CHAPTER 5.

CARBON, NITROGEN AND PHOSPHORUS SPATIALIZED BUDGET OF A VILLAGE TERRITORY OF THE WEST AFRICAN SAVANNA

II. THE FLUXES

Drift pasture on millet crop residue

Chapter 5. CARBON, NITROGEN & PHOSPHORUS SPATIALIZED BUDGET OF A VILLAGE TERRITORY OF THE WEST AFRICAN SAVANNA – II. THE FLUXES.

ABSTRACT

Organic matter availability in the plant-soil system, and multiple use of organic resources, are strong determinants of the viability of mixed-farming systems in West Africa. The management of organic stocks available at the onset of the dry season was characterised by estimating some of C, N and P biomass-mediated flows established between the different land use systems of a village of Southern Senegal.

Crop harvest, livestock, and wood and straw collecting were responsible for respectively 27, 59 and 14 % of the C outflows from the area exploited by the village. Livestock accounted for 83, 85 and 79 % of the C, N and P returns to the soil. Returns of crop residue represented only 13-15 % of C and nutrient recycling.

Main C losses were related to cattle respiration, wood burning and exportation of cash crop harvest. The latter was responsible for most of N and P outflows off the system, other nutrient losses being mainly unrecycled human dejecta.

As a result of these transfers and of the on-site recycling of herbaceous biomass, large C inputs (3.8 tC ha^{-1} y^{-1}) were brought to food crops of the compound ring. Positive N and P balances were recorded only for food crop fields of the bush and compound rings. N and P depletion of the system amounted to –4 kgN and –1 kgP ha^{-1} y^{-1} when taking into account other abiotic flows, that is much less than values usually reported for the region.

Simulated C flows related to crop and wood harvest and to livestock would double in 28 years as a result of demographic pressure. These flows would equal the C stored in above-ground biomass in 27 years. Hence, fast decrease of the sustainability of the system might occur within the next few decades if no intensification of the farming system is implemented.

KEY WORDS

Plant biomass, Carbon, Flow, Mixed-farming system, Nitrogen, Phosphorus, Savanna, Senegal

5.1. INTRODUCTION

In dry tropical Africa, climate and soil constraints, together with human past history, have generally given birth to more or less intensified farming systems with low use of exogenous inputs (Kowal and Kassam, 1978). One of the main features shared by self-sufficient tropical farming systems is the use of organic matter (OM) as a multi-purpose tool, which plays structural (construction) and energetic roles, and conveys nutrients (Ruthenberg, 1971). Organic matter is a valuable output (economic good) of the system that provides direct services such as feeding human beings and animals, heating, and housing them. It is also a means to drive the productivity, and even the viability of the farm agroecosystem, granted that it is carefully managed. For instance, livestock fed on local forage provides labour power while recycling organic matter and nutrients to the soil. In sub-Saharan Africa, organically based practices of fertility management (manuring, fallowing) are widespread and enhance soil organic status, on which soil physical, chemical, and biological properties largely rely in the Tropics (Kowal and Kassam, 1978; Pieri, 1989; Floret *et al.*, 1993; Tiessen *et al.*, 1994).

Factors such as abandonment of subsidy policies on fertilisers, or unsecured land tenure are likely to keep the viability of West African farming systems highly reliant on organic matter management (Pieri, 1989; Naseem and Kelly, 1999). Assessing the dynamics of carbon and organically mediated nitrogen (N) and phosphorus (P) resources should thus be a means to evaluate the sustainability of local agro-ecosystems (Woomer *et al.*, 1998; Dugué, 2000). In order to be operational, this assessment has to be made at the village scale in West Africa, since common land tenure and social organisation are frequent (Landais and Lhoste, 1993; Izac and Swift, 1994; Defoer *et al.*, 1998).

A noticeable feature of the carbon dynamic in tropical farming systems is its highly seasonal pattern. Plant biomass production occurs mainly during the wet season, even in perennial vegetation, leading to peak storage of organic matter at the offset of rains (Kowal and Kassam, 1978). Plant productivity remains very weak 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 are set up till the return of rains. Farmers directly manage some of these flows. The main ones are linked to food harvest (grain and haulm), livestock-mediated organic fluxes, and collecting of wood and of other non-ligneous products in fallows and savanna.

Except for the works of Woomer *et al.* (1998), Dugué (2000) and Ngamine and Altolna (2000), attempts to quantify organic matter fluxes at the scale of the farming seldom encompass all the uses of organic matter. Crop-livestock integration has initiated several studies dealing with various roles of organic matter. The role of livestock in transfers of fertility at the village scale is widely acknowledged (Landais and Guérin, 1992; Landais and Lhoste, 1993; Fernandez-Rivera *et al.*, 1994; Buerkert and Hiernaux, 1998), but spatialisation and quantification of livestock-mediated fluxes remain scarce (Murwira *et al.*, 1994; Hiernaux *et al.*, 1997; Achard *et al.*, 2000). Most of nutrient budgets for sub-Saharan are set at the field level (Bationo *et al.*, 1998) or at the regional scale (Stoorvogel *et al.*, 1993a; Stoorvogel *et al.*, 1993b); but few include the village level (Krogh, 1997; Defoer *et al.*, 1998). And when they do, carbon budgets miss.

