sheeting to prevent evaporative losses. Destructive soil sampling, based on the random compass-rose method (Reynolds, 1970), was used to take replicate (3) samples prior to water application, and at 1, 3, 10 and 30 hours after application. The samples were taken from the soil surface and at depths of 10, 20, 40, 60, 80 and 100 cm. Gravimetric water content was assessed and used to determine the rate of wetting front penetration as a measure of hydraulic conductivity [$K(\theta)$]. The topsoil moisture content 30 hours after water application was also used as a measure of field capacity (θ_{fc}) at the two sites.

Further field plot experiments using 2 m × 1 m unbounded areas were conducted at bush dominant and grass dominant sites (Figure 2). They were designed to investigate the effect on soil hydrochemistry of changes in organic matter inputs and vegetation characteristics caused by intensive cattle use. Using unbounded areas meant that the plots interacted with the surrounding soil and were not artificially confined. At each site, duplicate plots received either no surface inputs (control); intensive dung input (single layer of dung pats over plot surface); or artificial bovine urine application (Day and Detling, 1990) equivalent to 8 l m^{-2}, which is thought to be the average urine input of large bovines (Betteridge et al., 1986). The changes in soil water and soil nutrient availability through time were measured by limiting destructive soil sampling to 10-cm strips within the 2-m long plots. A 10 cm buffer between each sampling strip enabled 10 profile samples runs to be carried out in the period September 1993–January 1994. Two of the sample runs were undertaken prior to surface treatments at the end of the dry season (September 1993). Six sample runs were conducted during the dry season following application of dung and urine (October–November 1993). The final two runs were carried out in the subsequent wet season (January 1994) following storm events generating 197 mm of rainfall (including three high-magnitude events with daily rainfall over 40 mm). In all sample runs, bulked samples were taken from the soil surface and at depths of 20, 60 and 100 cm. These were used to investigate the temporal changes in profile distribution of soil water and extractable nutrient concentrations.

Analytical methods

Limited laboratory facilities were available in Botswana for this study, hence soil analyses relied on simple, cheap and rapid techniques. Fresh soil samples were analysed at the Botswana Government Soils Laboratory within 48 hours of sampling. Samples were split and part of the sample was analysed immediately for gravimetric water content. Extractable inorganic N (NO_3-N and NH_4-N) concentrations were quantified following standard soil extraction procedures, using distilled water for NO_3-N (Allen, 1989) and 6% KCl solution for NH_4-N (Allen, 1989). Subsequently, NO_3-N concentrations were measured using the colorimetric technique of Cataldo et al. (1975) (summarized in Anderson and Ingram, 1993). NH_4-N concentrations were also assessed colorimetrically, using the modified Bertholet reaction method described by Anderson and Ingram (1993). Extractable inorganic P (PO_4-P) was measured following a standard Olsens extraction (Allen, 1989) and colorimetric analysis based on the molybdenum blue technique described by Murphy and Riley (1962). The extracts were analysed using a Perkin–Elmer automated spectrophotometer. Total N (Bremner and Mulvaney, 1982) and total P (Olsen and Sommers, 1982) concentrations were

determined colorimetrically as above following sulfuric acid digestion at 450°C for 16 hours in Kjeldahl digestion blocks (Anderson and Ingram, 1993).

RESULTS

Soil column experiments

Soil water. Methylene blue dye tracing demonstrated uniformity in the depth of wetting zone penetration. The uniformity index [Equation (1)] showed that the maximum depth of penetration (Pd_{max}) never exceeded the modal penetration depth (Pd_{mod}) by more than 23% in the 16 small-scale tracer experiments (mean variation of Pd_{max} from $Pd_{mod} = 15.3\%$; $\sigma = 3.9\%$). Bypassing flow of water along macropores, which is important for nitrogen leaching to depth in some tropical soils (van Noordwijk *et al.*, 1991), appears to be an insignificant form of water movement in these soils. Matrix flow is the main pathway of water movement in Kalahari soils.

