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Effects of livestock grazing on physical and chemical properties of sandy soils in Sahelian rangelands

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The effects of grazing by livestock on soil surface features, bulk density and chemical properties were studied at the completion of a 4-year grazing experiment carried out in Sadoré, Niger. Grazing treatments were a factorial arrangement of two stocking rates (62·5 and 125 kg live weight ha^{-1}) and four sheep:goat ratios (0:6, 2:4, 4:2 and 6:0 animals per pasture), with two pastures per treatment and two ungrazed controls. Observations were also made in a fallow subjected to 9 years of intense and uncontrolled mixed grazing, and in a site that had been protected from grazing for 15 years. The topsoil was sampled (at depths of 0–2, 2–6, 6–14 and 14–30 cm) below shrub canopy in herbaceous vegetation and in bare soil patches within each of 20 paddocks for determination of pH, organic C, and total N and P concentrations. Soil bulk density was measured in a subset of soil profiles. The areal extent of different types of soil crusts and other soil surface features was assessed in one-half of the paddocks. Grazing resulted in a reduction ($p < 0{\cdot}01$) and fragmentation of the area of crusted soils. However, this trend was partially compensated for by an increase of newly formed crusts. As a result, the soil infiltration index slightly increased with moderate grazing, but decreased at higher stocking rates. Compaction due to trampling was observed in the topsoil beneath the shrub canopy and also in vegetated patches, but only under intense grazing pressure. Soil bulk density was not affected by grazing except for an increase observed below 10 cm depth at the understorey of shrubs which is therefore unlikely due to trampling. When compared to the ungrazed control, pH, organic C and N concentrations, and to lesser extent P concentration, decreased after 4 years of grazing. Soil P and pH further decreased after 9 years of very high grazing pressure. However, neither N nor organic C decreased further.

Keywords: Sahel; livestock trampling; soil crusting; bulk density; nutrient cycling; soil organic matter

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Introduction

Livestock grazing is often regarded as one of the main causes of vegetation and soil degradation in the Sahel (Le Houérou, 1976; Lusigi & Glaser, 1984; Sinclair & Fryxell, 1985; Warren & Khogali, 1992). However, as Dodd (1994) pointed out in a review paper on desertification and land degradation in sub-Saharan Africa, 'it is common to attribute undesirable changes to livestock and desirable changes to good weather'. Indeed, the impact of livestock grazing in the Sahel is poorly documented because of the scarcity of data obtained under controlled stocking rate and herd composition, and over a period long enough to allow for the effects to be manifest. A grazing experiment carried out from 1992 to 1995 on old fallows in Sadoré, Niger (Fernández-Rivera & Hiernaux, 1995) offered an opportunity to measure this impact for sandy soils and semi-arid Sahelian climate conditions. In general, the effect of livestock grazing on the rangeland proceeds from three processes: plant defoliation due to animal foraging, soil and litter trampling and deposition of faeces and urine. Practically, the effects of these processes are hardly separable, but their magnitude and direction may vary independently from one another as they are diversely influenced by soil texture (Valentin, 1985) and moisture content (Hoogmoed & Stroosnijder, 1984; Proffitt *et al.*, 1995), herbage phenological status (Hiernaux & Turner, 1996), and also by the animal species involved (Floate, 1981), the stocking rate and type of herd management (Milchunas *et al.*, 1988). Each of these processes have short-term effects on vegetation or soils and their repetition over time carries long-term effects on the species composition of the vegetation and the ability of the soil to support plant production (Floate, 1981). For this experiment the influence of stocking rate and herd composition on animal grazing behaviour and weight performances have been reported elsewhere (Fernández-Rivera & Hiernaux, 1995), as well as effects on vegetation growth during the wet season, disappearance during the dry season (Hiernaux & Fernández-Rivera, 1996) and longer-term effects on species composition (Hiernaux, 1998). This paper deals with the effects of 4 years of grazing treatments on the soil surface features, bulk density and chemical properties of the top 30 cm of soil. The results are discussed along three pairs of competing hypotheses: 1a *vs.* 1b; 2a *vs.* 2b; and 3a *vs.* 3b;

Hypotheses

Hypothesis 1: (1a) the fragile crusts that largely cap Sahelian sandy soils (d'Herbès & Valentin, 1997) are broken by trampling. This enhances soil rugosity and increases water infiltration in the soil (McCalla *et al.*, 1984); (1b) trampling reduces topsoil porosity by compaction and therefore reduces water infiltration in the soil (Blackburn, 1983; Mwendera & Mohamed Saleem, 1997).

Hypothesis 2: (2a) the breaking of soil surface crusts and the reduction of vegetation cover due to grazing results in larger areas covered with loose particules prone to aeolian erosion especially during the dry season (Valentin, 1985; Nickling & Wolfe, 1994); (2b) the reduction of the vegetation cover due to grazing reinforces the kinetic energy of rain impact and favours a rapid reformation of structural crusts at the onset of the rainy season. The new crusts reduce aeolian erosion but increase runoff and sedimentation (Backeus *et al.*, 1994).