A strong hypothesis underlying this work is that the viability of the farming systems of the West African Savannas (WAS) relies largely on the availability of the organic resource, and on the way this resource is managed during the dry season. The former hypothesis held the first part of this study (Chapter 4); for this purpose we quantified the storage of carbon (C), nitrogen (N) and phosphorus (P) as related to agro-social organisation of a mixed-farming system of southern Senegal (Chapter 4). On this village territory, as is often the case in the WAS, farmers have established a concentric spatial organisation, which exhibits a positive gradient of intensity of cultivation and fertility management from the peripheral rangelands and the bush ring to the compound ring (Pélissier, 1966; Ruthenberg, 1971; Prudencio, 1993). This paper is aimed at testing the second hypothesis by estimating some of the human-related C, N and P fluxes established in the village.

Here, we (1) quantify main spatial plant biomass-mediated C, N and P flows set by human activity between the different land use systems (LUS) of the village, mainly during the dry season, with emphasis on livestock activity (2) estimate possible future trends exhibited by carbon flows under different scenarios related to agriculture efficiency and evolution of the standard of living.

5.2. METHODS

5.2.1. Site characteristics

The study was carried out in Sare Yorobana (12°49'N, 14°53'W), a village of southern Senegal, located in the Region of High Casamance, Department of Kolda. Although high spatial diversity is found in soil conditions and land use patterns, the village is quite representative of mixed-farming systems of the zone.

A detailed description of the climate, soil and vegetation of the study site can be found in Chapters 1, 2 and 3. Main natural features are the following: (1) tropical dry climate with 960 mm of mean annual rainfall during the 1978-1997 period, from May to October (2) flat landscape harbouring sandy tropical ferruginous soils (group of ferric to haplic Lixisols; FAO 1998b) on the plateau and glacis and clayey Gleysols in seasonally flooded lowlands.

The farming system (land use, spatial allocation of organic resources) was depicted in Chapter 4. This system exhibits a ring-like organisation scheme typical of West African human settlements. A compound ring surrounds the dwellings. It is devoted to food production through continuous cropping of cereals, mainly pearl millet (*Pennisetum glaucum* L.), maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench), thanks to manuring and spreading of household wastes. Beyond, the bush ring encircles the compound ring. Various cropping patterns coexist (depending on manure availability), but semi-permanent cultivation dominates. Both staple and cash -groundnut (*Arachis hypogea* L.) and cotton (*Gossypium hirsutum* L.) to a lesser extent- crops are to be found there. The edge with the forest/savanna ring marks out the limits of the village on the plateau and glacis; the village owns a palm grove (*Elaeis guineensis* Jacq.) and rice (*Oryza sativa* L.) fields in the lowland too.

In 1997, the surface owned privately or in common by the 268 inhabitants was 260 ha, of which 110 were cropped. However, the space used by the village spreads largely beyond these boundaries, because of extensive livestock breeding. 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. The local *Ndama* race is trypano-tolerant but has rather poor zootechnical performances (Coulomb, 1976). Cattle is usually run by herdsmen in the savanna/forest ring during the cropping period, and they are left straying during the dry season (Richard *et al.*, 1991). Common grazing is the usual rule, but manuring during night corralling benefits to cattle owners only.

Settled Fulani (Peulh) people have been devoting themselves to cropping for more than a century, but they are basically herdsmen, with very variable ownership of animals between holdings.

5.2.2. Quantification and spatialisation of C, N & P fluxes

5.2.2.1. Flows at harvest

Estimate of C, N and P flows occurring at harvest of cropped biomass were based on data reported in Chapter 4. Organic matter flows from the fields to the farmyard encompassed the following components: panicle of millet, sorghum and rice; grain and cob of maize; groundnut haulms. Exportations off the village territory consisted of the groundnut pods and cotton grains (home consumption neglected). Returns from the farmyard to the compound ring were: non-edible components of millet, sorghum and rice panicle, maize cob, returns of haulm under faecal form after consumption as feed supplementation by small ruminants, calves and oxen. Biomass partitioning was made using traditional techniques of manual crushing.

5.2.2.2. Livestock-mediated transfers

Space mapping

Two kinds of mapping were performed to spatialize organic matter flows related to cattle activity. Firstly, the subregion district of Dioulacolon, to which Sare Yorobana belongs, was mapped and scaled to 1:12000 thanks to a photo-interpretation of the physiognomic types of vegetation. For this study, seven vegetation types were distinguished: woody savanna (upper woody strata or UWS above 7 m high); bush savanna (2 m<UWS<7 m); grass savanna (UWS<2 m); rice fields; rainfed fields and ponds (pooled as "Other" in what follows). This typology was used to characterise the flows occurring in the area outside the village (except for palm grove, which was pooled with bush savanna). Another mapping was performed for all the plots (cropped or not) owned by the village (see Chapter 4 for detailed method).

Livestock location

The day-straying movements of three out of the 10 herds managed by the village have been followed every 10 days for one day throughout the 1995-1996 dry season. These three herds represented up to 206 TLU, that is half of the size of cattle population of the village. Their location was determined using a global positioning system or a magnet with a topofil survey device (one record every five minutes).

