

SPATIAL CARBON, NITROGEN AND PHOSPHORUS BUDGET OF A VILLAGE TERRITORY OF THE WEST AFRICAN SAVANNA – II. ELEMENT FLOWS AND FUNCTIONING OF A MIXED-FARMING SYSTEM*

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Abstract

Management of organic resources plays a decisive role in the viability of mixed-farming systems in West African savannas. For this reason carbon (C), nitrogen (N) and phosphorus (P) flows initiated by the different uses of organic resources were quantified in the different land-use systems of a village in southern Senegal. Livestock, crop harvest, and wood and straw collecting were responsible for respectively 59, 27 and 14 % of the C outflows from the area exploited by the village. Livestock accounted for nearly 80 % of C, N and P returns to the soil. As a result of these transfers and of on-site recycling of herbaceous biomass, high C inputs were brought to staple crops in the compound ring. Nitrogen and P depletion of the system amounted to -4 kg N and -1 kg P ha⁻¹ y⁻¹ only when other abiotic flows were included. This study suggests that population growth is likely to rapidly alter the viability of this mixed-farming system, at least due to a modification in the balance between the supply of and demand for organic resources.

Keywords

Plant biomass, Carbon, Flux, Mixed-farming system, Nitrogen, Phosphorus, Savanna

Résumé

La gestion des ressources organiques joue un rôle essentiel dans la viabilité des systèmes agropastoraux d'Afrique de l'Ouest. Les flux de carbone (C), d'azote (N) et de phosphore (P) engendrés par les différents usages de ces ressources ont donc été quantifiés dans les différents systèmes d'utilisation de l'espace d'un terroir du Sud Sénégal. L'élevage, les récoltes et la collecte de bois et de paille ont été respectivement responsables de 59, 27 et 14 % des sorties de carbone de l'espace exploité par le village. L'élevage a contribué à environ 80 % des restitutions de C, N et P au sol. En conséquence de ces transferts et du recyclage *in situ* de la biomasse herbacée, des volumes importants de carbone ont été apportés aux cultures vivrières de l'auréole de case. Les pertes d'azote et de phosphore du système s'élevaient à seulement -4 kgN et -1 kgP ha⁻¹ an⁻¹ en tenant compte des autres flux abiotiques. L'étude suggère que la croissance démographique pourrait rapidement compromettre la durabilité du système agro-pastoral, au moins au regard de la modification du rapport entre offre et demande en ressources organiques.

Mots-clés

Azote, Biomasse végétale, Carbone, Flux, Phosphore, Savane, Système agropastoral

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BILANS SPATIALISES DE CARBONE, D'AZOTE ET DE PHOSPHORE D'UN TERROIR DE SAVANE OUEST-AFRICAINE – II. FLUX D'ELEMENTS ET FONCTIONNEMENT D'UN SYSTEME AGRO-PASTORAL

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Résumé

La disponibilité de la matière organique dans le système plante-sol, et les usages multiples des ressources organiques, sont d'importants déterminants de la viabilité des systèmes agropastoraux d'Afrique de l'Ouest. L'usage des stocks organiques disponibles au début de la saison sèche a donc été caractérisé par l'estimation des flux de carbone (C), d'azote (N) et de phosphore (P) provenant de la biomasse entre les différents systèmes d'utilisation de l'espace d'un village du Sud Sénégal.

La récolte de grains, l'élevage, et la récolte de bois et de paille ont été responsables respectivement de 27, 59 et 14 % des sorties de carbone de l'espace exploité par le village. L'élevage a contribué à 83, 86 et 79 % des restitutions de C, N et P au sol. Les retours provenant des résidus de cultures ont représenté seulement 13 à 15 % du recyclage du carbone et des nutriments.

Les principales pertes de carbone ont été liées à la respiration du bétail, à la combustion du bois et aux exportations par les récoltes des cultures de rente. Ces dernières ont été responsables de la plupart des sorties de d'azote et de phosphore du système, les autres pertes d'éléments minéraux étant principalement les déjections humaines non recyclées.

En conséquence de ces transferts et du recyclage *in situ* de la biomasse herbacée, des volumes importants de carbone (3,8 tC ha⁻¹ an⁻¹) ont été apportés aux cultures vivrières de l'auréole de case. Des bilans positifs d'azote et de phosphore n'ont été enregistrés que pour les cultures vivrières des auréoles de brousse et de case. En tenant compte des flux abiotiques, les pertes d'azote et de phosphore du système se sont chiffrées à -4 kgN et -1 kgP ha⁻¹ an⁻¹, c'est à dire bien moins que les valeurs couramment admises dans la région.

Les flux de carbone liés aux récoltes, à la collecte du bois, et à l'élevage, pourraient augmenter de 44% en 15 ans sous le fait de la pression démographique. Le rapport entre flux et stocks de carbone dans la biomasse aérienne doublerait en 12 ans. C'est pourquoi une rapide diminution de la durabilité du système pourrait se produire dans les prochaines décennies si aucune intensification des systèmes de production n'est initiée.