Hypothesis 3: (3a) the removal of organic matter due to animal consumption reduces soil biological activity, especially termite foraging above-ground. In the long-run this removal affects the soil organic matter and nutrient pools (Holt *et al.*, 1996); (3b) the deposition of excretions during grazing and resting on the range return a large fraction of the organic material consumed by livestock (Hiernaux *et al.*, 1998). The physical and chemical transformation occurring in the digestive track of the ruminants facilitate faeces mineralization (Ikpe, 1994; Somda *et al.*, 1995). Trampling of the litter by livestock hooves accelerates the mineralization of litter at the onset of rain. Both processes improve synchronization of mineralization with plant needs, promoting faster herbage growth and recycling of nutrients.

Material and methods

Site location and grazing treatments

A grazing experiment was carried out from June 1992 to November 1995 in a fallow site within the ICRISAT research station, at Sadoré, Niger (13°15′ N, 2°18′ E). The fallow, left uncropped and moderately grazed since 1981, was fenced into 18 paddocks subjected to nine different grazing treatments by a factorial arrangement of two stocking rates (62·5 and 125 kg live weight ha^{-1} $year^{-1}$) and four combinations of sheep and goats (6:0, 4:2, 2:4 and 0:6), with two replicates and two ungrazed control plots (4 years of protection in 1995). These stocking rates were selected to cover the range of livestock densities in the southern Sahel districts of Niger (Direction de la Statistique et des Comptes Nationaux, 1995). Animals grazed continuously for 9 months per year in 1·3 to 3·0 ha pastures, then were removed from the paddocks from December to February to graze on millet crop residues. The effects of the grazing treatments were compared to a 16 ha ungrazed control protected since 1981 (Renard *et al.*, 1993), and to an intensely grazed fallow located outside the station fence. The off-station site was open to uncontrolled and intense year-round grazing by cattle, sheep, goats and donkeys since it was last cropped in 1986.

Climate and soils

The climate is tropical semi-arid with an annual rainfall average (1921–1990) of 575 mm (S.D. 138) (Sivakumar *et al.*, 1993). Rains are distributed in a single rainy season from May to October, with 35 (S.D. 5) rainy days. From 1992 to 1995 annual rainfalls were 603, 542, 794 and 482 mm, respectively. All the plots were located on a fossil aeolian sand deposit of 2 to 6 m thick that overlays an indurated and truncated ferruginous soil developed on the sandstones of the 'continental terminal' (Greigert, 1966). Two different soil series occur in the paddocks, known as 'Labucheri' and 'Zogoti' (Table 1), which differ essentially in their thickness and are both classified as 'psammentic Paleustalf; sandy, siliceous, isohyperthermic' (West *et al.*, 1984) in the USDA system of soil classification and as a 'sol ferrugineux peu lessivé en argile et évolué' (Gavaud & Boulet, 1967) in the French system. These soils are largely sandy (90–95%), poor in organic matter content (0·15–0·2% organic C) and acidic (pH water 4·6–5·0). They have a very low cation exchange capacity (1–1·5 meq 100 mg^{-1}), low base saturation (25–50%) and have significant exchangeable aluminum (20–35%) in the top 50 cm. Because they are sandy and poor in organic matter, these soils are weakly structured and therefore highly susceptible to crust formation and wind erosion (Van der Watt & Valentin, 1992).

Soil surface features

Ten elementary types of soil surface features were identified following the classification set up in West Africa (Casenave & Valentin, 1989; Valentin & Bresson, 1992; d'Herbes & Valentin, 1997; Rockström & Valentin, 1997). These features are characterized (Table 2) and include noncrusted surfaces such as free sands, termite galleries and other forms of soil disturbance by biological activity, surfaces covered by mineral crusts such

Table 1. *Texture composition and physical and chemical proprieties of soils from the two series found at the experimental site, Sadoré, Niger*

Soil properties	Labucheri Topsoil *M*	($N=13$) SE	B horizon *M*	($N=35$) SE	Zogoti Topsoil *M*	($N=13$) SE	B horizon *M*	($N=35$) SE
Total sand (%)	91·2	0·5	87·5	0·5	90·4	1·2	82·5	0·6
Total silt (%)	4·7	0·3	4·7	0·2	4·1	0·5	5·8	0·5
Total clay (%)	4·2	0·4	7·6	0·3	5·6	1·0	12·0	0·3
Bulk density air dry* (g cm^{-3})	1·63	0·01	1·53	0·05	1·63	–	1·55	0·04
Water retention difference* (g cm^{-3})	0·13	0·06	0·18	0·09	0·09	–	0·18	0·11
pH (H_2O)	4·9	0·1	4·9	0·1	4·7	0·1	4·9	0·1
pH (KCl)*	4·4	1·1	4·4	0·3	3·7	–	4·0	0·3
CEC (meq 100 g^{-1})	1·3	0·1	1·3	0·1	1·4	0·1	1·8	0·1
Base saturation (%)	41·9	6·5	45·8	3·0	21·3	0·3	53·5	9·2
Al saturation (%)	23·5	4·0	21·1	2·4	38·7	9·0	22·6	6·1

*Meaures on two Labucheri soils and one Zogoti soil only (from West *et al.*, 1984).

as erosion crusts, sedimentation crusts, and structural crusts of either one or three layers, and surfaces covered by microbiotic crusts. The microbiotic crust types derive from the mineral crust type listed above by colonization of the top layer (50–250 μm) by a web of dark cyanobacteria filaments. Schizothrix, Scytonema and Microcoleus cyanobacteria genera were identified in a neighbour site in Niger where a small reduction in water infiltration (−14%) was observed as a result of crust colonization by cyanobacteria (Malam Issa *et al.*, in press).

