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Nutrient Cycling in Integrated Rangeland/Cropland Systems of the Sahel

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ABSTRACT

In the Sahel of West Africa, the productivities of rangelands, croplands and livestock are inextricably linked. Cattle, sheep and goats graze rangelands and crop residues, and their manure/urine is used to fertilize crops. Rangelands provide important feeds during the manuring period, resulting in a net nutrient transfer from rangelands to croplands. This paper examines the sustainability of nutrient transfers in integrated rangeland/cropland systems of the Sahel by examining the impact of grazing on rangeland vegetation structure and floristic composition, the impact of livestock on nutrient balances of rangelands and croplands, and the role of livestock in offsetting nutrient deficits through manuring. Rangeland nutrient balances are in equilibrium (inputs = offtakes) whereas croplands lack the internal capacity to replenish nutrient offtakes in grain (as food) and crop residues (as feed). Although soil nutrient mining is of general concern for the Sahel, local management practices of some farmers (e.g. corralling animals overnight on fields between cropping seasons, use of fertilizers) offset cropland nutrient deficits. The number of additional livestock, and their feed requirements needed to supply sufficient manure to offset cropland nutrient deficits, depend on rangeland and cropland productivity, livestock production goals, and management strategies of farmers. Livestock must be managed so they do not deplete the nutrient supply of rangelands in order to increase the manure supply for improving cropland productivity. Sustained rangeland productivity in the Sahel will depend largely on producing alternative feeds derived mostly from croplands. Land use and tenure policies that inhibit livestock mobility and, therefore, farmers' access to the manure of pastoralists herds, will greatly undermine the resilience of

Sahelian rangelands, and increase the need for other external nutrient inputs such as fertilizers to prevent declines in soil fertility and crop yields.

INTRODUCTION

The Sahel is a 400 km wide band situated immediately south of the Sahara desert. Rainfall varies between 100 and 600 mm annually. The drier, northern part of the Sahel is used for pastoralism, whereas the more humid south is used for mixed farming, involving the integration of crops and livestock.

In the Sahel of West Africa the productivities of rangelands, croplands and livestock are inextricably linked. Although most agricultural products are used for subsistence purposes, some outputs of rangeland (wood, bush straw, fruits), cropland (grains, crop residues, legume hays), and livestock (animals, milk, meat, skins) are sold (Fig. 1). Ruminants are the main source of cash for farmers of the Sahel. They also buffer food supplies during years of inadequate rainfall when crop production is low or fails completely.

The principal challenge facing cropping in the Sahel is how to achieve sustainable increases in grain production while maintaining or enhancing soil resources. The plant nutrients contained in animal manure, most of which are derived from rangelands, have long provided fertility to cropland. Fertilizers are generally unavailable and are not used in most cropping systems. For livestock, the major challenge is overcoming large seasonal fluctuations in feed supply and quality. Natural pastures and crop residues are the principal animal feeds. Diet supplements are used in few production systems. Sustainable feed supplies, and therefore livestock production, depend on maintaining or enhancing the productivity of both rangelands and croplands. An excessive removal of vegetation for animal feed (and other purposes such as fuel, construction materials, etc.) depletes soil nutrient reserves and increases the risk of soil erosion and environmental degradation. The purpose of this paper is to review research related to plant/livestock/soil interactions and nutrient cycling, and use these findings to suggest ways for setting research priorities and strategies that could enhance nutrient cycling and sustain the productive capacity of integrated rangeland/cropland systems of the Sahel.

LIVESTOCK PRODUCTION SYSTEMS OF THE SAHEL

Pure pastoralism, one of the few specialized forms of livestock husbandry still occurring in sub-Saharan Africa, is still widely practised in the Sahel,

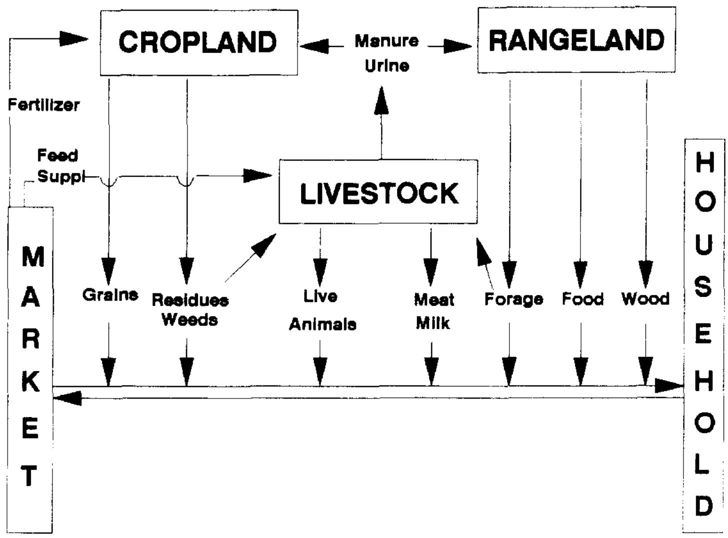

Fig. 1. Flow of agricultural products in integrated rangeland/cropland systems of the Sahel.

but is decreasing in importance. Increasing human populations combined with long-term weather changes are transforming pastoralist systems based on transhumance and communal grazing of rangelands, and cropping systems based on extensive shifting cultivation, to more sedentary, intensively managed enterprises (Winrock International, 1992). The transformation from specialized to integrated systems is a dynamic and evolutionary process. As livestock husbandry becomes more settled it incorporates crop production whereas specialized, extensive cropping systems integrate livestock (McCown *et al.*, 1979; McIntire *et al.*, 1992). Rangeland grazing is substituted slowly by cropland forages. The shift from pasture to cropland has several consequences for feed availability and quality. Not only is there a total reduction in the amount of pasture available, but pastures may become seasonally inaccessible due to fragmented cropping and/or the expansion of dry-season gardening in low-lying areas. An encroachment of cropping onto traditional dry season pastures is jeopardizing the livelihood of many pastoralists (Traoré & Breman, 1992). Also, as the pressure on land elevates and more land is cultivated, herds are confined to smaller rangeland areas during the cropping season to avoid crop damage. This may shift the nutritional constraint facing livestock from the dry to the wet season, and increase the risk of overgrazing and environmental degradation.