Nutrient mineralization. The mineralization studies were used with two objectives. First, to measure the rate of conversion of N and P into plant-available inorganic forms. Secondly, they also allowed testing of the two-layer model, through assessment of the likelihood of increased concentrations of water-soluble NO_3-N. Table II summarizes the results of the mineralization column studies. The net rates of N and P mineralization are shown together with the effect of cattle dung application on mineralization rates. Total N and total P concentrations are an order of magnitude greater than the extractable inorganic concentrations, suggesting that mineralization rates control the extent and timing of inorganic nutrient availability. Low rates of net nutrient mineralization were recorded: typically, *c.* 0.03 mg N 100 g^{-1} day^{-1}. Cattle dung addition significantly increased ($p < 0.001$) the rate of N mineralization to *c.* 0.09 mg N 100^{-1} day^{-1}. However, the results suggest that high concentrations of water-soluble inorganic nutrients are not expected in Kalahari soils following cattle dung input because transformation into NO_3-N remains a slow process. No significant net phosphorus mineralization was recorded, even with application of phosphorus-rich dung (Table II).

Nutrient leaching. Figure 3 presents leaching column data for the solubility of inorganic N in soils $\pm$ cattle dung and urine. Urine and dung addition appears to have a negligible effect on inorganic N concentrations in leachate, with nitrate concentrations around 10 mg l^{-1}, which are similar to those recorded from the
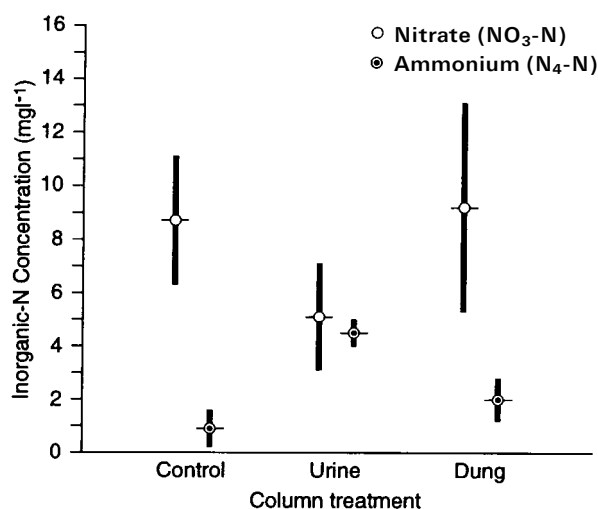

Figure 3. Mean inorganic N (NO_3-N + NH_4-N) concentrations in leachate from soil columns (30 cm depth) with different surface treatments. Plots display mean and 95% confidence intervals

Table II. Fractionation of soil nitrogen and phosphorus prior to and following four-week field incubation of soil columns (method of Anderson and Ingram, 1993). Changes represent net mineralization

Surface treatment	Prior to incubation				After four-week incubation		Mean net mineralization rates	
	Total N (mg N 100 g^{-1})	Inorganic N (NO-N+ NH-N) (mg N 100 g^{-1})	Total P (mg P 100 g^{-1})	Inorganic P (PO$_4$-P) (mg P 100 g^{-1})	Inorganic N (NO$_3$-N+ NH$_4$-N) (mg N 100 g^{-1})	Inorganic P (PO$_4$-P) (mg P 100 g^{-1})	Nitrogen (mg N 100 g^{-1} day^{-1})	Phosphorus (mg P 100 g^{-1} day^{-1})
Control (no dung addition)	498 ± 292 $n = 29$	6·73 ± 2·67 $n = 24$	106 ± 59 $n = 29$	1·19 ± 0·67 $n = 24$	7·49 ± 0·79 $n = 24$	0·90 ± 0·31 $n = 24$	0·027	−0·010
Dung addition (5 g of fresh dung to surface)	832 ± 328 $n = 15$	6·73 ± 2·67 $n = 24$	137 ± 84 $n = 15$	1·19 ± 0·67 $n = 24$	9·37 ± 1·46 $n = 24$	1·17 ± 0·54 $n = 24$	0·095	−0·007

control columns. This is despite the high organic N loading in dung and the high inorganic N concentration in the artificially applied bovine urine. Inorganic P concentrations in leachate were negligible, possibly owing to rapid uptake or the insolubility of PO_4-P.