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1. Introduction

One of the main features shared by traditional, self-sufficient tropical farming systems – especially in West African savannas (WAS) - is the use of organic matter (OM) as a multi-purpose tool, as it plays structural and energetic roles in the agro-ecosystem, and conveys nutrients (Ruthenberg, 1971; Kowal and Kassam, 1978). Organic matter is a valuable output (economic good) of the system and represents a promising way to increase productivity and ensure viability through biological maintenance.

Assessing the dynamics of carbon and organically mediated nitrogen (N) and phosphorus (P) resources thus represents one means to evaluate the sustainability of local agro-ecosystems (Woomer *et al.*, 1998; Dugué, 2000). To be valid in West Africa, this assessment must be carried out at the village scale, since common land tenure and social organisation are frequent (Landais and Lhoste, 1993; Izac and Swift, 1994; Defoer *et al.*, 1998). Studies should include an appraisal of the supply of organic resources through analysis of their spatial distribution. This has been accomplished for a mixed-farming system in Southern Senegal (Manlay *et al.*, this volume) and is completed here by a study of the uses made of these resources and their impact on the nutrient balance of the system.

Only a few efforts have been made to include all the different uses of organic matter in quantifying organic matter fluxes at the farming system level (Woomer *et al.*, 1998; Dugué, 2000; Ngamine and Altolna, 2000). However, the potential of crop-livestock integration for fertility transfers at the village scale has now been widely demonstrated (Landais and Guérin, 1992; Landais and Lhoste, 1993; Fernandez-Rivera *et al.*, 1994; Buerkert and Hiernaux, 1998), though accurate spatialisation and quantification remain rare in sub-Saharan Africa (Murwira *et al.*, 1994; Hiernaux *et al.*, 1997; Achard *et al.*, 2000).

A noticeable feature of carbon dynamics in tropical farming systems is its highly seasonal pattern. Production of plant biomass occurs mainly during the wet season, leading to peak storage of organic matter at the end of the rains (Kowal and Kassam, 1978). Plant productivity remains very low during the following months, while the continuous activity of human beings and animals results in the progressive exploitation of the newly created resource. As a consequence, substantial vertical flows and horizontal transfers of carbon and related nutrients occur until the return of the rains. Farmers manage some of these flows directly; the main flows controlled being related to food harvest (grain and haulm), livestock-mediated organic fluxes, and collection of wood in fallows and savanna.

This paper has three objectives: first to quantify and compare flows of C, N and P in plant biomass caused by human activity in the different land-use systems (LUS) in the village, second to assess their impact on the nutrient balance of each LUS, and third to estimate future trends in carbon flows for the village system.

2. Methods

2.1. Site characteristics

The study was carried out in the village territory of Sare Yorobana (12°49'N, 14°53'W), southern Senegal, located in the Region of High Casamance, Department of Kolda. A description of the climate, soil, vegetation and farming system of the study site appears in

Manlay *et al.* (2002a,b,c, and this volume). The farming system exhibits a ring-like organisation scheme that is typical of West African human settlements.

In 1997, the village managed 410 tropical livestock units (TLU; one TLU being equal to 250 kg of live weight or LW). Taurine cattle consist of the *Bos taurus* species (*Ndama* race). Cattle are usually run by herdsmen in the savanna/forest ring during the cropping period, and are left to stray during the dry season. Common grazing is the usual rule, but manuring during night corralling benefits cattle owners only.

Sedentary Fulani (Peulh) people have been devoting themselves to cropping for more than a century, but they are basically herdsmen. Ownership of animals varies considerably between holdings.

2.2. Quantification and spatialisation of carbon, nitrogen and phosphorus fluxes

2.2.1. Flows at harvest

Estimates of C, N and P flows occurring at harvest of cropped biomass were based on data reported in Manlay *et al.* (this volume). Organic matter flows from the fields to the farmyard included the following components: panicles of millet, sorghum and rice; grains and cobs of maize; groundnut haulms. Exports off the village territory consisted of groundnut pods and cotton bolls (home consumption not included). Returns from the farmyard to the compound ring were non-edible components of cereals and returns of haulm under faecal form after consumption as feed supplement by small ruminants, calves and oxen.

2.2.2. Livestock-mediated transfers

Space mapping. Two kinds of mapping were performed. Firstly, the subregion district of Dioulacolon, to which Sare Yorobana belongs, was mapped and scaled to 1:12000 thanks to photo-interpretation of the physiognomic types of vegetation.