Most livestock in the Sahel are integrated into mixed farming systems, or systems involving the integration of livestock (cattle, sheep and goats) with crop production. Millet (*Pennisetum glaucum*) and sorghum (*Sorghum bicolor*) are the principal grain crops in the region; fonio (*Digitaria exilis*) is important in some areas, and rice (*Oryza glaberrima*) is cultivated in delta areas and along the borders of the Niger river. The legumes cowpea (*Vigna unguiculata*) and groundnut (*Arachis hypogaea*) are both subsistence and cash crops; grain and hay may be sold. Livestock holdings of mixed farming systems range from a few to hundreds of head per household with varying ratios of cattle, sheep and goats (Wilson, 1986; Swinton, 1988).

In mixed-farming systems, crop residues provide vital feeds during the 6–8 month dry season and manure enhances soil fertility for crop production. Most cereal stovers are grazed freely in fields and groundnut and cowpea hays are stored for feeding during the dry season. Manure is obtained either from one's own livestock, from the livestock of other farmers, or through exchange relationships with pastoralists. Manuring contracts between farmers and pastoralists are still important in some areas, and farmers have developed a variety of ways to combine their own smaller herds in order to manure large areas of cropland. Common constraints to most mixed farming systems in the Sahel include inadequate feed resources, reduced fallow periods, declining soil fertility, soil erosion, lack of access to agricultural inputs and encroachment of cropping onto grazing lands.

LIVESTOCK AND NUTRIENT CYCLES

The predominantly sandy soils of the Sahel are very low in organic matter (Kowal & Kassam, 1978; Pieri, 1989), nitrogen and especially phosphorus (Breman & de Wit, 1983). Farmers in the region continue to rely principally on organic matter recycling to maintain the productivity of their cropland. Livestock have long played a key role in these processes.

In the Sahel, livestock are the principal vectors of nutrient transfer across the landscape. The cycling of biomass through livestock, and the use of manure and urine to fertilize the soil, has long been an important linkage between livestock and soil productivity in semi-arid Africa (McCown *et al.*, 1979; Swift *et al.*, 1989; McIntire *et al.*, 1992; Powell & Williams, 1993). While grazing crop residues, livestock remove more nutrients from croplands than they return in manure (Powell & Williams, 1993). Cropland nutrients are replenished by hand-spreading manure onto fields or by corralling livestock directly on fields overnight after daytime grazing of rangelands. These manuring practices result in a net nutrient transfer from rangelands to croplands (Sandford, 1989; Swift *et al.*, 1989).

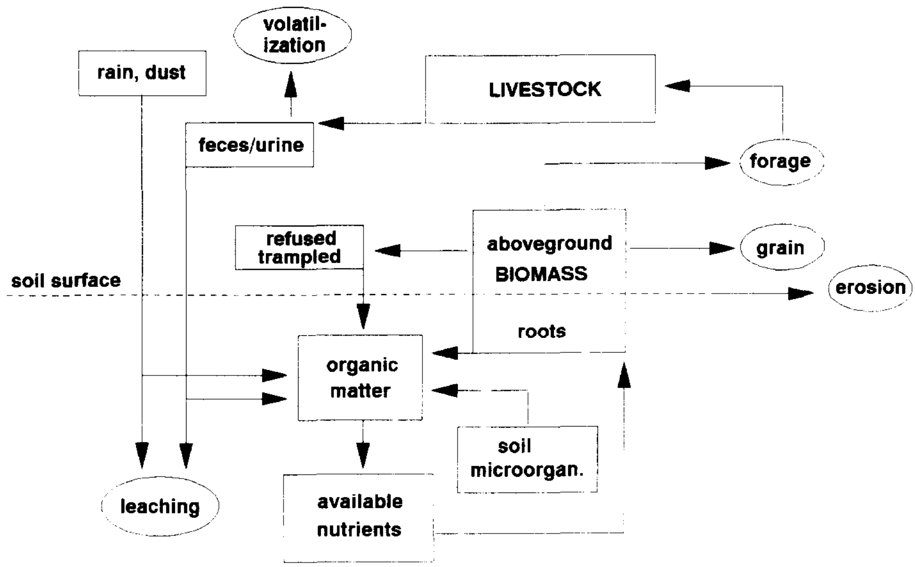

Fig. 2. Internal nitrogen flows in rangelands and croplands of the Sahel (inputs are rectangles, outputs are ovals).

Although animal manure is perhaps the most important soil fertility amendment farmers apply to cropland, the nutrient transfer mechanisms, and the ability of rangelands to support nutrient harvesting by livestock, are poorly understood. An identification of nutrient pools and quantitative estimates of nutrient flows across landscapes are essential for identifying management strategies that can improve and sustain their productive capacity. The internal capacity of rangelands and croplands to maintain a nutrient balance depends on the amount of nutrients harvested as grain and forage and nutrient losses (leaching, erosion, etc.) vs. nutrient returns via feed refusals, trampled biomass, roots and various natural inputs (Fig. 2).

Nutrient cycles of rangeland

For the Sahel in general, inadequate soil water constrains rangeland and cropland production in areas receiving less than 250 mm annual rainfall, whereas soil nutrients limit biomass production in higher rainfall areas (Breman & de Wit, 1983). For most parts of the Sahel, water appears to be limiting only in shallow soils and during years of low rainfall (Penning de Vries & Djitèye, 1982; van Keulen & Breman, 1990). The strong seasonality of Sahelian rangeland systems, due to extremely high rainfall variability, reduces the risk of overgrazing, and has long ensured their

TABLE 1

Annual Nitrogen Removals, Returns and Balances (kg/ha) for Rangelands in Integrated Rangeland/Cropland Systems of Mali

	Production system		
	Semi-arid rainfed crops	*Niger delta*	*Subhumid rainfed crops*
Nitrogen removals			
Wet season grazing	4·0	13·5	8·1
Dry season grazing	5·2	17·5	10·5
Nitrogen returns			
Non-consumed pasture	3·4	11·5	6·9
Manure	1·5	4·9	2·9
Roots	1·2	3·7	2·2
Other (rain/dust, soil microorganisms)	2·4	10·5[a]	4·6
Nitrogen balance	−0·8	−0·4	−1·9

[a]Approximately 8 kg/N added by floodwaters of the Niger river, 40% of which is eventually recycled through plants.
Source: Powell & Coulibaly (1995).

sustained productivity (Cissé, 1986; Hiernaux, 1993; Hiernaux *et al.*, 1995). Livestock-induced changes to Sahelian rangelands appear to be short-term and limited to small areas, such as around watering points, along trekking routes, etc.