Plot-scale studies

Soil water. The two-layer model assumes that reduced herbaceous vegetation cover will lead to increased leaching of rain-water to depth. This assumption was tested in a range of hydrological studies comparing water redistribution at bush dominant and grass dominant sites. Hydraulic conductivity measurements (used to estimate the rate of water movement) and the subsoil gravimetric moisture content following a wetting pulse (used to estimate the amount of rain water leaching into the subsoil) are summarized in Table III. The results demonstrate that there is no significant difference ($p < 0.05$) between the rate of wetting from movement during the initial wetting pulse at the two sites. Initial water movement is very rapid with a mean hydraulic conductivity over 12 cm h^{-1}. Furthermore, there is no significant difference ($p < 0.05$) between bush dominant and grass dominant sites in subsoil gravimetric moisture content around 1·0%. Further measurements showing similarities in field capacity and bulk density at the bush dominant and grass dominant sites (Table IV), add support (using the wetting front model of Rose *et al*., 1982) for the observation that wetting front penetration (both the rate and amount) will be similar at these two sites.

Soil water availability in the 1993 dry season for field plots in bush dominant and grass dominant areas are summarized in Table V. The similarity in moisture content distribution between the two sites is shown by the

Table III. Rate of wetting front movement and subsoil gravimetric moisture content following 40 mm equivalent rainfall addition at bush dominant and grass dominant sites (see figure 2 for locations)

Rate of wetting front movement [$K(\theta)$]. Estimated from Pd_{mod} 3 hours after water addition		Gravimetric moisture content (%) at 100 cm depth 30 hours after 40 mm storm event	
Bush dominant	Grass dominant	Bush dominant	Grass dominant
12·8 ± 5·2 $n = 17$	12·3 ± 4·9 $n = 14$	1·10 ± 0·85 $n = 17$	0·99 ± 0·74 $n = 14$

Table IV. Soil physical characteristics at bush dominant and grass dominant sites (Figure 2). Bulk density at 5 cm depth. Field capacty — moisture content at 10 and 20 cm depth 30 hours after thorough wetting of soil with evaporation losses prevented

Field capacity (θ_{fc}, cm^3 cm^{-3})		Bulk density (g cm^{-3})	
Bush dominant	Grass dominant	Bush dominant	Grass dominant
6·98 ± 0·24 ($n = 8$)	6·62 ± 0·59 ($n = 8$)	1·35 ± 0·03 ($n = 32$)	1·37 ± 0·02 ($n = 29$)

Table V. Mean soil moisture content (%) for the topsoil and subsoil under control plots at bush dominant and grass dominant sites in the 1993 dry season. The mean and 95% confidence intervals are given

Depth (cm)	Bush dominante site	Grass dominant site
20 cm (topsoil)	0·46 ± 0·14 $n = 19$	0·38 ± 0·10 $n = 19$
100 cm (subsoil)	0·90 ± 0·27 $n = 19$	0·93 ± 0·32 $n = 19$

Table VI. Mean soil moisture content (%) for the topsoil and subsoil under neighbouring control and urine plots in the wet season four days following a high-magnitude (62 mm) storm event ($n = 4$ in all cases). The mean and 95% confidence intervals are given

Depth (cm)	Bush dominant sites		Grass dominant sites	
	Control plots	Urine plots	Control plots	Urine plots
20 cm (topsoil)	3.34 ± 0.22	3.15 ± 0.16	3.20 ± 0.03	3.19 ± 0.16
60 and 100 cm (subsoil)	4.54 ± 0.24	4.15 ± 0.16	4.13 ± 0.14	4.08 ± 0.18

gravimetric moisture content at 100 cm depth. This similarity suggests that herbaceous vegetation removal has had a negligible effect on soil water redistribution. The limited effect of vegetation changes on soil hydrology is highlighted by changes under urine plots. Here, vegetation growth was lacking because of toxic concentrations of nutrients added in the artificial urine. We found that topsoil (20 cm depth) and subsoil (60 and 100 cm depth) gravimetric moisture contents under urine plots were not significantly different ($p < 0.05$) from that for neighbouring control plots following rainfall events (Table VI), suggesting vegetation removal has a negligible effect on soil water distribution.