Livestock location. The day-straying movements of three out of the 10 herds managed by the village were followed for one day out of every 15 throughout the 1995-1996 dry season. These three herds represented roughly half the cattle population of the village. Their trajectory was recorded using a global positioning system or a magnet with a topofil survey device (one recording every five minutes). The time spent by animals on each LUS (vegetation type outside the village, basic plot inside the village) was computed by criss-crossing herd trajectories with land-use maps. Browsing activity is quite steady during straying irrespective of land use (Ickowicz *et al.*, 1999); spatial distribution of plant biomass intake was thus inferred linearly from the length of time spent.

Estimate of plant biomass uptake and dung deposition by livestock. Methods used to assess the quantity and quality of faecal production and plant uptake and preliminary results were detailed in Ickowicz *et al.* (1998; 1999) and Manlay (2000). Briefly, faecal organic matter excretion (FOME) ranged from 19-48 g OM per kilo of metabolic weight or MW throughout the year, with peak production recorded at the beginning of the dry season. Dung deposition was almost equally distributed between night (53 %) and day (47 %). Estimated consumption ranged from 46-103 g OM kg LW⁻¹ d⁻¹. Carbon intake was estimated assuming that only herbaceous biomass was ingested by cattle. It was computed from mean carbon contents reported for herbaceous biomass of cropped and fallow fields in Manlay *et al.* (2002-a,c) and from dry matter intake (DMI) values. Total P intake during the dry season was thus estimated

as being equal to P faecal excretion, corrected for the variation in P stored in the biomass of animals between the beginning and the end of the dry season.

Night corralling practices

Kraaling was studied throughout the 1996-1997 dry season. The plot location, date and number of animals in each corral were recorded. Dung deposition was computed (in t DM ha⁻¹ and t OM ha⁻¹) and used for the establishment of C, N and P budgets.

2.2.3. Energy and construction needs

Fuel wood needs were estimated using population census (Manlay, 2000) and the work of Bazile (1998) carried out in a village in southern Mali, which has climatic conditions and living habits comparable to those in Sare Yorobana. Firewood was assumed to be harvested from fallows in the bush ring only. Full combustion at the farmyard was hypothesised, leading to full loss of C and N, while P was returned to the compound fields as ashes. Fuel wood consumption was compared to net annual production of live and dead wood in fallows over two years old. Live wood production was estimated as the increase in trunk biomass (TB) for each fallow stand in Sare Yorobana, estimated by a logistic-like model relating TB accumulation to length of fallow (Manlay, 2000). Dead wood production was estimated from Shackleton (1998) and Manlay *et al.* (2002a). Both local models for live trunk biomass increase and dead wood production were applied to the plot database presented in Manlay *et al.* (this volume) to obtain wood production estimates for the whole territory. Stalks needed for roof construction were quantified (see Manlay, 2000).

2.3. Outlook on carbon flows

The ratio of the uptake of the C resource to the amount of the C resource in the standing biomass is an indicator of the viability of the farming system. To predict how this uptake may evolve over the next 15 years, a simplified representation of its dynamics was made using a spreadsheet relating C amounts to land use, which in turn was linked to manure availability and human needs (see Manlay *et al.*, this volume and 2000) for a detailed description of the model). Output variables monitored were C flows (C intake by livestock, crop, wood and straw harvest) and the ratio of C flow to C amount.

3. Results

3.1. Carbon, nitrogen and phosphorus flows

3.1.1. Crop harvest

Seventy five per cent of the outflow related to plant biomass harvest stemmed from the bush ring, with half of it being exported as groundnut pods and cotton bolls for sale, the rest being transferred to the farmyard in the form of panicles and ears of cereals, and groundnut haulms (Figure 1a). An optimistic estimate of recycling of crop residues and weeds gave 45 t C (excluding loss to fire). Eighteen tons of carbon from non-edible plant biomass and faecal returns from haulm consumption were transferred from the farmyard to plots adjoining dwellings. In the food-crop fields in the compound ring these returns counterbalanced N and P intakes due to harvest (Table 1). As a whole, 46 % of N and 35 % of P harvested were exported, and 511 kg N and 99 kg P lost in septic tanks (Table 1).