Short-term effects of livestock on rangelands

Over the short-term, grazing lowers vegetation cover and above-ground biomass production. The effects of grazing during the wet season on subsequent plant growth depend on timing, frequency and intensity of the defoliations. Although frequent grazing can reduce the dry matter (DM) production of annual grasses by 50%, cumulative plant nitrogen (N) and phosphorus (P) uptake in grazed areas is equal to, or is slightly greater than nutrient uptake in ungrazed controls (Hiernaux & Turner, 1996). In contrast to annuals, perennial grasses are very sensitive to repeated defoliation during the wet season (Oesterheld & McNaughton, 1991). Nutrient concentration in above-ground DM increases, but nutrient uptake does not, in perennials cut repeatedly during the wet season (Ruess *et al.*, 1983).

Grazing, especially of annual grasses during the dry season, results in DM losses due to trampling. This return of litter to soils enhances seed germination and seedling establishment at the start of the following rainy season (Renard *et al.*, 1993), and is important to cycling nutrients in these rangeland systems (Table 1; Fig. 2). Grazing perennial grass regrowth stimulates their DM production and nutrient uptake (Hiernaux & Diarra, 1986).

The short-term effects of browsing on tree and shrub phenology and production vary among species, intensity and season (Cissé, 1980). The effects of browsing on foliage production is minor compared to the effects of interannual climatic fluctuations (Hiernaux *et al.*, 1994). However, lopping branches to feed livestock, slashing shrubs and cutting trees for fuel, construction materials, etc., may severely affect their phenology and production.

Long-term effects of livestock on rangelands

Over the long-term, grazing can influence the floristic composition of rangelands, plant morphology, as well as plant productivity and feed quality. Defoliation can promote vegetative regrowth at the expense of reproductive organs. When grazing pressure remains high, especially on annual plants, flowering and the production of seeds can be substantially reduced, threatening the propagation of the plant species over years (Carrière, 1989; O'Connor & Pickett, 1992). Because grazing in the Sahel is often location and plant species-specific (Diarra *et al.*, 1995), the preferred spots and species are more strongly affected, which leads to rapid and patchy changes in the floristic composition of these range sites.

In the Sahel, preferred species are replaced either by less palatable ones, or by species that cope better with defoliation because of their short growing cycle (Turner, 1992). Less palatable, long-cycle species tend to encroach in the vicinity of watering points, corral sites and transhumance pathways, where soil fertility is enhanced due to manure and urine deposition (Hanan *et al.*, 1991). Although these less palatable plants reduce forage and nutrient availability for livestock, more organic matter is returned to the soil which can then lessen the risk of soil erosion in these spots of extremely high grazing pressure.

Many of the annual plants promoted by heavy grazing have low production potential due to their small size and short growing cycle (Hiernaux *et al.*, 1995). The forage produced by these species is palatable and of good nutritional quality, but they remain green during only a few weeks of the year. The large number of seeds produced and their staggered germination pattern promote their resilience to both grazing pressures and hiatus in rainfall (Elberse & Breman, 1990).

The long-term effect of livestock on woody plants is difficult to assess. Browsing is highly species-selective and diffuse, both among plants in a population and within a canopy of individual trees and shrubs. Even preferred species are not systematically damaged by livestock, even following the 1983–84 drought (Hiernaux, 1993). The establishment of some browse species is favoured by livestock, because seed dormancy can be broken in the animal's digestive tract.

In the Sahel, the high rainfall variability and traditional mobility of pastoralists' herds has ensured a natural equilibrium between rangeland productivity and livestock numbers. In the Gorma region of northern Mali, Hiernaux (1993) found that forage yields in 25 rangeland sites over a 10-year period have been more affected by rainfall amount and its distribution, and soil type and topography, than by grazing pressure. This study continues to show that the influence of grazing history on plant communities is only conspicuous in situations of extreme livestock pressure: in the vicinity of camps, watering points and other livestock resting and concentration points. Elsewhere, the influence of grazing on the floristic composition of these range sites is masked by the strong interaction between seed germination, plant establishment and the distribution of the early rains (Cissé, 1986). The influence of grazing on rangelands is also confounded by various plant responses (tillering, high seed production, etc.) to drought and herbivory. Species promoted by heavy grazing during the growing season in a given biome are also often found in lightly or ungrazed sites in drier climates or more xeric conditions (Breman & Cissé, 1977).

On a regional scale, the long-term resilience of Sahelian rangelands to drought and herbivory is due primarily to a strong dynamism among seed production, dispersion and germination of annual plants and an equilibrium between herbaceous and woody plants. However, local livestock management practices can greatly influence these factors (Turner, 1995). In sedentary agropastoral systems, persistent grazing of rangelands around villages during the rainy season can lead to rapid changes in the floristic composition of the vegetation, to the benefit of either unpalatable or short-cycle and poorly productive plant species. This can reduce livestock production and therefore nutrient transfer to croplands, which in turn can diminish crop residue availability to livestock. Organizing the seasonal mobility of livestock to avoid continuous grazing during the growing season could overcome such a regressive trend. Exploiting the feed quality gradient across the landscape (Westoby *et al.*, 1989; Scoones, 1994) provides some flexibility for management at local scales while preserving the ecosystem resilience.