Soil nutrients. The plot studies were used to provide field measurements of the effect of both vegetation removal (through bush dominant and grass dominant site comparisons) and cattle dung and urine additions (through comparisons of control plots with those receiving dung and urine inputs). Figures 4 and 5 summarize the changes in extractable inorganic N concentrations, both with time and following dung and urine treatments, for plots at bush dominant and grass dominant sites. Comparison of extractable soil inorganic N at bush and grass dominant sites reveals no significant difference ($p < 0.05$) between sites in either the dry season or the subsequent wet season. This finding is demonstrated by the overlap of 95% confidence intervals of NO_3-N (Figure 4) and NH_4-N concentrations (Figure 5) for the two sites. Soil inorganic N concentrations are characterized by an inherent variability which appears to override the effects of different vegetation communities or cattle dung inputs. Only in the case of artificial urine addition, which resulted in extremely high concentrations of NH_4-N (over 50 mg N 100 g^{-1}) at the soil surface together with complete vegetation die-back, is any significant leaching of inorganic N into the subsoil recorded. Here NH_4-N concentrations over 20 mg N 100 g^{-1} were found at depths of 60 cm in soil profiles (Figure 4). Even for this extreme example, leaching was restricted and never reached beyond 100 cm depth. Mobilization of phosphate P was not recorded under the plots, with virtually all applied P being retained at the soil surface.

DISCUSSION

By integrating the range of studies reported here we hope to provide a clearer understanding of the effects of intensified cattle use on soil hydrochemical characteristics because these in turn determine the ecological structure and productivity of semi-arid rangelands. We found that water redistribution in the sandy Kalahari soils studied occurs predominantly as uniform matrix flow. This has a number of important implications for soil water and nutrient availability. The slower percolation rate, typical of matrix flow (compared with bypassing flow pathways), allows greater equilibration between soil nutrients and solutes (White, 1985a,b). This is particularly important in areas characterized by infertile soils because adsorption on to nutrient-poor soil particles can occur, thereby reducing leaching into the subsoil. Such results contradict those postulated in the two-layer model, where increased leaching of water and soluble nutrients into the subsoil is thought to favour bush dominance. We suggest that changes in soil characteristics are not required to explain changes in vegetation.