Land use maps and herd position data were managed using the Atlas Geographic Information System software (SMI, 1993). Lengths of frequentation by animals of each LUS (vegetation type outside the village, plot inside the village) were computed by criss-crossing herd trajectories with land use maps. Ickowicz *et al.* (1998) have shown that browsing activity was quite steady during straying, whatever the land use; thus, spatial distribution of plant biomass intake was linearly inferred from lengths of frequentation. Because of little interannual change in land use and climate when this study was held, the distribution of the frequentation of the different LUS by livestock recorded during the 1995-1996 dry season was estimated to be still relevant for the 1996-1997 dry season.

Estimate of plant biomass uptake and dung deposition by livestock

A detailed description of the method used to assess the quantity and quality of faecal production can be found in Ickowicz *et al.* (1998). Faecal organic matter excretion (FOME) was found to range 19-48 gOM per kilo of metabolic weight or MW (for one animal, metabolic weight = live weight$^{0.75}$) throughout the year, with peak production recorded at the beginning of the dry season (see Table 5.3 for dry season data). Dung deposition was well balanced between night (53 %) and day (47 %). Faecal indexes were used to estimate OM intake (OMI) and nitrogen intake from FOME values (Guérin *et al.*, 1989). Estimated consumption varied in the same way as faecal production and ranged 46-103 gOM kgLW^{-1} d^{-1}. C content was determined using chromatography after burning at 850 °C (Thermoquest NC soil 2000); P content was measured after acid attack (HCl) on ashes followed by ICP spectrophotometry. Carbon uptake was estimated assuming that only herbaceous biomass was ingested by cattle, since tree fodder represents only 7-14 % of the forage consumed by cattle on the study site (Delacharlerie, 1994). Mean carbon contents reported for herbaceous biomass of maize, millet, groundnut rice fields and fallows in Chapters 1 and 3 were thus applied to dry matter intake (DMI) values to calculate C intake (DMI was derived from OMI assuming ash content to be 10 %). This method could not be used for the estimate of phosphorus intake, since livestock must select nutrient-rich plant components. We thus estimated total P intake during the dry season as being equal to P faecal excretion, corrected for the variation of P stored in the biomass of animals between the beginning and the end of the dry season (assuming P content of animals to be

11g $kgLW^{-1}$ according to Winter, 1999). We then dispatched this total amount between LUS, proportionally to the time spent on each unit.

Location of night corrals and impact of night manuring on millet yield

Kraaling practices were studied throughout the 1996-1997 dry season. The plot location, date and number of animals of each corral were recorded. Using data for faecal excretion from Ickowicz *et al.* (1998), the intensity of dung deposition was computed (expressed in $tDM\ ha^{-1}$ and $tOM\ ha^{-1}$). It was used for the establishment of a map of dung deposition density, and as an explanatory variable to predict the yield measured in 25 plots cropped with millet only (14 in the compound ring; 11 in the bush ring).

5.2.2.3. Energy and construction needs

The need for fuel wood was assessed using population census (see Chapter 4) and the work of Bazile (1998) carried out in a village of southern Mali, which was estimated to share climate conditions and habits of living similar to those of Sare Yorobana. In Mali, the author related wood consumption C (in $kgDM\ hab^{-1}\ y^{-1}$) to the size S of the population of the holding in the following manner: $C = 5.68 * S^{-0.73}$. Firewood was assumed to be harvested from fallows of the bush ring, since the wood resource stored in these fallows is the closest to the village. 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. Needs for construction wood were almost impossible to assess, because of the diversity of uses.

Stalk need for roof construction was quantified. Mean weight of local bundles was determined from 20 replicates. A regression relationship was determined between the number of bundles needed for roofing (obtained from enquiries) and hut diameter (10 replicates), using NLIN procedure from SAS Software (Hatcher and Stepanski, 1994). The straw biomass stored on the roofs of all the dwellings was then computed, and a turnover rate -estimated from investigations among farmers- applied for computation of annual flux needed to renew this spoiled biomass, which is then returned to the compound fields as household waste.

5.2.3. Outlook on carbon flows

To predict how the organic flows of the village territory may evolve during the next decades, 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 Chapter 4 for a detailed description of the model). Five scenarios were tested, combining three modality levels of increase of cereal yield (0, 30 and 100 %) and two modalities of increase of the standard of living (0 and 30 %). Output variables monitored were C flows (C intake by livestock, crop, wood and straw harvest). Ratio of C flow to C amount (as simulated in Chapter 4) was also examined as an indicator for the viability of the system under different constraint options.

5.3. RESULTS

5.3.1. Current C, N & P fluxes

5.3.1.1. Crop harvest

Grains accounted for 57 to 70% of the biomass in samples of cereal panicle and ear (Table 5.1).

Plant biomass harvested in cropped fields was 185 tDM, or 69 tC (Figure 5.1a). Seventy five per cent of the outflow stemmed from the bush ring, with half of it being exported abroad as groundnut pod and cotton grain for sale, the rest being transferred to farmyard as panicle and ear of cereal (59 %), and groundnut haulms. Optimistic estimate of on-site recycling of crop residues and weeds represented 45 tC (excluding fire loss). Eighteen tons of carbon of non-edible plant biomass and faecal returns from haulm consumption were transferred from the farmyard to the plots adjoining the dwellings. These returns counterbalanced N and P intakes due to harvest in the food crop fields of the compound ring. As a whole, 46 % of N and 35 % of P harvested were exported (Figure 5.2a, Figure 5.3a), and 511 kgN and 99 kgP lost in septic tanks (Table 5.2).