Indirect effects of livestock on rangelands

Vegetation removal and trampling by livestock can enhance water run-off and soil erosion. Trampling increases soil bulk density and decreases water infiltration rates (Mbakaya *et al.*, 1988; Mulholland & Fullen, 1991). Fine-textured or wet soils are more susceptible to trampling than coarse-textured or dry soils (Abdel-Magid *et al.*, 1987). Treading some soils, however, may increase soil surface roughness and improve infiltra-

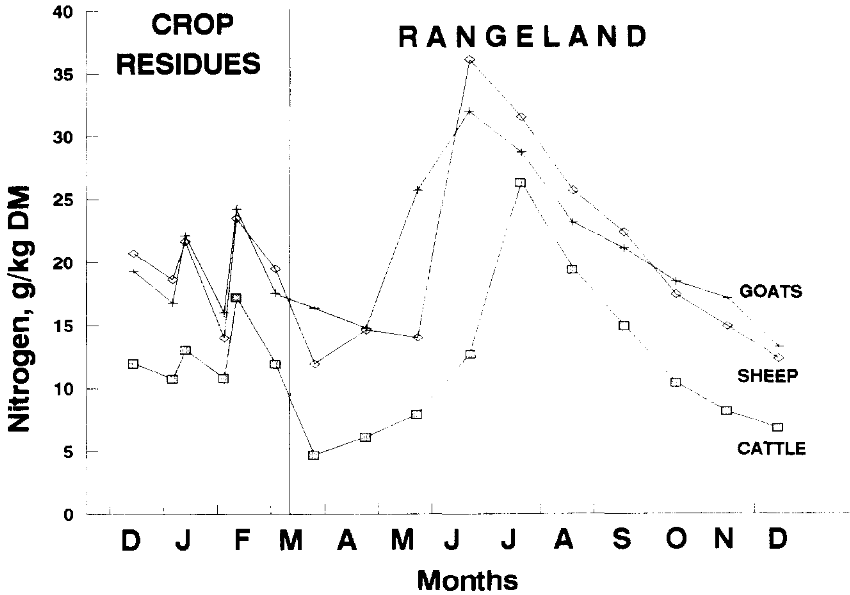

Fig. 3. Nitrogen concentration in the diet selected by cattle, sheep and goats grazing rangeland and crop residues in the Sahel (source: Fernández-Rivera, unpubl.).

tion by breaking soil surface crusts (Casenave & Valentin, 1989). In some cases, breaking crusts can facilitate wind erosion, leading to mosaics of deflation and accumulation patches in the landscape. Water runoff from livestock tracks may also erode soils, especially when slopes are steep enough to trigger the formation of gullies (Valentin, 1985).

Nutrient removal from rangeland as animal products

Livestock can be major vectors of nutrient removal from rangelands (Senft *et al.*, 1987). The quantity of feed consumed and the concentration of nutrients in the diet vary seasonally and across animal species. The diet selected by cattle in Sadoré, Niger, is lower in N than that selected by small ruminants and can vary dramatically during the year (Fig. 3). In Mali, Schlecht *et al.* (1995) observed that the dietary N selected by cattle varied from 1·3% in the late dry season to 4·2% in the early wet season. Data from other studies reviewed by Diarra *et al.* (1995) suggested averages in N concentration in cattle's diet of 2·0% in the mid-wet season, 1·2% in the early-dry and 0·6% in the late-dry season.

Cattle grazing Sahelian rangelands ingest approximately 35 kg N and 5 kg P per year (Diarra *et al.*, 1995; Schlecht *et al.*, 1995). Assuming stocking densities of 15 TLU/km^2 (TLU is a tropical livestock unit, or a 250 kg animal liveweight basis), dry matter yields of 1·2 tons/ha and average concentrations of 1·5% N and 0·125% P in the plant material, the nutrient removal rates (5·2 kg N and 0·75 kg P/ha) would be equivalent to approximately 30% of the total N and 50% of the total P assimilated by plants for above-ground dry matter production.

Only a small proportion of the nutrients ingested by livestock are transformed into animal tissues during growth. Assuming annual live-weight increases of 30 kg/TLU and concentrations of N and P in cattle tissue as given by A.R.C. (1980), Diarra *et al.* (1995) estimated that 0·75 kg N and 0·24 kg P are retained in the animal's organism. With stocking rates of 15 TLU/km^2, these removal rates would be equivalent to annual exports of 134 g N and 43 g P/ha. Greater amounts of nutrients are exported through the offtake of milk and production of young animals. Cattle weight gains contain approximately 25 g N and 8 g P/kg in adult animals and 30 g N and 8 g P/kg in young animals. Milk contains about 6 g N and 1 g P/kg (A.R.C., 1980). Issoufou (1994) found slightly higher concentrations of N in the milk of Zebu cows in Filingué, Niger (7–8 g N/kg). About 60% of the animals in the herds are adult females; calving rates rarely exceed 0·75 and lactation yields are usually less than 750 kg (Wilson, 1986). Therefore, the annual export of nutrients from rangelands for herd reproduction and milk production would amount to approximately 550 g N and 110 g P/ha (Diarra *et al.*, 1995).

The calculations above indicate that livestock grazing at stocking rates of 15 TLU/km^2 would injest annually about 5·2 kg N and 750 g P/ha, but would retain as animal products only about 700 g N and 150 g P. The difference (i.e. 4·5 kg N and 600 g P/ha) are excreted through feces (N and P) and urine (N) and either returned to the rangeland or transferred to encampments, watering points, travelling routes or resting areas outside the range. Most of the urinary N and a lower fraction of fecal N is lost to volatilization (Floate, 1981; Russelle, 1992). Therefore net losses or accelerated flows of N can result from livestock production. Grazing also leads to a spatial redistribution of N and P, because fecal and urinary spots are localized in small and heterogeneous patches (Russelle, 1992).

Nutrient balances of rangeland

On a regional scale, even in situations of intense grazing pressure, N exports from rangelands remain lower or equivalent to N inputs (Diarra *et al.*, 1995; de Leeuw *et al.*, 1995). The amount of N removed through grazing appears to be compensated by that returned through trampling, plant roots and various natural sources (Table 1). In the Sahel, rainfall and dust deposit about 3 kg N and 1 kg P/ha (Pieri, 1989; Herrmann *et al.*, 1993; Stahr *et al.*, 1993) and soil microorganisms fix approximately 1–3 kg N/ha (Penning de Vries & Djitèye, 1982). Even long histories of high animal densities appear to have no measurable impact on soil and plant uptake of N and only marginally increases soil and plant uptake of P (Tolsma *et al.*, 1987; Turner, 1992).