The hydrological studies we report at the soil column and plot scale, together with those at the ranch scale (Dougill and Cox, 1995), suggest that vegetation change in intensively grazed areas has a negligible effect on soil water redistribution in Kalahari soils. There appears to be little evidence for a link between
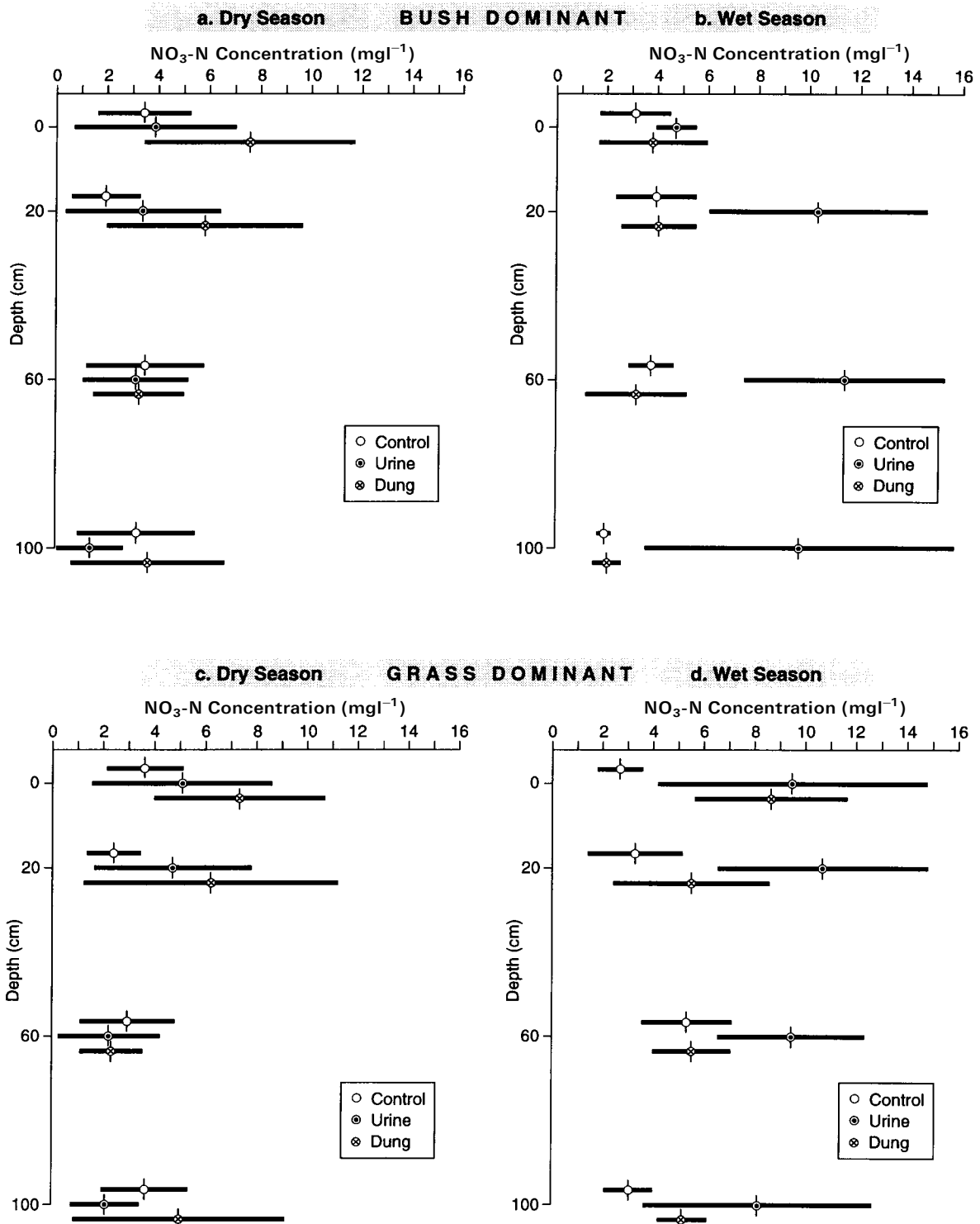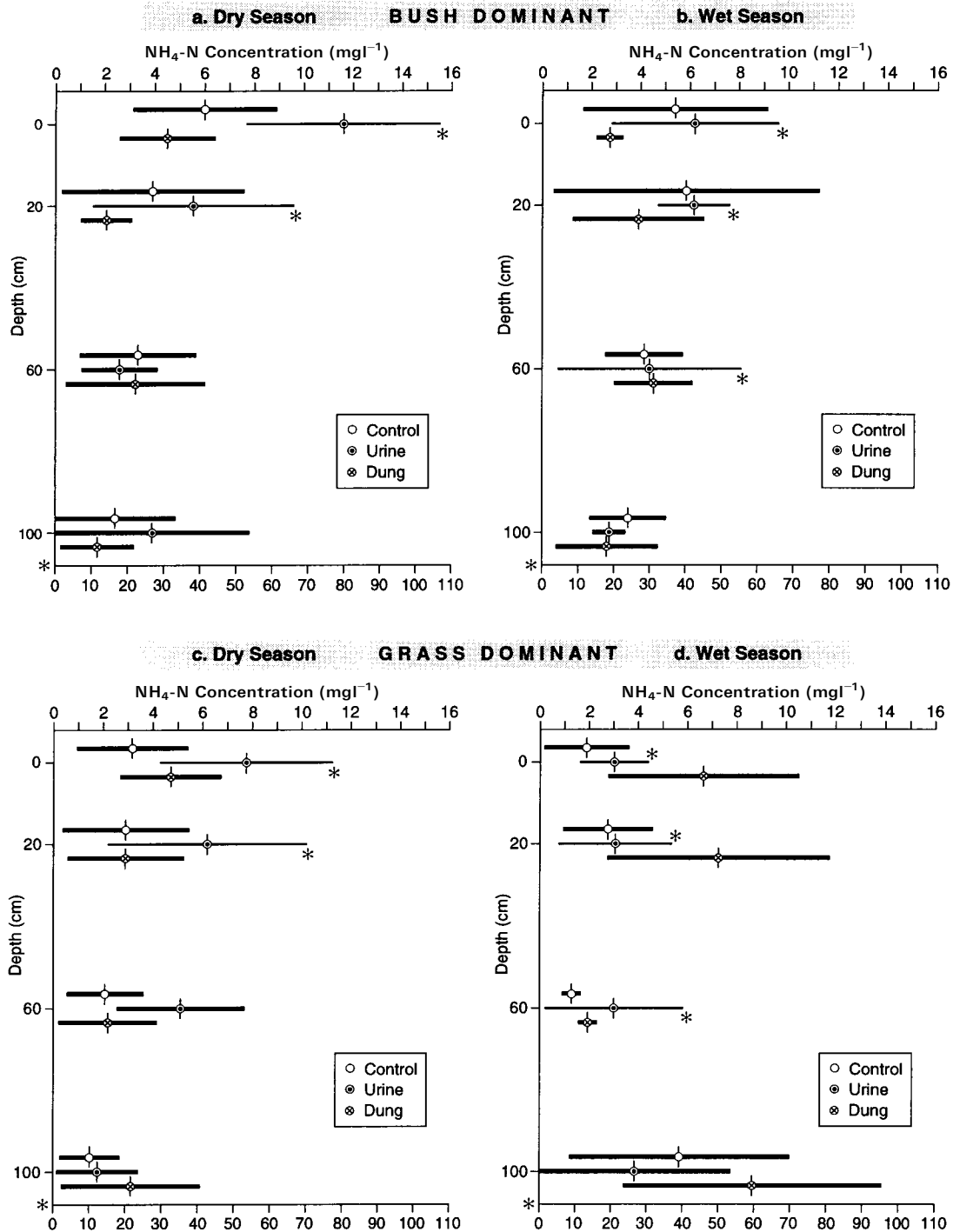
Figure 4. Extractable NO_3-N concentration variations in soil profiles under experimental plots at bush dominant and grass dominant sites. Plots display mean and 95% confidence intervals ($n = 10$ for all dry season points; $n = 4$ for wet season points)