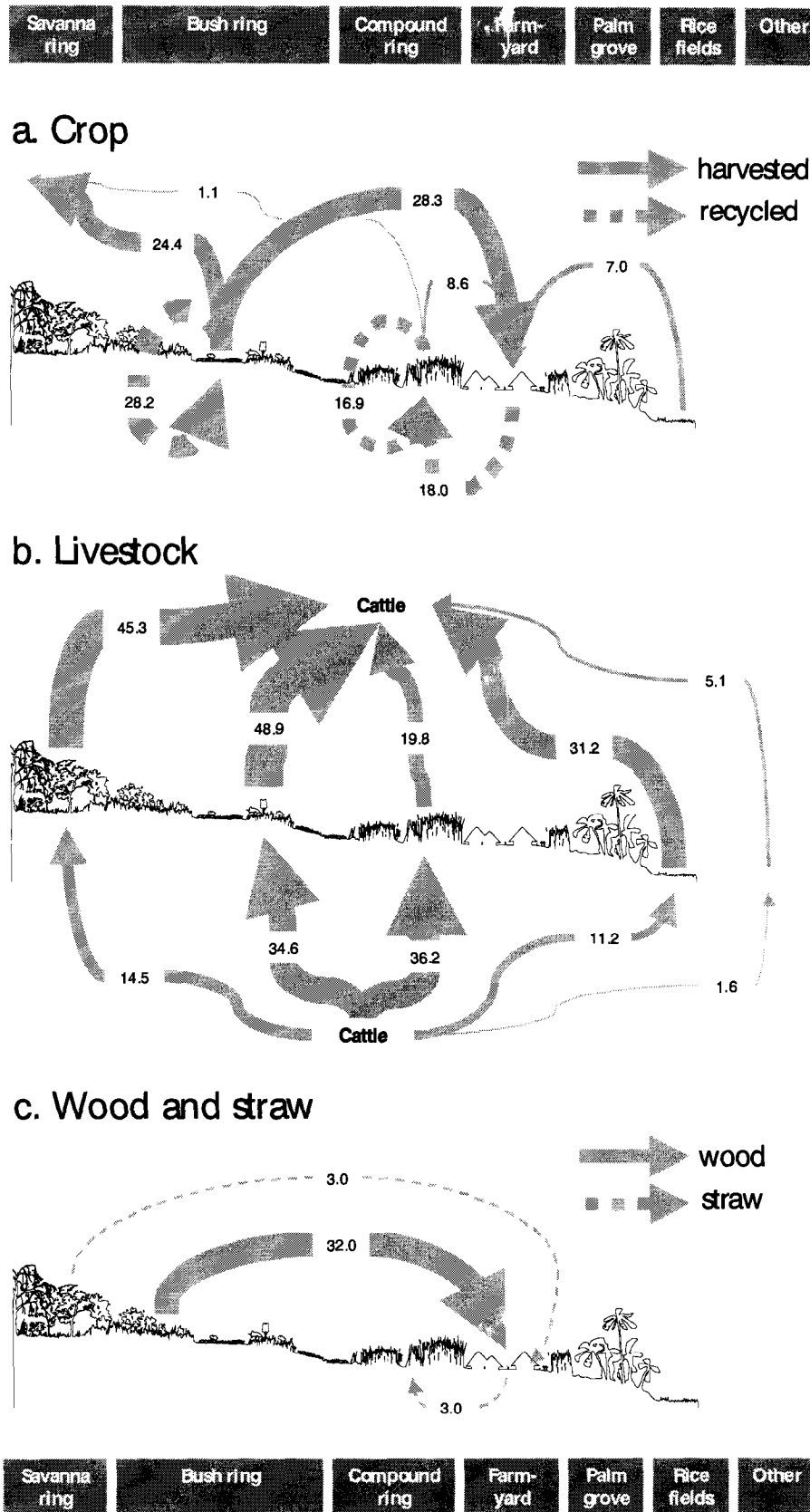


Figure 1 Anthropogenic flows of carbon established from November 1996 to November 1997 in Sare Yorobana. Livestock flows include the dry season only. Arrow width is proportional to flow value. All values in tons.

Table 1. Dry matter, carbon, nitrogen and phosphorus budgets of the land use systems exploited by peasants of Sare Yorobana in and around the village territory, as related to crop harvest, livestock-mediated transfers, wood and straw harvest, and residue recycling

Vector	Savanna ring		Bush ring				Compound ring				Farmyard		Rice field	
	In	Out	Fallow		Cash		Food		Food		In	Out	In	Out
Carbon (t ha⁻¹)														
Harvest						1.0	0.0	0.4	1.0	0.4	43.9	27.3		0.4
Cattle	0.0	0.1	0.0	0.1	0.2	0.3	0.8	0.8	1.9	1.0			0.1	0.4
Wood				0.3							32.2	32.2		
Straw		0.0							0.1		2.8	2.8		
Residue			nd		0.1		0.9		0.8					0.4
Total	0.0	0.1	0.0	0.4	0.2	1.3	1.8	1.2	3.8	1.4	79.0	62.4	0.5	0.8
Nitrogen (kg ha⁻¹)														
Harvest						56		13	63	15	1704	1193		8
Cattle	2	6	3	7	12	21	93	48	146	59			11	28
Wood				2							200	200		
Straw		0							3		57	57		
Total	2	6	3	8	12	77	93	61	212	74	1961	1450	11	36
Balance		-4		-5		-65		+33		+138		+511		-25
Phosphorus (kg ha⁻¹)														
Harvest						3.6		2.5	5.2	3.0	198	99		1.8
Cattle	0.2	0.4	0.2	0.4	0.9	1.3	5.2	2.9	11.8	3.5			0.9	1.7
Wood				0.5					3.1		59	59		
Straw		0.0							0.3		6	6		
Total	0.2	0.4	0.2	0.9	0.9	4.8	5.2	5.4	20.4	6.5	262	163	0.9	3.5
Balance		-0.2		-0.7		-3.9		-0.1		+13.8		+99		-2.6
Surface (ha)														
		445		117		42		28		19				16

All data in amount per hectare, except for farmyard (computed in absolute amounts).