The area covered by the different types of soil surface (Valentin & Bresson, 1992) was measured along a diagonal transect in the nine paddocks where soils were homogeneously classified as 'Labucheri' soils. The transect line was divided into segments for which the proportions of each elementary type were established. Statistics estimated per paddock were used to calculate the index K_i (soil aptitude for water infiltration) as: $K_i = \sum_{i=l}^{i=n}(K_{\text{in}} \cdot C_n)$, where K_{in} is the mean infiltration coefficient for a the specific crust type n, i.e. the ratio of infiltration depth to rainfall depth in per cent (Table 2), and C_n is the relative areas extent of the specific crust type n.

Soil chemical characteristics

In each paddock, five randomly located pits were dug in each of three situations: beneath the canopy of the most common shrub *Guiera senegalensis* J. F. Gmel.; remote from the canopy; and in an area covered with vegetation or a bare patch, excluding termite mounds and ant nests, which together cover 0·4 ± 0·2% of the site area (density 2·5 ± 1 ha^{-1} with no significant difference between grazing treatments). Soil was sampled in December 1996, with samples taken at four depths: 0–2, 2–6, 6–14 and 14–30 cm. Five samples from the same depth, sampling site and paddock were mixed together and subsampled. Subsamples were air-dried at 35°C and crusted to pass a 2 mm sieve. The pH was measured with a glass electrode in water (pH H_2O) and 1 M KCl (pH KCl) with a 1:1 soil:solution ratio. Samples were analysed for organic carbon (OC), total N by microKjeldhal and autoanalyser, and total P by reduction with amino-naphtol sulphonic acid and autoanalyser (Bray & Kurtz, 1945).

Table 2. *Pattern, physical attributes, rate of infiltration at saturation* (I_l) *and mean coefficient of infiltration* (K_i) *of the main soil surface features encounterd in the study site at Sadore, Niger*

Soil surface feature (*n*)	Pattern	Thickness (mm)	Strength	Porosity	I_l (mm h^{-1})	K_i (%)
One-layered structural crust	Rough surface made of coalescing partially slaked aggregates	5–15	low	moderate	5–10	40–60
Three-layered structural crust	Laminar: coarse sandy at the top, vesicular and fine sandy in the middle, seal of fine particules at bottom	1–3	moderate	low	0–5	15–25
Erosion crust	Smooth surface made of a single seal of fine cemented particles	< 1	high	very low	0–2	2o–30
Sedimentation crust	Laminar multi-layered: larger particle at the top, finer at the bottom	2–50	moderate	low	0–2	20–35
Biotic/termite galleries	A mix of litter, termite galleries, biotic macropores and loose particles	2–20	moderate	very high	25–40	85–100
Free sands	Loose particles with or without litter	15–50	nul	high	15–25	60–75

Adapted from Casenave & Valentin (1992).

Soil bulk density

In the two replicates of three selected treatments (4 years protection from grazing; sheep grazing at 125 kg live weight ha^{-1}; intensive and uncontrolled grazing), 300 cm^3 soil cores were taken using 7-cm wide metallic rings hammered into the same soil profile as the one used for chemical analysis at two depth: 0–7 and 10–17 cm. Sampling of soil cores was performed 2 months after the end of the rains. Determination of the bulk density was done by oven-drying at 105°C for 48 h.

Nomenclature

Plant species are named according to the *Flora of West Tropical African* (2nd Edn) (Hutchinson & Dalziel, 1954–1972).

Results

Soil surface features

Grazing resulted in a reduction ($p < 0{\cdot}01$) and fragmentation of the area crusted despite the concomitant small decrease in noncrusted areas promoted by mesofauna activity (Table 3). The area with microbiotic crusts decreased from 51·5% in the ungrazed control to 18·8% and 14·0% in the paddocks under moderate and heavy sheep–goat grazing, respectively. However, this trend was partially compensated by an increase of newly formed mineral crusts from 4·7% in the ungrazed control to 17·2% and 23·7% under moderate and heavy stocking rates, respectively. The expansion of mineral crusts was explained by an increase of the three-layered structural crusts and, to a lesser extent, erosion and sedimentation crusts. Although not statistically significant, there was a trend for these changes to be more acute when sheep dominated the sheep–goat mix, especially at the higher stocking rate. The infiltration index K_i slightly increased with moderate grazing because of the reduction of crusted soil area, but it decreased at higher stocking rates because of the appearance of new crusts (Fig. 1).