Table 5.1 Plant biomass partitioning of crop harvest measured for cereals in Sare Yorobana. All data in per cent.

	Grain	Non-edible in panicle	Cob	Spathe	n
Maize	70.4 ±0.5		18.3 ±0.5	11.3 ±0.5	16
Millet	61.0 ±1.5	39.0 ±1.5			24
Sorghum	67.1 ±1.3	32.9 ±1.3			8
Rice	57.5 ±2.5	42.5 ±2.5			8

±*: standard error.*
See Appendix 35 for data.

5.3.1.2. Livestock-mediated flows

Uptake

The weight of herds decreased slightly from 422 in November 1996 to 404 in June 1997 (Appendix 42). N faecal excretion ranged 1.0-2.0 gN kgMW^{-1} (Table 5.3). Daily N intake was estimated to vary between 1.2 and 2.4 gN kgMW^{-1}. Highest values of N intake and excretion were recorded at the beginning of the dry season. C and P contents of faeces did not vary much during the dry season; thus, intake and faecal excretion expressed in amounts of C, P or organic matter exhibited similar temporal patterns.

Table 5.2 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. All data in mass per hectare, except for farmyard (computed in absolute amounts).

	Savanna ring								Bush ring							
	Woody sav.		Bush sav.		Grass sav.		Total		Fallow		Cash		Food		Total	
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
Dry matter (t ha^{-1})																
Harvest												2.6	0.0	1.0	0.0	0.7
Cattle	0.1	0.3	0.0	0.0	0.2	0.8	0.1	0.3	0.1	0.3	0.4	1.0	2.0	2.2	0.5	0.8
Wood										0.7						0.5
Straw						0.1		0.0								
Residue	nd		nd		nd				nd		0.0		2.5		0.4	
Total	**0.1**	**0.3**	**0.0**	**0.0**	**0.2**	**0.9**	**0.1**	**0.3**	**0.1**	**1.0**	**0.4**	**3.5**	**4.5**	**3.3**	**0.8**	**1.9**
Carbon (t ha^{-1})																
Harvest												1.0	0.0	0.4	0.0	0.3
Cattle	0.0	0.1	0.0	0.0	0.1	0.3	0.0	0.1	0.0	0.1	0.2	0.3	0.8	0.8	0.2	0.3
Wood										0.3						0.2
Straw						0.0		0.0								
Residue	nd		nd		nd				nd		0.1		0.9		0.2	
Total	**0.0**	**0.1**	**0.0**	**0.0**	**0.1**	**0.3**	**0.0**	**0.1**	**0.0**	**0.4**	**0.2**	**1.3**	**1.8**	**1.2**	**0.3**	**0.7**
Nitrogen (kg ha^{-1})																
Harvest												56		13		14
Cattle	2	6	0	1	7	16	2	6	3	7	12	21	93	48	19	16
Wood										2						1
Straw						1		0								
Total	**2**	**6**	**0**	**1**	**7**	**17**	**2**	**6**	**3**	**8**	**12**	**77**	**93**	**61**	**19**	**32**
Balance		*-3*		*0*		*-10*		*-4*		*-5*		*-65*		*+33*		*-13*
Phosphorus (kg ha^{-1})																
Harvest												3.6		2.5		1.2
Cattle	0.2	0.4	0.0	0.1	0.5	1.1	0.2	0.4	0.2	0.4	0.9	1.3	5.2	2.9	1.2	1.0
Wood										0.5						0.3
Straw						0.1		0.0								
Total	**0.2**	**0.4**	**0.0**	**0.1**	**0.5**	**1.1**	**0.2**	**0.4**	**0.2**	**0.9**	**0.9**	**4.8**	**5.2**	**5.4**	**1.2**	**2.5**
Balance		*-0.2*		*0.0*		*-0.6*		*-0.2*		*-0.7*		*-3.9*		*-0.1*		*-1.3*
Surface (ha)		171		175		99		445		117		42		28		187

Table 5.2 (continued)