Figure 5. Extractable NH_4-N concentration variations in soil profiles under experimental plots at bush dominant and grass dominant sites. Plots display mean and 95% confidence intervals ($n = 10$ for all dry season points; $n = 4$ for wet season points)

reduced herbaceous biomass cover and increases in the amount of rain-water leached into the subsoil. We suggest that Kalahari soils provide the ecosystem with a degree of resilience that prevents any shift in ecological competitive dominance. High hydraulic conductivities, over 12 cm h^{-1}, enable rapid water movement from the topsoil to the subsoil, thus reducing direct evaporative losses, which are restricted to the upper 50 cm (Vossen, 1990). Water use efficiency in such soils is therefore high because of the rapid infiltration of all incident rainfall, the rapid movement of water beyond the topsoil and the rapid plant uptake of topsoil water (Drew, 1979).

In addition to water movement during the initial wetting pulse in the period following rainfall, the availability of soil water is also dependent on redistribution following this initial wetting phase. Water redistribution after the wetting pulse in arid sandy soils, has been described by Youngs (1988) using the Richards equation [Equation (2) below]. The high hydraulic conductivity of Kalahari soils can be used to explain the processes affecting water redistribution after the initial wetting pulse. Contrasting situations of high-magnitude and low-magnitude storms provide a theoretical framework for consideration of this subsequent soil water redistribution.

$$\frac{\delta\theta}{\delta t} = \delta/\delta z \left[K(\theta)\left(\frac{\delta\psi}{\delta z} - 1\right)\right] \qquad (2)$$

where $\delta\theta/\delta t$ is the rate of water movement, $\delta\psi/\delta z$ is the potential gradient, and $K(\theta)$ is the hydraulic conductivity at the given moisture content (θ).