Nutrient cycles of cropland

In Niger, pearl millet and cowpea are the principal staples and they are often intercropped. Annual uptake of N by pearl millet in farmers fields of Niger varies between 22 and 38 kg/ha, whereas P uptake varies between 2 and 6 kg/ha (Williams *et al.*, 1995). Not all nutrient uptake by crops is removed from the field. Under the most common situations, essentially all of the grain is used for food and most of the leaf and a small fraction of millet stems are used as livestock feed. The fraction not removed by farmers or livestock may be burned (resulting in N loss) or incorporated into the soil by insects and microbial activity.

Variable amounts of nutrients are also exported from croplands through the removal of weeds by grazing animals, or by carrying them to the homestead for feeding animals, or for selling in markets. Between 400 and 500 kg/ha of weed DM are produced in millet fields from planting to grain harvest, and their N concentration is 4·5% during the first 6 weeks and about 2% by grain harvest (Schlecht *et al.*, 1994). It is likely that most of the nutrients taken up by weeds remain in cropland. However, some weeds are consumed by grazing animals early after planting, when farmers let animals graze fields for weeding purposes. Weeds consumed during crop residue grazing improve the protein concentration in animal's diet (ILCA, 1992). Grazing is the most common way of using crop residues as feed. A small fraction of the nutrients removed by animals is returned through feces and urine during grazing, although these returns appear to be less than nutrient removals (Powell & Williams, 1993). Depending on the stocking rate, between 200 and 300 kg/ha of fecal dry matter are returned by grazing sheep until the time millet leaves disappear from the field (ILCA, 1992). This represents about 3–5 kg N and 0·5 kg P/ha. Similar amounts of N could be returned through urine (Powell *et al.*, 1994).

Nutrient balances of cropland

A recent analysis of nutrient balances of four mixed farming systems in Mali (Powell & Coulibaly, 1995) showed that croplands lack an internal capacity to replenish N offtakes in grain and crop residues (Table 2). Apparent N deficits are greatest for irrigated rice systems due to high grain yields. For all production systems, nutrient deficits approximately equal the amount of N removed by grain. The amount of nutrients removed by livestock from cropland in the form of crop residues appears

TABLE 2
Annual Nitrogen Removals, Returns and Balances (kg/ha) for Croplands in Integrated Rangeland/Cropland Systems of Mali

	Production system			
	Semi-arid, rainfed crops	*Niger delta*	*Flooded rice*	*Subhumid, rainfed crops*
Nitrogen removals				
Grain				
range	11–28	17–28	26–30	14–19
mean	18	17	29	16
Crop residues				
range	8–14	11–12	19–23	9–16
mean	11	11	22	14
Nitrogen returns				
Crop residues				
range	3–5	3–4	4–4	4–5
mean	4	3	4	5
Manure				
range	0–6	1–3	0–2	0–2
mean	1	2	1	1
Crop roots				
range	2–3	2–2	3–4	2–3
mean	2	2	4	3
Other (rain/dust, soil microorganisms)				
mean	4	6[a]	7[a]	5
Nitrogen balance				
range	−29 to −12	−19 to −16	−38 to −31	−17 to −11
mean	−18	−18	−37	−15

[a]Approximately 8 kg N/ha added by floodwaters of the Niger river, 40% of which is eventually recycled through plains.
Source: Powell & Coulibaly (1995).

to be small with respect to that removed as grain. The estimated maximum potential amount of N that could be removed as crop residues for livestock feed approximately equals the N return in trampled fractions of crop residue, in manure, and via rain and soil bacteria.

Although returning all crop residues to soils rather than feeding them to livestock results in greater crop yields (Geiger *et al.*, 1992; Bationo *et al.*, 1995), this is not a viable strategy for most farmers. The absence of alternative dry season feeds would create too great a tradeoff in livestock production. The stability of agricultural production in the Sahel depends heavily on livestock. Animals can be consumed or sold to purchase grain during years of low rainfall when crop production is poor or fails completely. Most biomass, therefore, must be fed to livestock and the manure/urine used to fertilize the soil.

BALANCING NUTRIENT REQUIREMENTS

Farmers in the Sahel make little use of external nutrient inputs. Low rural incomes and the high cost of inorganic fertilizers, among other factors, prevent their widespread use. Supplemental feeds are limited to small amounts of minerals, cereal by-products, and protein meals. These are used mostly in semi-intensive livestock fattening operations around urban areas and for fattening animals prior to religious and social festivals.

The internal capacity of rangelands (Table 1) and croplands (Table 2) to replenish N harvests did not account for N inputs from animal urine and N-fixing shrubs and trees such *Faidherbia albida* which can be important to N cycling in rangeland and cropland systems of the Sahel. Approximately 50% of the N excreted by animals is in urine. Although much of this urine N may be susceptible to loss through volatilization, manure requirements for N replenishment would be less if it came from animals corralled on the field (feces plus urine returned) instead of manure only being collected from stalls and handspread on cropland (Williams *et al.*, 1995). Additions of N returns in urine and N-fixing plants would improve the internal N balances of both rangelands and croplands.

Nutrient transfers from rangelands to croplands

Animal manure is the main source of nutrients for crop production in the Sahel. There are two principal methods of manuring cropland: (a) livestock are corralled overnight on fields between cropping seasons; or (b) manure is gathered from corrals, transported by animal-drawn carts and hand-spread on cropland. Corralling returns both manure and urine to soil, and results in greater crop yields than when manure only is applied (Powell & Ikpe, 1992; ILCA, 1993; Williams *et al.*, 1995). Corralling also requires no labour for manure handling, storage, and spreading. Allowing animals to graze natural pastures during the day and manure cropland at night results in a net transfer of nutrients from rangeland to cropland (Sandford, 1989; Swift *et al.*, 1989).