3.1.2. Livestock-mediated flows

Uptake

The total area explored by animals was 812 ha, including 268 ha owned by the village, corresponding to a mean stocking rate of 51 TLU ha⁻¹.

Previous cropping and land use considerably influenced frequentation by animals during the day, as illustrated by the contrasted organic matter flow densities recorded among land uses (crop type, Table 1). Most intensively grazed crops and LUS were respectively millet or maize, and the compound ring; fallow stands and savanna were the least frequented. In absolute values, main forage sources were the bush ring and the savanna ring (63 %) (Figure 1b); the compound ring ranked behind the rice fields. Nitrogen and phosphorus flows showed spatial patterns similar to C; they rose to 9.4 t N and 580 kg P.

The herbaceous DM “annual uptake:annual production” ratio would slightly exceed 50 % in the cropped fields in the compound and bush rings, but be less than 10 % in fallow stands (Table 2).

Table 2. Annual uptake:annual production ratio (in %) for woody and herbaceous resources with regard to some farming activities in Sare Yorobana

Plant AG component	Land use system	Land use	Activities		
			livestock	harvest	wood collecting
Herbaceous biomass	Bush ring	Crop	61	16	
		Fallow	8	0	
	Compound ring	56	8		
	Rice fields	50	18		
	Whole territory	29	14		
Wood	Bush ring				42

Faecal excretion

Night corralling was mainly practised close to the dwellings (Figure 2). Strong contrasts in the intensity of manuring (ranging from 0-13.4 t DM ha⁻¹) were recorded between plots. Night corralling took place in plots planned for cereal cropping. The most manured plots were mixed stands of millet and maize, while groundnut received the smallest quantities. With regard to manuring rates, other cereals were ranked as follows: maize > millet > sorghum.

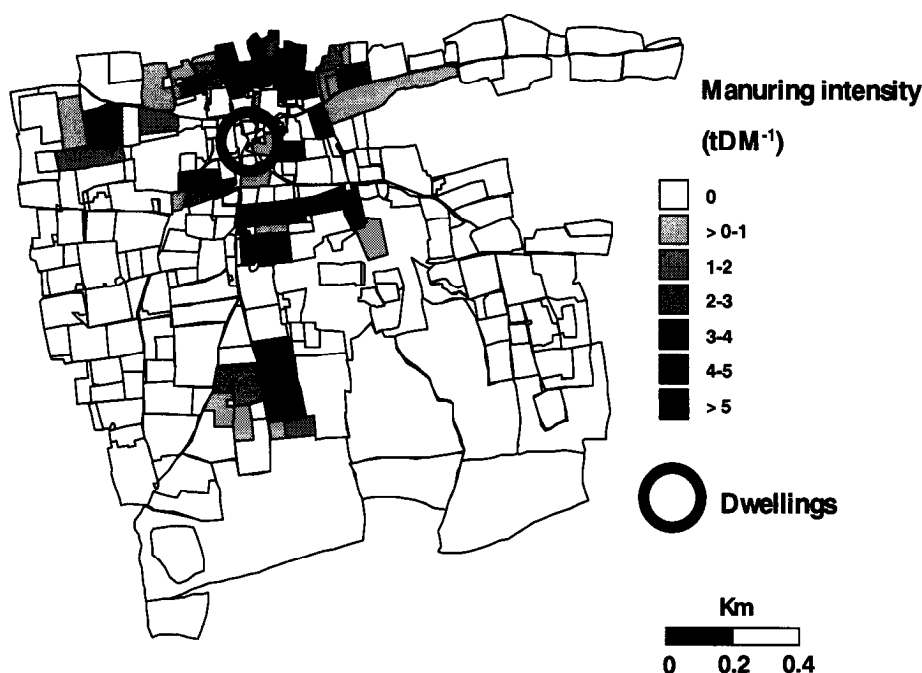


Figure 2 Manuring intensity from night corralling in the village of Sare Yorobana during the 1996-1997 dry season.

Total faecal excretion amounted to 239 t DM, half of which was dropped during night tethering. This was equivalent to 98 t C (Figure 1b), 7.5 t N and 610 kg P. Overall dung deposition mainly occurred in the bush and compound rings (85 %); in these rings carbon inputs from manure offset C intake (input:output ratio = 1.4); this was not the case for the savanna ring and rice fields, in which only a third of C loss was recovered (Figure 1b, Table 1).