Soil bulk density

Despite a narrow range (1·44–1·65 g cm^{-3}) due to the homogeneous sandy texture, soil bulk density in the ungrazed control was lower under the shrub canopy, especially in the top horizon ($p < 0{\cdot}001$), and only marginally greater in patches covered with vegetation than in the bare patches (Table 4). Grazing increased the bulk density of the top horizon found beneath the shrub canopy at any of the stocking rates, but only with high stocking rates for soils in herbage patches away from shrub canopies. Grazing had no effect on the bulk density of the deeper horizon except for a decrease observed in the bare soil patches subjected to intense grazing.

Soil OC, N and P contents

In all situations, the content in OC decreased sharply between the top 2 cm (about 0·5% C) to the horizons below, down to 30 cm (about 0·25% C). Controlled grazing for 4 years led to a minor but consistent decline of OC across all topsoil depths and situations (Fig. 2). However, OC concentrations under intense grazing varied from those observed in soils under controlled grazing and those under protection from grazing. Total N concentration followed the same trend. It decreased sharply between

Table 3. *Area covered (%) by different soil surface features in fallow subjected to continuous sheep-goat grazing at stocking rates of 62·5 (moderate) and 125 kg ha⁻¹ (heavy) for 4 years, at Sadoré, Niger*

Type of soil surface features	Area covered by each soil feature type (%)					
	ungrazed control		moderate sheep grazing		heavy sheep grazing	
	mean (SE)		mean (SE)		mean (SE)	
Surface disturbed by biological activity	30·5		24·1 (4·4)		25·2 (6·4)	
Termite galleries	8·2		5·9 (1·4)		5·2 (3·0)	
Free sands	5·0		32·4 (3·4)		31·8 (12·1)	
Total with no crust		43·7		62·5 (3·3)		62·2 (3·8)
Structural crust, 1-layered	4·7		14·0 (8·6)		10·2 (4·0)	
Structural crust, 3-layered	0·0		4·3 (6·3)		12·0 (6·2)	
Erosion crust	0·0		0·4 (0·6)		1·5 (2·3)	
Total minerals crusts		4·7		18·7 (5·0)		23·7 (2·4)
Sedimentation crust + cyanobacteria	4·6		2·6 (5·1)		0·3 (0·3)	
Structural crust + cyanobacteria	47·0		16·1 (6·5)		12·0 (4·7)	
Erosion crust + cyanobacteria	0·0		0·1 (0·3)		1·8 (0·6)	
Total microbiotic crusts		51·6		18·8 (2·6)		14·1 (2·6)

the first 2 cm and the rest of the topsoil (Fig. 3). Four years of controlled grazing markedly reduced the N concentration, especially in the second 2–6 cm layer in all situations. However, in the intensely grazed range, the N concentration profile did not show this decrease below the surface layer. On the contrary, N concentration was slightly higher that in the ungrazed control. The profiles for total P were less regular and generally did not show a sharp reduction between the surface layer and the rest of the topsoil. Larger values are found in the second layer (2–6 cm), both under the shrub canopy and in 'bare patches' of the ungrazed control, than in the top 2 cm layer. Reduction of total P content with 4 years of controlled grazing was not consistent and did not apply to the vegetated patches away from shrub canopies. However, unlike total N, the P content in the intensely grazed range was systematically lower than in the grazed and ungrazed paddocks.

Soil pH

Soil acidity increased with depth in all soil profiles, but less sharply under the shrub canopy than elsewhere (Fig. 2). Controlled grazing tended to increase acidity at the soil