Despite manure's important role in sustaining crop productivity, two key questions arise: (a) are sufficient amounts of manure available to permit adequate food production and improvement of soil quality on a long-term basis (Schleich, 1986; Sandford, 1989; de Ridder & van Keulen, 1990; McIntire *et al.*, 1992); and (b) what is the capacity of rangelands to support livestock and nutrient harvesting for manuring cropland? Manure output in the Sahel is affected by the wide fluctuation in feed availability and quality. Livestock gain weight during the latter part of the rainy season and early part of the dry season when sufficient good-quality pastures and crop residues are available. Animals lose weight during the latter dry season and early wet season as grazing resources diminish. As a consequence of these variations in feed availability, manure output and quality also varies.

Manure availability for cropping is limited by livestock types and numbers, spatial location of livestock at manuring time, manure output per animal, efficiency of manure collection, and the amounts of feed and land resources available. Fernández-Rivera *et al.* (1995) estimated that during the 8-month period when farmers manure cropland, about 300 kg DM of manure could be collected from a 300-kg cow, 60 kg from a 35-kg sheep and 45 kg from a 25-kg goat. Bosma & Jager (1992) reported that when cattle are used for manuring 14 h/day for 4 months, only between 80 and 190 kg of manure per TLU can be collected. In another study, Khombe *et al.* (1992) reported that 424 kg of manure (with 41% sand) can be collected annually from 170-kg steers when they are penned for 14 h/day. In manuring studies at ILCA/Niger, less than 1 kg of fecal DM is collected daily from cattle (Powell, unpublished data) during night corralling. Schlecht *et al.* (1995) also found that less than 1 kg of fecal organic matter (OM) is excreted daily during the night by grazing cattle. Berger *et al.* (1987) assumed levels of collection of 600 kg manure per year for 400-kg cattle and Landais & Lhoste (1993) reported the same levels of manure deposition per TLU per year.

The chemical composition of feces varies seasonally (Landais & Lhoste, 1993) and is influenced greatly by the type of feed consumed by animals (Somda *et al.*, 1995). Lower concentrations of OM, N and P are found during the dry season, when the quality of feed is lowest (Landais & Lhoste, 1993). As the concentration of polyphenolic compounds in the feed increases, the excretion of urinary N decreases whereas fecal N excretion increases (Powell *et al.*, 1994). Therefore volatilization losses would decrease when tanniferous feeds are consumed. The insoluble N fraction in the feces also increases in response to the consumption of polyphenolic compounds, which may lower the mineralization rate and increase the availability of N to crops when manure is used as a source of soil nutrients (Powell *et al.*, 1994).

The concentrations of N and P in feces from selected studies conducted in West Africa are shown in Table 3. From these figures it follows that if half of the feces excreted during 8 months of the dry season (October–May) are deposited in the cultivated fields, about 4·5 kg N and 0·6 kg P would be collected from a 300-kg cattle, 1·2 kg N and 0·1 kg P from a 35-kg sheep and 1·0 kg N and less than 0·1 kg P from a 25-kg goat. These figures would lead to removal rates per hectare of rangeland lower than those estimated by Diarra *et al.* (1995). One reason for the different estimates is that Diarra *et al.* (1995) considered the total quantities of

TABLE 3
Nitrogen (N), Phosphorus (P) and Potassium (K) Content (% DM) of Manure at Various Sites in the Sahel of West Africa

Location and manure type	*N*	*P*	*K*	*Source*
Saria, Burkina Faso				
Farm manure	1·5–2·5	0·09–0·11	1·3–3·7	1
Northern Burkina Faso				
Cattle manure	1·28	0·11	0·46	2
Small ruminant manure	2·20	0·12	0·73	2
Senegal				
Fresh cattle dung	1·44	0·35	0·58	3
Dry cattle manure	0·89	0·13	0·25	3
Niger				
Cattle manure	1·2–1·7	0·15–0·21	—	4
Sheep manure	1·0–2·2	0·13–0·27	—	4

Sources: 1. Pichot *et al.* (1981); 2. Quilfen & Milleville (1981); 3. Landais & Lhoste (1993); 4. Powell, J. M. (Unpublished data).

nutrients removed from the range, whereas these calculations refer only to the quantities of nutrients removed that would be transferred to cropland.

Farmers in western Niger annually manure between 30 and 50% of their millet fields at a rate of about 1·3 ton/ha (Powell & Williams, 1993). Livestock holdings of most farmers, however, are insufficient to produce adequate manure for replenishing annual nutrient harvests from cropland. To overcome this problem farmers pool herds and also enter into crop residue/manure/water exchange contracts with transhumant herders (McCown *et al.*, 1979; Toulmin, 1983, 1992*a*,*b*; McIntire *et al.*, 1992). The manure of transhumant livestock continues to be an important source of nutrients for semi-arid, rainfed cropping systems of Mali (Powell & Coulibaly, 1995). However, the growing transaction costs involved in securing manuring contracts between farmers and herders in these regions provides an increased incentive for farmers to invest in livestock of their own to secure manure and other livestock goods (Toulmin, 1992*a*; Thébaud, 1993; Scoones & Toulmin, 1995).

Farmers with many livestock have the potential capacity to maintain soil fertility through manuring, either with their own livestock or through their financial resources to engage transhumant herds in manuring their fields. The majority of farmers practising mixed farming in the Sahel, however, are poor in livestock assets (and cash income) and therefore less capable of countering the nutrient depletion of their cropland. As long as natural pastures remain the major source of livestock feed, transhumant and settled pastoralists, and the livestock-rich settled farmers, will benefit the most from nutrient harvesting from rangelands and transport to cropland via manure (Scoones & Toulmin, 1995). Improvement of transfer mechanisms would spread these benefits more widely and would reduce the disparity in soil fertility status at different spatial levels (between farmers, communities, etc.).

SUSTAINABLE NUTRIENT BALANCES

Given the lack of alternative dry season feeds, crop residues will continue to provide vital livestock feeds in mixed farming systems of the Sahel. Sustainable increases in livestock production, while protecting rangelands against overgrazing will depend, therefore, on sustainable increases in crop productivity. Continuous N removals without adequate replenishment result in soil nutrient mining (Stoorvogel & Samling, 1990), and both crop and livestock yields will eventually decline.