	Compound ring*						Farmyard		Rice field						Other	
	Cash		Food		Total				Village		Outer		Total			
	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
Dry matter (t ha^{-1})																
Harvest		1.3	2.9	1.2	2.5	1.2	128.9	80.7		1.3				0.3		
Cattle	0.0	0.0	4.6	2.7	4.1	2.6			0.3	1.3	0.3	1.3	0.3	1.3	0.0	0.2
Wood							86.0	86.0								
Straw			0.4		0.4		8.1	8.1								
Residue	1.0		2.2		2.1				1.2		nd		0.3		nd	
Total	**1.0**	**1.3**	**10.2**	**4.0**	**9.1**	**3.8**	**223.0**	**174.8**	**1.6**	**2.6**	**0.3**	**1.3**	**0.6**	**1.6**	**0.0**	**0.2**
Carbon (t ha^{-1})																
Harvest		0.5	1.0	0.4	0.9	0.5	43.9	27.3		0.4				0.1		
Cattle	0.0	0.0	1.9	1.0	1.7	0.9			0.1	0.4	0.1	0.4	0.1	0.4	0.0	0.1
Wood							32.2	32.2								
Straw			0.1		0.1		2.8	2.8								
Residue	0.4		0.8		0.8				0.4		nd		0.1		nd	
Total	**0.4**	**0.6**	**3.8**	**1.4**	**3.5**	**1.4**	**79.0**	**62.4**	**0.5**	**0.8**	**0.1**	**0.4**	**0.2**	**0.5**	**0.0**	**0.1**
Nitrogen (kg ha^{-1})																
Harvest		25	63	15	56	16	1704	1193		8				2		
Cattle	0	1	146	59	130	55			11	28	11	28	11	28	2	4
Wood							200	200								
Straw			3		3		57	57								
Total	**0**	**25**	**212**	**74**	**188**	**71**	**1961**	**1450**	**11**	**36**	**11**	**28**	**11**	**30**	**2**	**4**
Balance		*-25*		*+138*		*+117*		*+511*		*-25*		*-17*		*-19*		*-2*
Phosphorus (kg ha^{-1})																
Harvest		2.7	5.2	3.0	4.6	3.0	198	99		1.8				0.4		
Cattle	0.0	0.0	11.8	3.5	10.5	3.3			0.9	1.7	0.9	1.7	0.9	1.7	0.1	0.2
Wood			3.1		2.7		59	59								
Straw			0.3		0.3		6	6								
Total	**0.0**	**2.8**	**20.4**	**6.5**	**18.1**	**6.2**	**262**	**163**	**0.9**	**3.5**	**0.9**	**1.7**	**0.9**	**2.1**	**0.1**	**0.2**
Balance		*-2.8*		*+13.8*		*+11.8*		*+99*		*-2.6*		*-0.8*		*-1.2*		*-0.1*
Surface (ha)		2		19		21				16		62		79		81

** data for fallows in the compound ring not detailed (less than 0.5 ha).*
See Appendix 41 for absolute amounts and distribution.

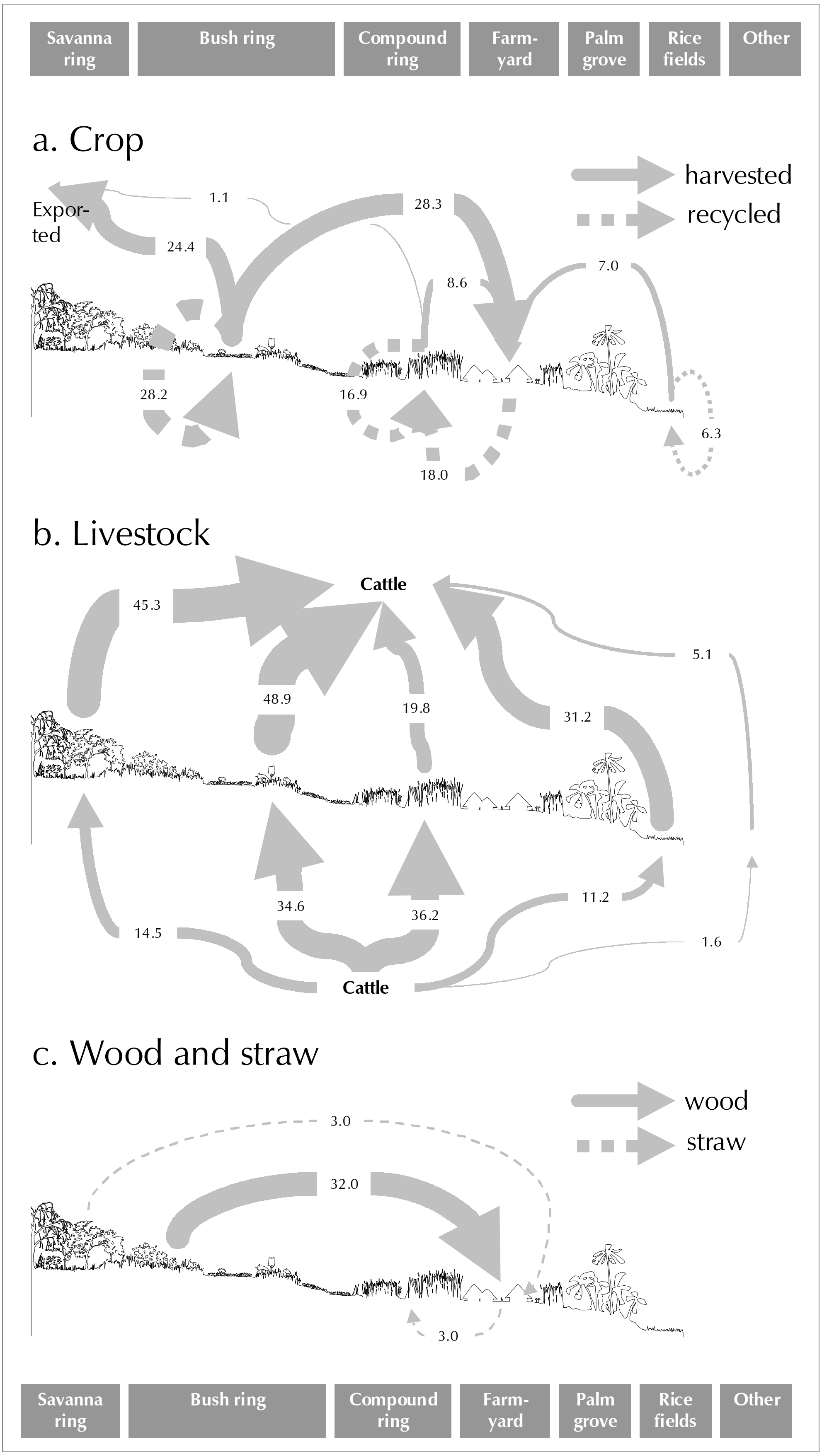


Figure 5.1 Anthropogenic flows of carbon (tons) established from November 1996 to November 1997 in Sare Yorobana.
Livestock flows include the dry season only. Arrow width is proportional to flow value.
See Appendix 41 for data.