3.1.3. Other anthropogenic flows

Wood consumption per permanent inhabitant was estimated at 280 kg DM per year (320 kg DM when added that of temporary workers needed for cropping). It represented less than half net annual wood production on the village territory (Table 2). Wood harvest generated a considerable flow of carbon between the bush ring and the farmyard (Figure 1c), equivalent to 200 kg N and 58 kg P. Total herbaceous biomass stored on roofs of the village was estimated at 40.7 t DM. Turnover rate was 0.2 y^{-1} , equivalent to a yearly input of 30 kg of straw per capita to the compound ring.

3.1.4. Global carbon and nutrient balance

Livestock activity accounted for more than half of the anthropogenic outflows of C, N and P, the proportion of crop harvest accounting for only 25-32% of these flows (Table 3). The proportion of animal activity was even higher when considering C and nutrient returns to the soil (79-86%). Wood- and straw-mediated transfers were significant for carbon only.

Table 3. Participation of crop harvest, livestock, and collecting of wood and straw to anthropogenic carbon, nitrogen and phosphorus transfers due to farming activities

	Crop (%)	Livestock (%)	Wood and straw (%)	Total (%)	(abs)
Removal					
C	27	59	14	100	255 t
N	25	73	2	100	12.8 t
P	32	61	7	100	956 kg
Return					
C	15	83	2	100	119 t
N	14	86	1	100	8.7 t
P	13	79	8	100	773 kg

C, N and P balances resulting from organic input/output due to human activity were very contrasted between LUS (Table 1). Highest carbon inputs per hectare occurred in fields cropped for food production in the compound and bush rings (3.8 and 1.8 t C ha^{-1} , respectively). Carbon input in these rings was mainly due to dung deposition (45 and 55% in the compound and bush rings respectively) and crop biomass recycling (mainly residue). Exogenous N and P inputs during the dry season mainly originated from manuring in both rings. The situation in the village rice fields was slightly different, with 75% of the C inputs stemming from residue recycling.

Carbon uptake in the bush ring was mainly related to harvest and browsing and was more or less evenly distributed between the two. In the compound ring, browsing accounted for 67% of C withdrawal. In the rice fields, intake was evenly distributed between animals and human beings.

Nitrogen and P balances were strongly positive in the compound fields cropped with cereals: $+117 \text{ kg N ha}^{-1}$, and $+11.8 \text{ kg P ha}^{-1}$ respectively. A net positive nitrogen balance was also recorded in the food crop fields in the bush ring, while the P budget was close to equilibrium. All other land-use units had N and P deficits, with the highest nutrient depletion in cash crops in the bush ring.

The overall uptake from crop harvest and grazing would amount to nearly half herbaceous resources (Table 2), with major differences (8-77 %) between LUS.

3.2. Outlook on future carbon outflows

In the village territory, carbon uptake due to crop and wood harvest and browsing by livestock is expected to increase by 44 % within the next 15 years (Figure 3). The ratio of C outflows to amounts of C stored in plant AGB would increase much faster and would more than double within the next 12 years. Carbon needs are expected to reach nearly half of plant C disposal by 2012.

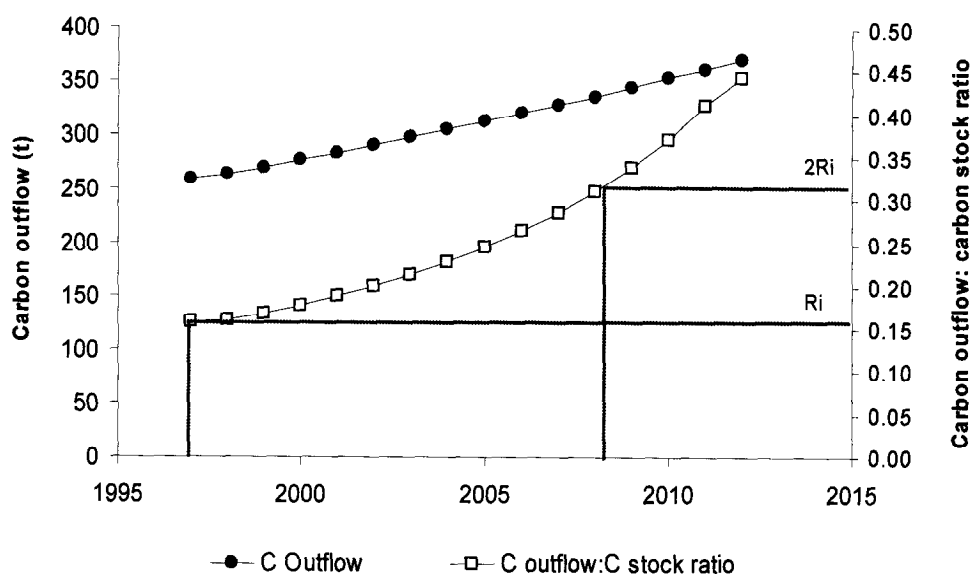


Figure 3 Evolution of anthropogenic carbon outflows and ratio of C outflow to amount of C stored in plant above-ground biomass for the territory of the village of Sare Yorobana for the 1997-2012 period. Outflows considered were: harvested crop biomass, livestock uptake during the dry season, and wood and straw collecting. * F_i : initial flow. See description of model in Manlay et al.(this volume).