The N balances calculated for croplands (Table 2) were based solely on internal nutrient sources, or the capacity of mixed farming systems to replenish N offtakes from the amounts of non-consumed crop residues, manure from the farmers own animals and natural N sources. Of prime interest to achieving sustainable increases in crop and livestock production would be estimates of the amount of external nutrients (fertilizer and/or livestock manure) required to offset internal nutrient deficits.

Based on regional and national data of nutrient inputs and harvests, it is widely believed that farmers are 'mining' their soils of nutrients (Breman, 1990; Stoorvogel & Samling, 1990; Van Der Pol, 1992; Stoorvogel *et al.*, 1993). However, local management practices allow many farmers to apply sufficient fertilizers and/or manures to offset nutrient harvests. In Mali, for example, farmers who cultivate subsistence crops with commercial rice and cotton appear to apply sufficient fertilizers to offset internal nutrient deficits (Powell & Coulibaly, 1995). The same authors estimated that farmers relying on rainfed crop production in semi-arid areas could offset N harvests by applying two to four sacks of fertilizer ($28–70) per hectare of cropland, or applying more N in the form of manure. Many of these farmers currently engage transhumant herders to corral their animals on fields, so they may already be attaining N balances on their croplands.

Number of livestock needed to offset nitrogen deficits

Based on the amount of cattle and small ruminant manure N that can be captured during the dry season (Fernández-Rivera *et al.*, 1995), spread onto fields and assimilated by plants during the subsequent cropping season, various authors have estimated the number of additional animals needed to offset cropland N deficits. In Niger, for example, an additional nine to 21 cattle per hectare of millet would be required (depending on rainfall) to replenish N harvests in grain and crop residues (Williams *et al.*, 1995). For the purpose of replenishing N and P harvests by millet, it was estimated that small ruminants could replace cattle in the ratio of approximately 5:1. Based on cattle:small ruminant ratios of surveyed household herds, Powell & Coulibaly (1995) estimated that 3–7 cattle and 7–12 small ruminants additional to their current livestock holdings would be required to replenish the N harvests from various cropping systems in Mali.

Estimates of additional nutrient requirements to offset nutrient harvests do not necessarily advocate using a particular fertilizer type, or increasing the herd size for manure production. Fertilizer N sources need to be appropriate to specific soils, crops and rainfall conditions. Fertilizers are much more effective when applied in combination with organic fertilizer sources (manures, compost, crop residues, etc.) and if proper management is used to apply them. Before advocating an increase in herd size, more information would be needed on current rangeland and cropland carrying capacities and stocking rates, especially the ability of rangelands to support more animals for manuring cropland. The manuring practices of farmers would also need to be evaluated to estimate more precisely how much additional manure would be required to offset nutrient harvests. In Niger, for example, farmers manure their fields only every 2–3 years depending on rainfall and manure availability (Powell & Williams, 1993). The positive residual effects of manure on crop yields (Powell & Ikpe, 1992; ILCA, 1993) indicates that only a fraction of farmers' total cultivated fields would have to be manured annually.

Rangeland:cropland ratios

The amount of rangeland needed to feed livestock and capture enough manure for manuring cropland needs to take into account the high variability in the productivity of rangelands (Hiernaux, 1993), livestock production goals (Breman & Traoré, 1987) and the management strategies of farmers (Turner, 1995). Estimates of rangeland:cropland ratios (RCRs) typically range from 15 to 45 ha of rangeland needed to support the livestock required to manure one hectare of cropland adequately (Quilfen & Milleville, 1981; Breman & Traoré, 1987; Swift *et al.*, 1989; van Keulen & Breman, 1990). Williams *et al.* (1995) estimated that nine cattle (or 42 sheep) needed to replenish annual N and P harvests in millet fields of an arid location (350 mm annual rainfall) in Niger would require 10–40 ha of dry season grazing land and 3–10 ha of rangeland for wet season grazing. A grazing land requirement for 21 cattle (or 95 sheep) in a more humid environment (600 mm annual rainfall) was estimated to be from 32 to 129 ha for the dry season and 6–24 ha for the wet season.

RCRs place a ceiling on the amount (4–9%) of cultivated land that can be manured annually (Turner, 1995), well below the total cultivated fractions of many areas in the Sahel (van Keulen & Breman, 1990). The wide range of RCRs reflects the high uncertainties associated with variations in cropland and rangeland yields, and perhaps most importantly, the particular management strategies of farmers at household, farm and community levels (Turner, 1995). A decline in the productivity of rangeland, reflected in a combination of lower manure quality, livestock productivity, and local livestock presence, will result in a decline in the productivity of the cropland supported by its nutrient exports.

EFFECT OF DROUGHT ON NUTRIENT TRANSFERS

Drought, a common occurrence in the Sahel, has had a tremendous impact on the number and type of livestock kept by farmers and, therefore, manure availability. Between 1972 and 1974 the cattle herd in the Sahelian zone of Mali declined from 4·75 to 2·64 million. Thereafter, it increased to 4·02 million in 1982, but this was followed by a sharp drop between 1983 and 1985 when a new low of 2·69 million cattle was recorded (IEMVT, 1989; de Leeuw *et al.*, 1990). It has been reported that herd sizes in many parts of the Sahel region of Mali remain much lower than what has been supported in the recent past (Eriksen & Traoré, 1995).

The effect of drought on livestock depends on a variety of factors including the duration and pervasiveness of the shortfall in rainfall, rangeland productivity and grazing pressure on pastures prior to drought, the species of livestock, herd management techniques etc. (Sandford, 1977; Penning de Vries, 1983; Toulmin, 1983, 1985). Localized rainfall shortages can easily be accommodated by moving animals to areas with better rainfall. This opportunity becomes limited, however, when drought is widespread.

Apart from its negative effect on livestock numbers, drought may also influence the type of livestock kept by farmers. Cattle, sheep and goats have varying degrees of susceptibility to drought. During drought, small ruminants, particularly goats, have a higher survival rate than cattle (Arnal & Garcia, 1974; Dahl & Hjort, 1976). The rapid reproduction and growth rates of small ruminants also allow these flocks to be reconstituted much faster than cattle herds.