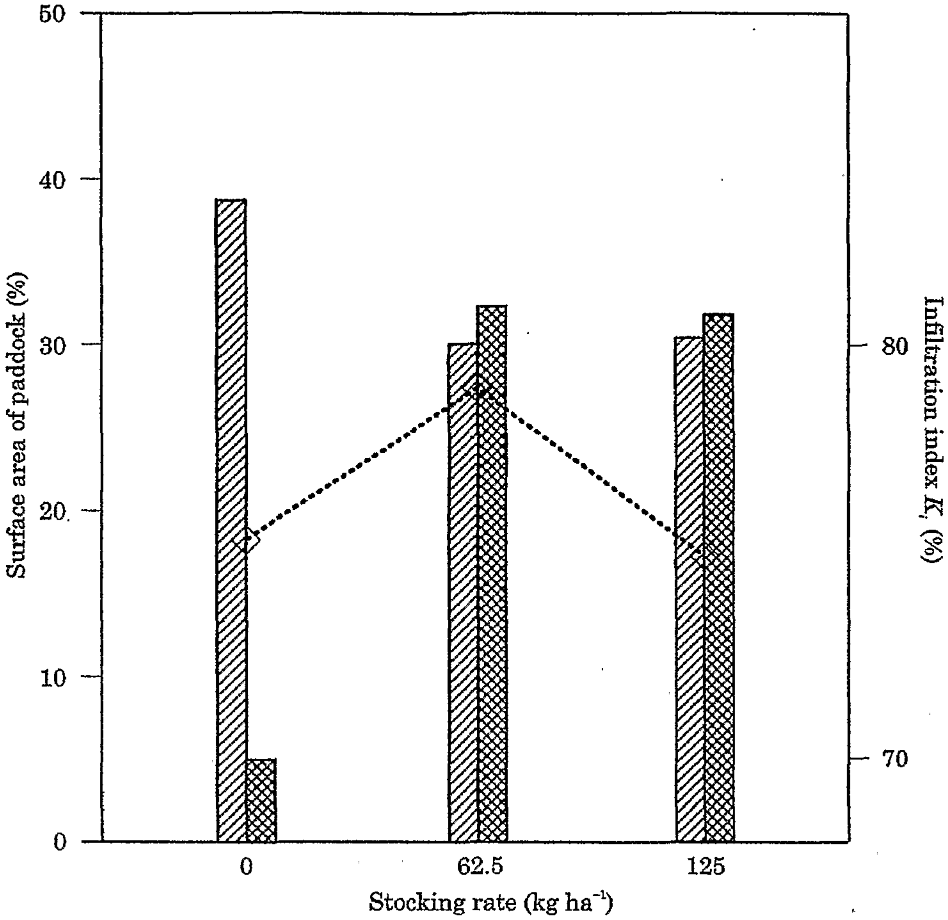

Figure 1. Extent of soil surfaces with no crusts, either disturbed by mesofauna activities (▨) or free sands (⊠), in per cent of paddock area, and soil infiltration index (K_i, ◇ ··· ◇) resulting from 4 years of grazing at two stocking rates, or with protection from grazing in Sadoré, Niger.

surface but not in the deeper horizon except in the bare soils patches where the pH was strikingly higher in the ungrazed control. The acidity measured in the intensely grazed fallow outside the station fence was higher than in any other treatments.

Discussion

The effects of trampling

Four years of grazing by sheep and goats reduced and fragmented the soil crusts (Table 3). Moreover, 'sedimentation surfaces' also decreased as stocking rates increased, supporting the notion that trampling improves water infiltration (hypothesis 1a). However, the small differences observed in these effects as the stocking rate doubled indicate that the trampling effect on crusts is not simply proportional to stocking rate. It could rather follow the model proposed by Guthery & Bingham (1996). The diminution of soil porosity as a result of soil trampling by sheep and goats (Table 3) was observed in soils located below shrub canopies where the soil porosity was higher to

Table 4. *Bulk density (air-dried) of topsoil of fallow sites in Sadoré, Niger, according to grazing history and type of vegetation cover*

				Away from shrub canopy			
		Under shrub canopy		vegetated patch		bare patch	
Grazing treatments	Soil depth (cm)	mean ($g\ cm^{-3}$)	S.D. ($g\ cm^{-3}$)	mean ($g\ cm^{-3}$)	S.D. ($g\ cm^{-3}$)	mean ($g\ cm^{-3}$)	S.D. ($g\ cm^{-3}$)
Ungrazed control (4 years)	0–7	1·44	0·08	1·59	0·07	1·61	0·05
	10–17	1·52	0·05	1·59	0·05	1·62	0·03
High sheep stocking rate (4 years)	0–7	1·53	0·11	1·58	0·07	1·60	0·04
	10–17	1·56	0·03	1·58	0·04	1·64	0·05
Intense mixed grazing (9 years)	0–7	1·55	0·05	1·65	0·02	1·64	0·02
	10–17	1·54	0·03	1·58	0·05	1·54	0·04

start with and where the kinetic energy of the rain is attenuated by the canopy shelter (Hoogmoed & Stroosnijder, 1984). Even in the off-station site, 9 years of intense and year-round grazing by sheep, goats, cattle and donkeys only marginally increased soil bulk density in the top layer. These results contradict the systematic increases in bulk density (from 1·50 to 1·64) of the soil layer directly under the surface of loose sands observed when getting closer to water holes in Senegal rangelands (Valentin, 1985). Ten per cent more silt in the Senegal sandy soils could contribute to this difference. It is concluded that, unlike in other soils of the Sahel, compaction by trampling in grazing situations is marginal on these extremely sandy soils (i.e. 90 to 95% sand including about 30% of coarse to medium sand) (hypothesis 1b).

Unlike structural and sedimentation crusts, erosion crusts expand with grazing intensity together with free sand surfaces (Table 3). This could indicate a higher sensitivity to wind erosion as trampling intensifies (hypothesis 2a). A similar interpretation has already been proposed for such changes in soil surface observed in heavily trampled sites in Senegal and Mali (de Wispelaere, 1980; Valentin, 1985; Nickling & Wolfe, 1994). Although wind erosion was not measured in any of these studies, the observed trend is consistent with experimental results obtained in wind tunnels on soils surfaces disturbed by driving a truck over the soil (Gillette *et al.*, 1980). The formation of new mineral crusts that partially compensated for the destruction of the old microbiotic crusts for up to a third of the old crust area at moderate stocking rate, and up to half of that area at high stocking rate supports the fact that grazing increases soil susceptibility to crust formation (hypothesis 2b). The reduction in vegetation cover, lower soil organic carbon contents in the topsoil (Fig. 2) and the deflation of fine granulometric fractions from the top layer (Valentin, 1985) could all contribute to enhance susceptibility to crusting.