4. Discussion

4.1. Control of stocks over flows: livestock-mediated transfers

At the end of the rains, herding of animals becomes less restricted and cattle are left free to feed wherever they wish at the lowest metabolic cost, preferentially on plots with high-quality forage. Biomass availability also influences grazing trajectories of animals, as testified by the low frequentation of groundnut fields, in which the removal of haulm leaves only little edible biomass for livestock (Table 1).

Animals left to graze freely exploit only a fraction of available plant biomass (Table 2). Cereal leaves and weeds are eaten first, but much of stalk biomass is left because of its poor feed value, tainting by urine, and trampling during browsing. As a result, frequentation of cropped rainfed areas drops rapidly within the first two dry months; later, animals prefer to explore rice fields (where they have access to rice straw and limited grass regrowth) and rangelands (fallow, savanna) (Ickowicz *et al.*, 1998). The rapidly decreasing feed quality of

the herbaceous layer during the dry season, and removal of large amounts of plant biomass by uncontrolled fires may well account for the low frequentation of fallow stands.

As a result, only 29 % of available herbaceous forage on the village territory (not including the palm grove) is eaten by animals, which is consistent with other findings for Burkina Faso (Quilfen and Milleville, 1983).

4.2. Global carbon and nutrient balance of the village agro-ecosystem

4.2.1. On-site recycling

From a pastoralist point of view and given the facts mentioned above, common grazing saves labour but not forage resources. From an agricultural perspective, organic matter recycling through animals speeds up biogeochemical cycles (Landais and Guérin, 1992), but leads to the withdrawal of a third of carbon from the system through animal respiration. Plot studies carried out on various agro-ecosystems in Sare Yorobana have underlined the necessity of ensuring steady C flows through the soil to maintain soil quality (Manlay *et al.*, 2002b,c). Thus proposals aimed at improving the quality and availability of manure through herd expansion and stalling of cattle (Bosma *et al.*, 1999) should take into account their cost in energy (carbon). Organic matter/energy loss is all the more likely to occur, since the return of manure from stall to field is often limited due to a lack of means of transport and of labour (Schleich, 1986).

4.2.2. Spatial organic transfers, carbon inputs and nutrient balances

The bush ring represented the main carbon source for the village. Due to the extension of this ring, C outflows have up to now only represented 8.9 % of the carbon stored in above-ground biomass, not including litter (Manlay *et al.*, this volume). Inside the bush ring, C uptake was high in cropped fields and low in fallow stands (75 and 3 % of the C-AGB pool, respectively). High values were also recorded for the food crops in the compound ring (65 %) and rice fields (68 %). But C redistribution benefits to the compound ring were at the expense of other rings (Table 1). Carbon inputs in food crops in this ring ($3.8 \text{ t C ha}^{-1} \text{ y}^{-1}$) were much higher than amounts usually recommended to compensate for soil organic carbon mineralization, which assumes a rate of soil organic matter mineralization of 0.06 y^{-1} (de Ridder and van Keulen, 1990).

When considering nutrient dynamics, N and P outflows stemmed equally from rainfed cropped fields and other land-use systems. But positive N and P balances recorded for staple crops would not have been possible without the recycling of exogenous nutrients, of which nearly all benefited staple crops. Thus, the current system acts as an impluvium for carbon and nutrient elements, since it taps organic resources from peripheral areas to rainfed food crops. In this way, the ring-like organisation scheme enables sustainable continuous cultivation of cereals at relatively high yields on 7 % of the surface area owned by the village (Manlay *et al.*, this volume).

In semi-arid Burkina Faso, Krogh (1997) showed how the nutrient balance of farming systems depends on the spatial scale considered. Most of the N and P balances of staple fields reported in his work were negative. Things were different at the village level, since outputs due to staple crop harvest were kept within the village boundaries. The present study yielded the same kind of results: the nutrient balance in the bush ring was negative, but that of the village territory as a whole was positive when N and P stored in septic tanks were integrated. However, our conclusion differs from Krogh's, since a distinction has to be made between

geographic and functional balances: N and P excreted by human beings are not recycled and are consequently lost for the cropping system.