Application of the wetting front model [Equation (3) below; Rose *et al.*, 1982] predicts that high-magnitude storms ($\geqslant 40$ mm) cause wetting front penetration in Kalahari soils to depths of over 1·5 m within 48 hours of rainfall. At this depth, the gravimetric soil moisture content remains high throughout the year. Even at the end of the dry season, the gravimetric moisture content at 1·5 m depth is in excess of 2%. The maintenance of this relatively high moisture content means subsequent drainage below the wetting front is limited by a low hydraulic gradient [Equation (2)]. The high residual subsoil moisture content results from the lack of evaporative loss at this depth in sandy soils and the physiological traits of semi-arid vegetation, which maintain a dormant state in the dry season ensuring negligible transpiration loss. This dormancy maintains the higher subsoil moisture contents through the year, preventing significant leaching loss beyond the rooting zone.

$$D_p = \frac{Q}{(\theta_{fc} - \theta_a)} \qquad (3)$$

where D_p is the penetration depth of the wetting front (cm), θ_{fc} is the volumetric moisture content (cm^3 cm^{-3}) at field capacity, θ_a is the antecedent volumetric moisture content (cm^3 cm^{-3}) and Q is the rainfall input (cm).

Rainfall from lower magnitude storm events ($\leqslant 40$ mm) is subject to different processes following initial wetting. Moisture derived from such storms is initially restricted to the topsoil (0–50 cm depth). The gravimetric soil moisture content of this layer is typically as low as 0·5%, implying that soil water is subject to steep hydraulic gradients which cause continued downward drainage of soil water. Drainage beyond the topsoil reduces direct evaporation loss. Drainage also enables the maintenance of a residually higher moisture content in the subsoil, which prevents leaching loss beyond the rooting zone (as described above), thus ensuring high water use efficiency.

The above factors provide a physical basis supporting the claim that the Kalahari sand soils are responsible for imparting the ecological resilience characteristic of the Kalahari (Perkins and Thomas, 1993a). This view directly opposes that postulated by Bailleul (1975, p. 501) who suggested that Kalahari soils offer little in the way of hydrological potential as "rainwater . . . is held in the upper layers from whence it readily evaporates." The results reported here show that the physical properties of sandy soils enable a high water use efficiency and appear largely unaffected by vegetation changes associated with intensive cattle grazing.

Whilst demonstrating that hydrological characteristics are typified by resilience, it is important to consider the effects of changes in land use practices on soil nutrient availability. Such work has not been reported previously for the Kalahari. The two-layer model (Walker and Noy-Meir, 1982) suggests that with reduced herbaceous vegetation growth in intensively grazed areas, leaching of inorganic nutrients (especially NO_3-N) will occur into the subsoil. We found, however, that low mineralization rates together with the rapid uptake of plant nutrients typical of semi-arid vegetation (McNaughton and Chapin, 1985; Gross et al., 1993) limit the build-up of elevated nitrate concentrations. Kalahari soils experience very low rates of N mineralization (<0.1 mg N 100 g^{-1} day^{-1}) even compared with those recorded in other semi-arid areas (e.g. Debosz and Vinther, 1989; Singh et al., 1991; Scholes and Walker, 1993) where 'low' rates of c. 0.3– 0.9 mg N 100 g^{-1} day^{-1} are reported. Nitrate leaching into the subsoil is unlikely owing to the synchrony between mineralization and plant uptake. Leaching may also be limited by nutrient adsorption in the topsoil owing to the predominance of matrix flow and the infertile nature of soil particles. This suggestion is supported by leaching column experiments (Figure 3), which show that surface additions of cattle dung or urine do not cause increased NO_3-N concentrations in leachate at 30 cm depth from soil columns from which surface vegetation has been removed. Thus it appears that rapid, efficient and topsoil-dominated nitrogen cycling dominates in semi-arid ecosystems with infertile sandy soils. This is the result of both the hydrochemical soil characteristics and the physiological adaptations of vegetation. Here we have shown that nitrogen cycling is not greatly affected by the shift in ecosystem structure, from grass dominance to bush dominance. Furthermore, cattle dung inputs appear to have a negligible effect on extractable inorganic N distribution owing to the controlling influence of low net mineralization rates. The claim that vegetation changes can be explained by leaching of water-soluble nutrients into the subsoil (Walker and Noy-Meir, 1982) is therefore unlikely to be applicable to semi-arid rangeland ecosystems developed on sandy infertile soils.