Grazing reduced the area of soil surfaces displaying mesofauna activities including termite galleries by about 20% and led to a reduction of OC and N in the topsoil, which indicates a reduction of soil biological activity (hypothesis 3a). The reduction in apparent mesofauna activity at the soil surface could be due, at least in part, to the difficulty to appreciate more diffuse patterns of activities in trampled soils. On the other hand, reduction in organic C and N contents could reflect higher mineralization rates, although P content is not affected as much. Nevertheless, the trends did not increase as stocking rates doubled, despite the observed reduction in herbage production

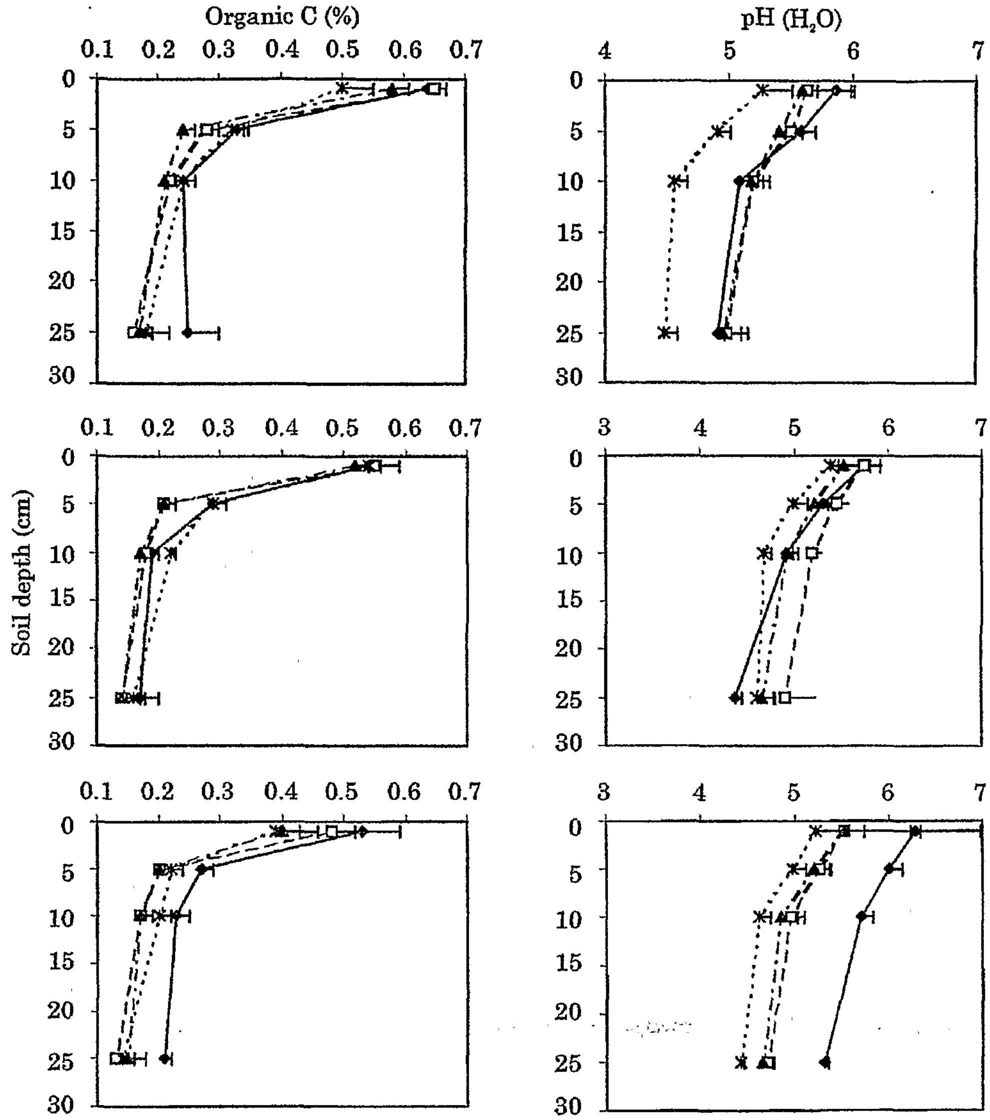

Figure 2. Topsoil profile of the pH (H_2O) and organic carbon content in a Sahelian fallow subjected to four continuous grazing treatments: sheep at moderate (62·5 kg ha^{-1}; □) and heavy (125 kg h^{-1}; ▲) stocking rates, ungrazed control (◆), and an intense but uncontrolled mixed grazing for 9 years (×) at Sandoré, Niger. Top panel: beneath shrub canopy; middle panel: herbage away from shrub; lower panel: denuded soil patch away from shrub.