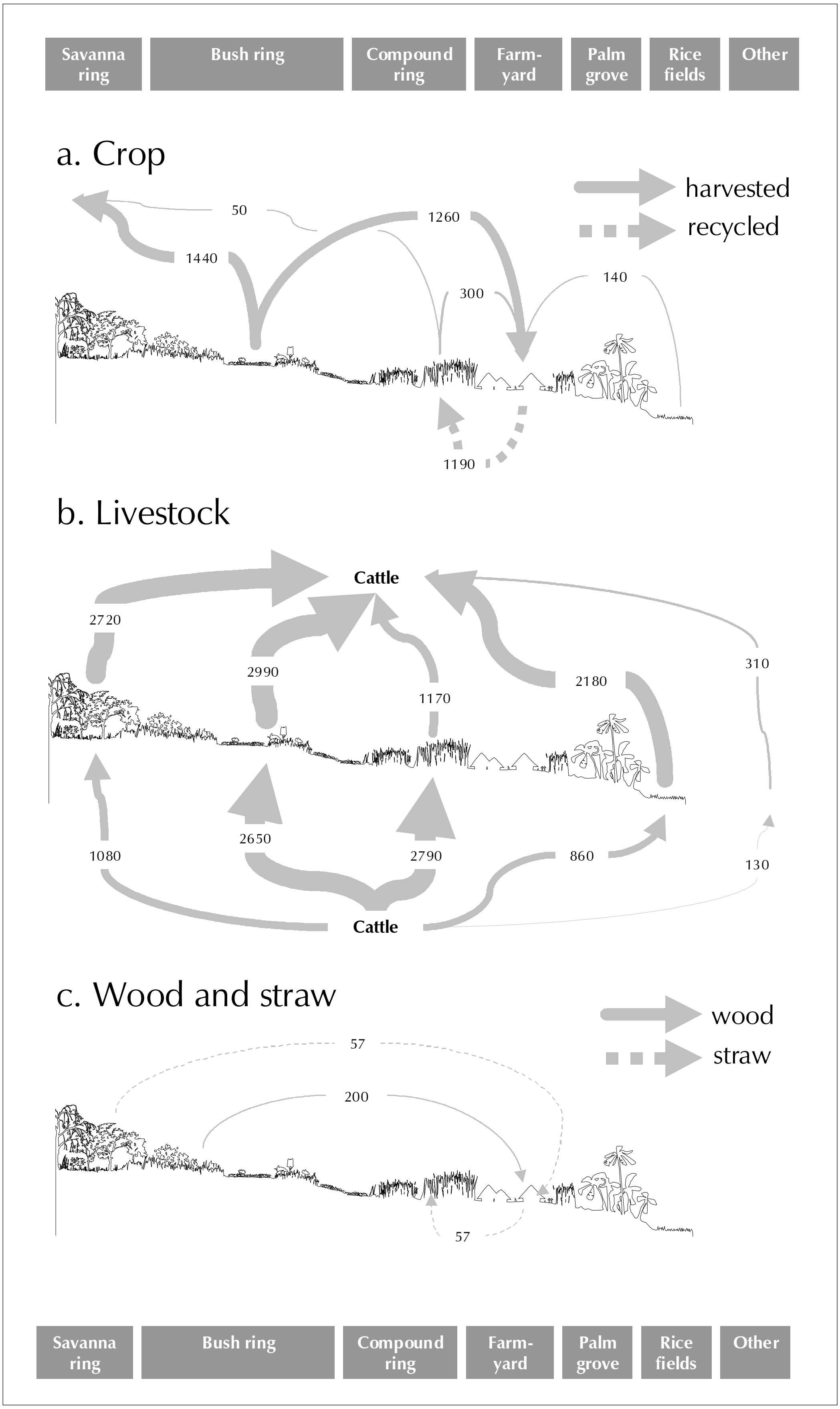


Figure 5.2 Anthropogenic flows of nitrogen (kg) established from November 1996 to November 1997 in Sare Yorobana.
Livestock flows include the dry season only. Arrow width is proportional to flow value. See Appendix 41 for data.