From a nutrient viewpoint, the system as a whole might be considered close to sustainability. However, one of the major prerequisites is livestock availability, which mediates most of C, N and P flows. The potential of higher herd densities to sustain agricultural systems through manure production has been well demonstrated in West Africa (Schleich, 1986; Williams *et al.*, 1994; Bosma *et al.*, 1999). But unless there is a switch to more intensified farming patterns such as fertilised ley and improved fallow (Hoefsloot *et al.*, 1993), forage availability quickly impedes the maintenance of animal husbandry in crowded areas. Another condition ensuring the sustainability of the farming system in Sare Yorobana is thus satisfactory land availability. The accessibility of wide peripheral rangelands (1) ensures forage availability during the cropping period, thus avoiding seasonal – and mostly definitive - migration of livestock as widely experienced in the Groundnut Belt of Central Senegal (Lericollais and Milleville, 1993), (2) lessens competition between human and animal needs for plant biomass, since large amounts of fuel wood are stored in the fallow and savanna ring, and (3) compensates for nutrient losses from the system at a low mineral depletion rate. Reporting good carbon and chemical status of soils in the compound ring in villages under various climates in Burkina Faso, Prudencio (1993) concludes that the move toward more permanent cultivation systems will mine the fertility of fields in the outer ring, but not that of the chemically well endowed soils in the compound ring. This conclusion cannot apply to Sare Yorobana, since the soil quality of plots neighbouring the compounds relies on organic mining flows from the bush and savanna rings. Intensification may thus reduce the surface area of nutrient sources and threaten both biological mechanisms of mineral repletion and crop-livestock integration (Giller *et al.*, 1997).

4.2.3. Other carbon, nitrogen and phosphorus flows in soil

Carbon transfers through erosion, runoff and leaching should remain limited: assuming such C flows related to the water cycle to be 20 and 84 kg C ha⁻¹ y⁻¹ in fallow and cropped fields respectively (Roose and Barthes, 2001), C transfers would amount to 10.6 t ha⁻¹ over the whole area owned by the village, which is less than 2 % of the flows of fresh plant biomass. Factors affecting N and P balances not taken into account here were: atmospheric deposition, biological fixation of nitrogen, leaching, gaseous losses and erosion. For cropping fields under uncertain rainfall in Senegal, Stoorvogel and Smaling (1990) estimate the net balance of these factors to be -3.5 kg N and -1.5 kg P ha⁻¹ y⁻¹, and biological N and P accumulation in fallow to +2.0 kg N and +0.87 kg P ha⁻¹ y⁻¹. Applying these figures to Sare Yorobana village, the final nutrient balance of the system would be -4kg N and -1 kg P ha⁻¹ y⁻¹, which is closer to equilibrium than the findings of these authors (-20 kg N and -3kg P ha⁻¹ y⁻¹) for the uncertain rainfall area in Senegal.

4.3. Future trends in the use of carbon resources

Although the current proportion of carbon amounts redirected by farmers for their needs to that stored on AGB of the village territory was low (16 % in 1997 according to the model), it is likely to increase rapidly during the coming years as a result of the growing need for cropped land. This - among other consequences - could easily lead to exclusion of livestock, as experienced by the Sereer farming system in Central Senegal during the 1965-1985 period, and, more recently, by farmers throughout the Sine-Saloum region, not far from High-Casamance. Coexistence of continuous cultivation and animal husbandry is another way in which this agricultural system may evolve. It would require drastic changes in farming

practices, land tenure status, increased chemical inputs, and thus the existence of financial and technical advisory structures (Dugué, 1998).

5. Conclusion

Limited nutrient depletion and the rate of anthropogenic uptake of annual production of plant above-ground biomass suggest that Sare Yorobana is closer to viability than is generally reported for smallholder farming in sub-Saharan Africa. Levels of availability in livestock and land per capita that are unusual for the sub-region would be required (Landais and Lhoste, 1993). From an ecological viewpoint, and in a context of preeminence of biological maintenance over substitutional maintenance (*senso* Izac and Swift 1994), a notable parallel can be drawn with the role of carbon circulation in sustaining the organisation and functions of the ecosystem at the plot and the village territory scale. Since fluxes of matter and energy are determined by the conservation of gradients of elements across landscape, the quantitative comparison of organic pools and fluxes (this study and Manlay *et al.*, this volume) yields more than the assessment of uptake pressure on natural resources or of the nutrient balance of the farming system.

In all likelihood, rapid changes in the balance between human, livestock and land factors in Sare Yorobana will alter patterns of C cycling in the future, hence the need for intensified management of organic resources. Based on this study, realistic proposals for the region implying light investments should include the recycling - on cropped fields - of (1) manure produced during the dry season, which represented more than half total dung production over the year, and (2) human dejecta that are a major sink of nitrogen and phosphorus. However, the feasibility of both proposals is likely to be influenced by more than technical considerations since they would require funding to improve transport (carts), and the abandonment of certain cultural taboos.

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