(Hiernaux & Fernández-Rivera, 1995). Thus, a reduction of soil biological activity is most probable whenever the balance of organic material returned to soil is negatively affected by grazing. In the restricted areas where the balance of organic material is improved by grazing, with returns exceeding offtake, such as in livestock resting sites, pathways and at the vicinity of water points, soil biological activity is boosted and mineralization accelerated to the benefit of herbage growth (hypothesis 3b). In this experiment, night resting sites were not sampled, but the contrast between the environmental conditions and the high vegetation productivity of sites much frequented by

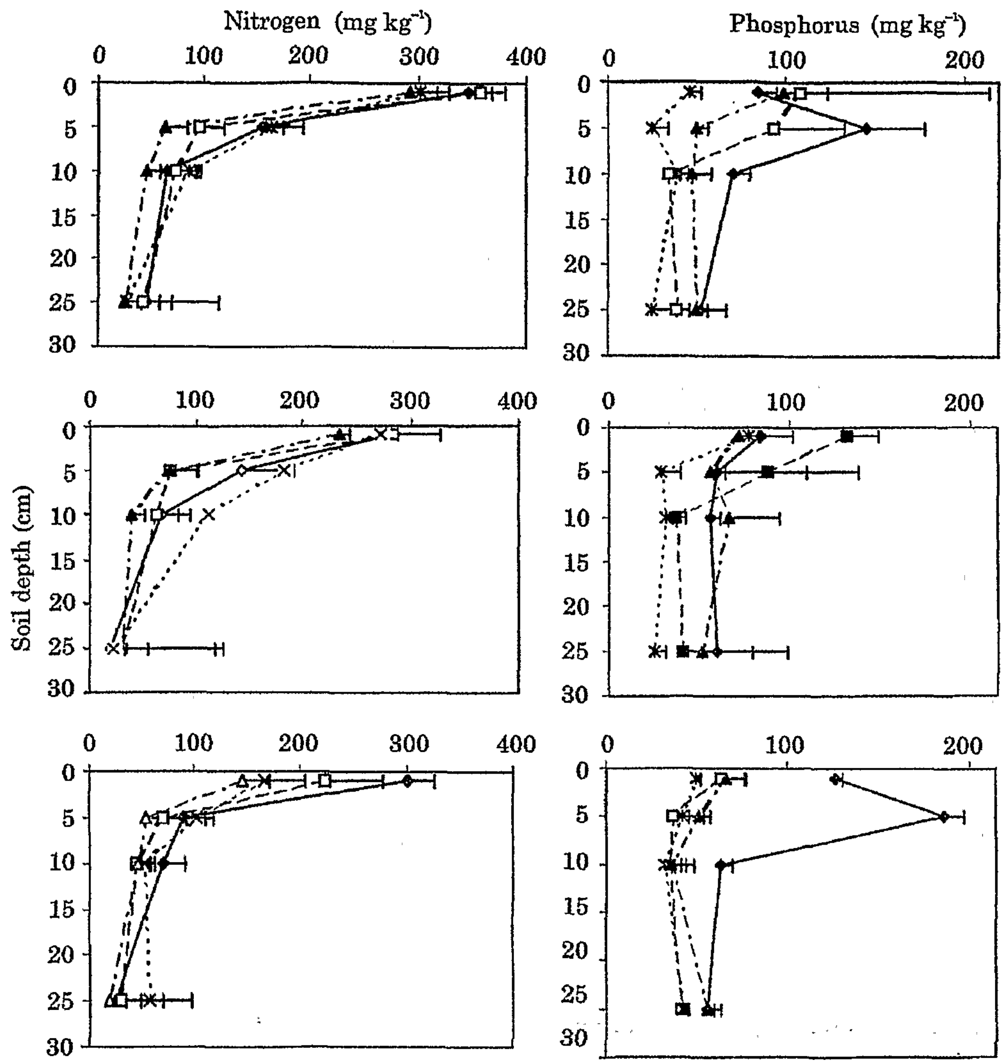

Figure 3. Topsoil profile of the total nitrogen and phosphorus contents in a Sahelian fallow subjected to four continous grazing treatments: sheep at moderate (62·5 kg ha^{-1}; □) and heavy (125 kg ha^{-1}; ▲) stocking rate, ungrazed control (◆) and an intense but uncontrolled mixed grazing for 9 years (×) at Sadoré, Niger, Top panel: beneath shrub canopy; middle panel: herbage patch away from shrub; lower panel: denuded soil patch away from shrub.

livestock has often been noted in the Sahel (Valenza, 1981; Valentin, 1985; Hanan *et al.*, 1991).

Implications for water balance, runoff and soil erosion

The effect of the grazing treatments on rain infiltration, runoff and soil water balance was not measured. However, following the indications given by the soil infiltration index, the ability of sandy soils to infiltrate water was enhanced at moderate stocking rates and returned to the values found in the ungrazed control at the higher stocking rate.

The first trend is easily explained by the breaking of soil surface crusts (hypothesis 1a). It is in agreement with the effects of superficial tillage practised on millet fields in the Sahel during manual weeding with a hoe or an 'iler' (Peugeot *et al.*, 1997; Rockström & Valentin, 1997). Soil compaction does not appear to be the main cause for increased runoff at high stocking rates in these extremely sandy soils, unlike on the finer textured red duplex soils of Australia (Proffitt *et al.*, 1995). Instead, the reduction of infiltration at higher stocking rates could be due to the higher susceptibility to new crust formation (hypothesis 2b) favoured by the reduction of vegetation cover and by stronger wind erosion (Nicking & Wolfe, 1994).