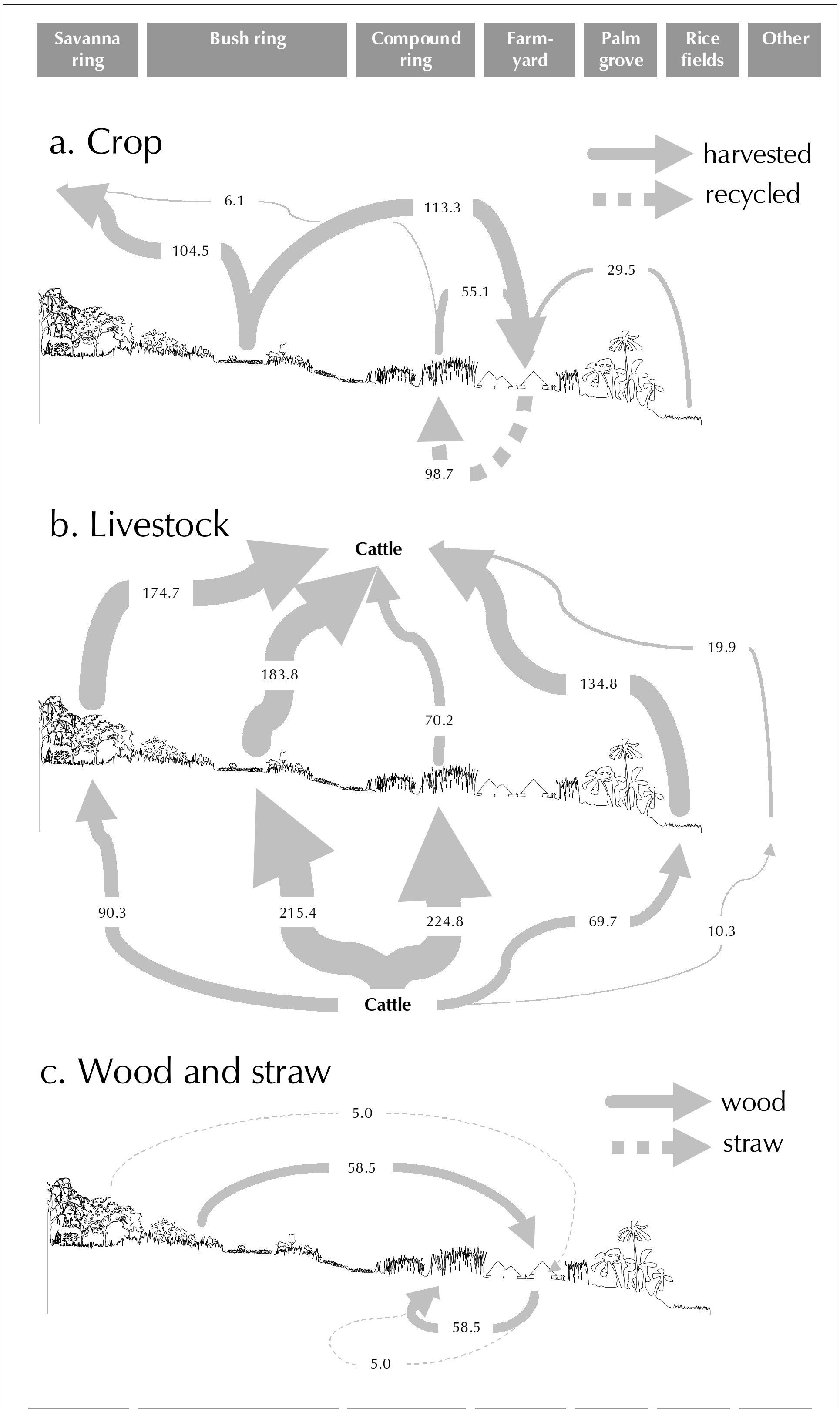


Figure 5.3 Anthropogenic flows of phosphorus (kg) established from November 1996 to November 1997 in Sare Yorobana.
Livestock flows include the dry season only. Arrow width is proportional to flow value. See Appendix 41 for data.

Table 5.3 Dry matter, carbon, nitrogen and phosphorus intake and excretion by livestock measured during the 1997-1998 dry season.

	Organic matter		Nitrogen		Carbon	Phosphorus
Month	intake	excretion	intake	excretion	excretion	excretion
November	74.4	34.9	1.92	1.63	18.0	0.111
December	103.2	47.6	2.42	1.98	24.6	0.152
January	66.8	31.8	1.74	1.45	18.0	0.114
February	61.8	31.2	1.32	1.11	16.1	0.093
March	64.5	32.5	1.35	1.19	16.1	0.102
April	54.5	27.9	1.31	1.12	14.7	0.098
May	51.9	26.4	1.19	1.00	14.0	0.081
June	53.4	25.2	1.40	1.20	14.7	0.095

All data expressed in g of element per day per kilo of metabolic weight.
Source: ISRA/CIRAD-EMVT, Program ABT (Ickowicz et al., 1998).
See Appendix 43 for carbon, nitrogen and phosphorus content of cow dung.

Total space explored by animals was 812 ha, including 268 ha owned by the village, corresponding to a mean stocking rate of 51 TLU ha^{-1}.

Land tenure was a more or less important determinant driving the trajectory of cattle herds, depending on herd size and surface owned by the holding (Table 5.4). The smallest herd spent five more times on its owner's fields than on all the village plots. The ratio dropped to less than two for the largest herd. It was also found that the higher the available surface owned by the holding per TLU, the higher the preference of animals for the owner's fields.

Table 5.4 Behaviour of the cattle of three holdings during day straying as influenced by land tenure, herd size and surface owned by the holding (dry season 1995-1996).