TECHNOLOGIES FOR SUSTAINABLE RANGELAND, CROPLAND AND LIVESTOCK PRODUCTION

An increase in feed productivity and quality, and the development of diet supplementation techniques to overcome the seasonal nutritional constraints are needed for livestock production systems in the Sahel. Approaches to achieving these aims will differ widely and require various technologies that improve both rangeland and cropland production.

Rangelands

Pastoralism will continue to provide not only food security and income to herders and farmers alike, but also a vital supply of manure for maintaining the productivity of cropland. The survival of pastoralism depends on herd mobility to exploit seasonal water and forage supplies. The expansion of wet season cropping and dry season gardening is encroaching onto traditional pasture land. This not only jeopardizes the livelihood of pastoralists (Traoré & Breman, 1992) but also manure supplies and, therefore, crop yields. Land tenure and use policies are needed that enhance transhumance and farmers' access to the manure of transhumance herds for maintaining the productivity of cropland.

The capacity of rangelands to support livestock and nutrient harvesting needs to be assessed at various rangeland:cropland ratios, particularly for production systems where manure provides a vital nutrient input to cropland. Information needs to be gathered systematically on nutrient acquisition and use by livestock, including grazing behaviour and orbits, and the effects of grazing and browsing on rangeland vegetation, especially during the (dry or wet) season when grazing pressures are the highest. Reducing the risks to rangeland degradation due to overgrazing can also come from adopting technologies other than manuring that increase the productivity of cropland.

Improving cropland productivity

Sustainable improvements in feed offtake from croplands can be achieved by incorporating high yielding grain and forage legumes into the cropping systems and by improving the quality of crop residues through fertilizers and genetic means. The proper use of chemical fertilizers will be crucial in increasing both food and feed supply and its quality (Breman, 1990; Powell & Fussell, 1993; McIntire & Powell, 1995). The small amounts of fertilizers that are available need to be used judiciously with organic nutrient sources such as N-fixing legumes, crop residues and manures.

These agronomic interventions will be particularly important in locations having high yield potential due to favorable soil water conditions. The necessary increase in fertilizer use may require loans and/or the granting of subsidies to farmers, proper instruction in fertilizer use, the provision of fertilizer-responsive varieties and policies that give farmers timely access to fertilizers, at reasonable costs and attractive prices for their commodities.

Improving plant/animal/soil linkages

The integration of forage legumes and browse trees (agroforestry) can serve an important role in reducing the pressure on rangelands and in sustaining the productivity of both crops and livestock. In production systems where fallowing is still practised, forages which fix atmospheric N can be more effective than native grasses in restoring soil fertility, thereby reducing fallow period requirements. Forage legumes can improve animal feed supply and quality, suppress weed growth, accelerate nutrient cycling, and improve soil moisture conservation. Leguminous browse and perennial grasses can control soil erosion, enhance soil productivity, and provide food, fodder and wood.

The adoption of forage legume fallows, instead of utilizing the natural regeneration of indigenous plant species, depends on their superior ability to support more livestock and restore soil fertility (Ruthenberg, 1980). Land allocation to forage production is positively related to land tenure security (especially of access rights) and is negatively related to access to communal or other land, and to the ability to acquire additional land. Increased labor requirements to produce forages in relation to the effect of forages on livestock output impedes forage production for most producers (McIntire *et al.*, 1992). Long-term trials with producers' involvement are needed to assess the feasibility and impact of various forage management techniques on livestock, soil nutrient balances and trampling, etc.

The evolution from extensive livestock management, based on grazing to semi-intensive stall feeding of livestock, will require not only more feed of high quality but also improved feed harvesting and storage techniques aimed at minimizing the competition between livestock and soil conservation for the use of crop residues. Improved methods of capturing and recycling the nutrients contained in feed refusals, manure and urine are also needed for all integrated rangeland/cropland systems, especially where livestock are stall-fed. Strategies are also required that synchronize manure and compost application to cropland, and its nutrient release with plant nutrient demands (McGill & Myers, 1987; Swift *et al.*, 1989; Ingram & Swift, 1989). Corralling livestock on cropland should be more widely encouraged where soils are sandy and the risk of soil compaction due to animal trampling is minimal.

CONCLUSIONS

Rangelands in the Sahel are under increasing pressure to produce more food, fuel, and feed for growing human and livestock populations. The sustained productivity of rangeland will depend largely on resource management strategies that alleviate overgrazing and nutrient depletion (for manuring cropland), and on producing alternative feeds, derived mostly from croplands. A balance between the food and feed supply, nutrient inputs, and human and livestock populations will be critical to the long-term sustainability of rangeland, cropland and livestock production in the Sahel.

Whereas biophysical factors (soil, water, nutrients, etc.) and their interactions strongly affect crop and livestock productivity, national policies and local management factors strongly influence the impact of agriculture on the environment. Technologies for improving agricultural production in the Sahel must consider not only the biophysical aspects of production but also the resources available to producers and how they are used. Successful agricultural intensification is currently underway in many villages of the Sahel. There may be lessons to be learned from these enterprises in terms of what incentives are needed for farmers to invest in technologies and practices that conserve natural resources. Stronger linkages among producers, institutional programs, national ministries, and sub-regional and regional research and development programs are needed, yet communication networks remain poor and there is often a lack of integration between producers and the adaptive research needed to move and keep technologies on farms.

The manure of transhumant herds remains vital to sustaining cropland productivity in many rangeland/cropland farming systems. Access to manure and, therefore, transhumance needs to be encouraged in these production systems. Factors that inhibit livestock movement, and therefore, farmers' access to the manure of transhumant herds, will greatly increase the need for other external nutrient inputs such as fertilizers to prevent declines in soil fertility and crop yields (Breman, 1990; de Ridder & van Keulen, 1990; McIntire & Powell, 1995).

Natural fluxes in pasture productivity and livestock numbers due to erratic rainfall and drought should not be disrupted. Policies that advocate the purposeful supplemental feeding of animals during drought, or rapid restocking during post-drought years could easily offset these natural balances, degrade rangelands, and undermine the sustainability of these production systems. The climatic limitations on feed availability and animal presence imply the need for flexible technologies that assure the integrity of rangelands and croplands in the Sahel.

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