Indirect effects of livestock grazing on soil organic matter and nutrient cycling

Lower contents of OC, N and P found after 4 years of controlled grazing when compared to the ungrazed control (Figs 2 & 3) could be accounted for by the reduction in organic matter returned to the soil due to the negative balance between feed intake and faeces plus urine excretion in the paddock (Fernández-Rivera *et al.*, 1995). In the case of the higher stocking rate it may also be accounted for by the reduction in herbage production (hypothesis 3a) due to defoliation (Hiernaux & Turner, 1996). The differences in OC, N and P concentrations due to grazing apply more to the 2–6 and 6–14 cm soil layers than to the top 2 cm. More active mineralization, higher nutrient uptake by stressed plants (hypothesis 3b) and greater leaching with increased infiltration could have contributed to these larger decreases in soil OC, N and P just below the top layer but no measures were made of mineralization or leaching that could verify these hypotheses. On the other hand, changes in species composition with the grazing treatments could also have affected topsoil organic matter and nutrient contents. Light grazing favoured grasses and enhanced herbage production while heavy grazing promoted dicotyledons, especially unpalatable species such as *Sida cordifolia, Cassia mimosoides* and *Mitracarpus scaber* (Hiernaux, 1998). These dicotyledons differ markedly from the annual grasses in having higher N and P concentrations and by the shedding of the leaves at wilting by the end of the growing season so that they rapidly decompose if the soil is still moist and soil fauna very active (Ikpe, 1994). The large dominance of *Sida cordifolia* Linn. and *Mitracarpus scaber* Zucc. in the pasture subjected to intense grazing (61·2% of plant cover in September 1996) could account for soil organic matter and nitrogen contents being equal to or greater than the ungrazed control (Somda *et al.*, 1995). On the contrary, total phosphorus was markedly lower at all depths in the soil of the the intensively grazed pasture compared to soils under other treatments. It is not possible, however, to determine if the lower P contents are due to the cumulative effect of grazing treatment, through selective intake by livestock (cattle consume *Sida cordifolia* inflorescences that are relatively rich in P) or if it results from deficiency of the soils. The surprisingly high values of pH, organic matter and P content in the bare patches found away from shrub canopies in the ungrazed control were associated with the accumulation of organic matter in previous years (confirmed by the relatively high organic matter content in the topsoil) that locally impeded the germination of annual herbs, leaving the patch temporarily bare (Hiernaux, 1998). In addition, the soil in these bare patches was covered by a solid 3-layered structural crust densely colonized by cyanobacteria which might have contributed to the high pH values (Harper & Pendleton, 1993; Verrechia *et al.*, 1995).

Implications for soil fertility management

Topsoil pH (H_2O) increased from 4·7–5·4 to 5·2–6·0 in the top 15 cm, and the content of organic carbon marginally increased from 0·17–0·31 to 0·33–0·45%, while bulk density remained constant between August 1982 (Table 1), just prior to the fencing of the Research Station (West *et al.*, 1984), and November 1995. These increases after 13 years of fallowing under moderate grazing are marginal. They led to a modest improvement of the soil fertility status which contrasts, however, with the extremely low fertility status (topsoil pH (H_2O) of 4·7 and organic C of 0·15) of soils of the same research station that had been planted with millet for 8 years without amendment (Bationo & Mokwunye, 1991).

The small reduction in OC, N and P contents of the topsoil after only 4 years of controlled sheep and goat grazing when compared to the soils of fallow that remained ungrazed during the same period confirm the sensitivity of soil fertility to grazing. However, on the off-station site that was intensively grazed for 9 years, P contents were only slightly lower, while N and OC were slightly higher than after 4 years of controlled grazing. This may be due to differences in soils but could also be explained by the adaptation of the vegetation composition to grazing pressure with the development of poorly palatable dicotyledon species which ensure high primary production, high N content in the litter and a fast recycling of the organic material.

Conclusion

Four years of grazing by sheep and goats had a major impact on the soil surface features of old Sahelian fallows but no significant effect on the soil bulk density of very sandy soils, and led to minor decreases in OC, N and P contents in the topsoil. These effects did not develop homogeneously over the landscape nor in proportion to the stocking rates and duration of grazing. Soil biological activity, water infiltration, and topsoil contents of OC, N and P were greater in soils sheltered by shrubs and lower in bare soil away from the shrubs. They were also more affected by grazing than in soils away from shrubs but covered by herbaceous plants. The nonlinearity of changes in soil properties with grazing intensity is illustrated by the increase in the soil water infiltration index at moderate stocking rate and its decrease as stocking rate further increased (Fig. 1). The lag time required for some of the feedback processes to operate could explain the nonlinearity of other changes. This would apply to the effects on soils of the changes in the vegetation pattern and composition that took place over the years in adaptation to grazing pressure (Hiernaux, 1998). Changes in soil surface features, bulk density and topsoil organic matter and nutrient contents were good indicators of the effect of livestock grazing on soils, however direct measures of the livestock impact on wind erosion, water runoff, infiltration and leaching would be required to establish a quantitative model of livestock impact. Extrapolation of the results of this trial to the Sahel region would also require a diversification of the study sites (land use, soil texture, topography), animal species and grazing system considered.

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