The insolubility of inorganic P (Tiessen, 1995) means that alterations to P cycling have not been widely incorporated into models attempting to explain changes in ecosystem structure, such as the two-layer model. However, PO_4-P is important in influencing ecosystem productivity, thus it cannot be ignored in studies of soil chemical degradation. The soil column experiments reported here (Table II) show that negligible net phosphorus mineralization is recorded even in moist Kalahari soils following dung addition. This suggests that either immobilization or inorganic fixation of phosphate is prevalent thus preventing the build-up of inorganic P under conditions where no plant uptake is experienced. Inorganic fixation of PO_4-P could occur because of the relatively high Fe and Ca concentrations of Kalahari soils (Table I). Such inorganic fixation of phosphate in Kalahari soils would suggest that changes in total P distribution in soils would be long lived, as redistribution mechanisms, such as through plant root systems, act principally through plant-available PO_4-P. The longevity of P enrichment in soils is a factor that has been noted in previous studies investigating spatial patterns of P in southern African soils (Denbow and Wilmsen, 1986; Blackmore et al., 1990). Such findings suggest that whilst grazing will cause significant increases in total P concentrations in intensively grazed areas, dung additions are unlikely to increase inorganic P availability. This suggestion was supported by ranch-scale studies (Dougill and Cox, 1995), which showed no significant differences in PO_4-P concentrations between intensively grazed and ungrazed sites. Vegetation growth therefore remains dependent on pulses of net P mineralization, not the total P input into the soil, which is the key determinant affected by intensified cattle use (Botkin et al., 1981; Tolsma et al., 1987). Consequently, we suggest that no evidence exists to link vegetation changes with chemical soil degradation.

CONCLUSIONS

In semi-arid Kalahari sand soils, intensive cattle use, and associated vegetation changes, appear to have a negligible effect on soil water redistribution and extractable nutrient concentrations. This provides at least one possible explanation for the increasingly cited, but little explained, resilience in semi-arid soil–vegetation systems. Whilst intensive cattle use does affect total nutrient inputs, the Kalahari soils possess an inherent

resilience to changes in profile patterns of soil water and nutrient availability. This resilience stems directly from the dominance of matrix flow in sandy soils and their infertility. Together these factors provide soils with a high water use and nutrient use efficiency. Efficient nutrient use occurs as a result of the opportunity for adsorption on to nutrient-poor soil particles during matrix flow and the synchrony between mineralization and plant uptake of nutrients. The synchrony of nutrient production and use also implies that nutrient movement models, such as the two-layer model of environmental change (Walker and Noy-Meir, 1982), do not adequately explain vegetation changes in rangelands with sandy soils, as previously postulated by Skarpe (1990) and Perkins and Thomas (1993a). Sandy soils provide semi-arid ecosystems with a resilience to permanent ecological change, as opposed to favouring permanent vegetation changes. Alternative explanations for bush encroachment are required. In particular, there should be more focus on the interactions of grazing levels, rainfall variability and fires. It is clear that long-term ecological monitoring is needed in order to assess whether intensive cattle grazing during drought events may lead to bush encroachment. This may occur through direct grass mortality effects (Mott *et al.*, 1992) and/or reductions in the extent and intensity of fires caused by decreases in the amount and continuity of grass cover. As fires may cause a transition back to a grass-dominant state, their role in enhancing the ecological resilience of soil characteristics merits further investigation.

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