Behaviour features of the herd during straying		Cattle owner		
		Diao	Mama	Mamo
Owned surface (ha)	(1)	6.6	19	14.4
Herd size (TLU)	(2)	21.1	36.2	99.6
Available surface per animal (ha TLU^{-1})	(1)/(2)	0.31	0.27 *	0.14
Time (d ha^{-1}) spent on the plots of				
- the cattle owner		2.58	1.28	0.76
- the village:				
. all plots		0.52	0.4	0.45
. plots clustered per compound (n=17)	Mean (±SE)	0.98 ±0.27	0.57 ±0.17	0.72 ±0.14
Rank		2/17	2/17	8/17

TLU: tropical livestock unit (1TLU=250 kg of live weight)
[*] *includes the size of another herd managed by the holding (34.5 TLU).*
See data in Appendix 44.

A clear influence of previous cropping and land use on frequentations by animals during day straying was also evidenced, as illustrated by the contrasted organic matter flow densities recorded among land uses (crop type) and LUS (ring management, physiognomy of the vegetation of uncropped areas) (Table 5.2, Figure 5.4). According to grazing intensity, previous cropping ranked in the following order in the area owned by the village: millet > maize > millet intercropped with maize > groundnut > sorghum > fallow. When considering the whole territory prospected by animals, ranking was: compound ring > rice field > grass savanna = bush ring > woody savanna >bush savanna. When computing absolute intake values, main forage sources were the bush ring and the savanna ring (61 % out of the 443 tDM removed, equivalent to 63 % of 150tC) (Figure 5.1b); the compound ring ranked behind the rice fields. Nitrogen and phosphorus flows showed spatial patterns similar to C; they rose to 9.4 tN and 580 kgP (Figure 5.2b, Figure 5.3b).

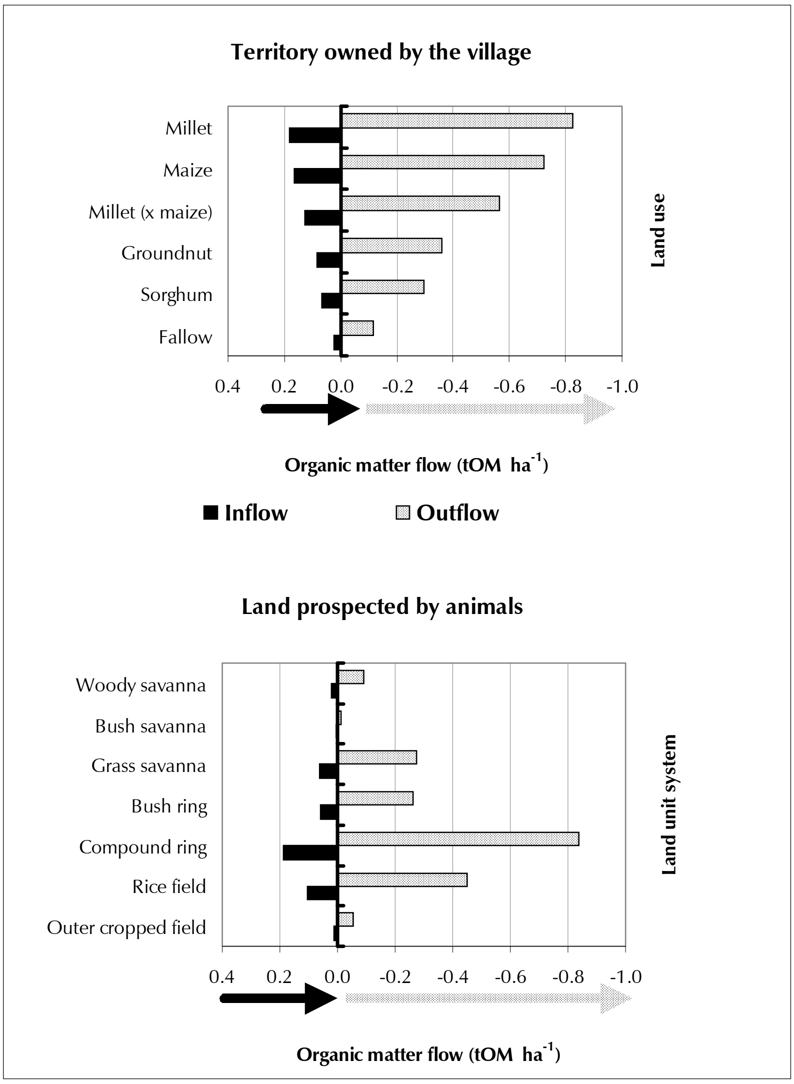


Figure 5.4 Organic matter inflows and outflows initiated by intake and faecal excretion of three herds during the 1995-1996 dry season. See Appendix 46 for data.

Faecal excretion

Night corralling was mainly practised near the dwellings (Figure 5.5). Strong contrasts of manuring intensity (ranging 0-13.4 tDM ha^{-1}) were recorded between plots. Night corralling was applied to plots planned for cereal cropping (Table 5.5). Highest manuring rates were found on plots cropped with millet x maize (3.9±1.3 tDM ha^{-1}; ± standard error), while groundnut received the lowest rates (0.02±0.01 tDM ha^{-1}). With regard to manuring rates, other cereals ranked in the following manner: maize> millet > sorghum.

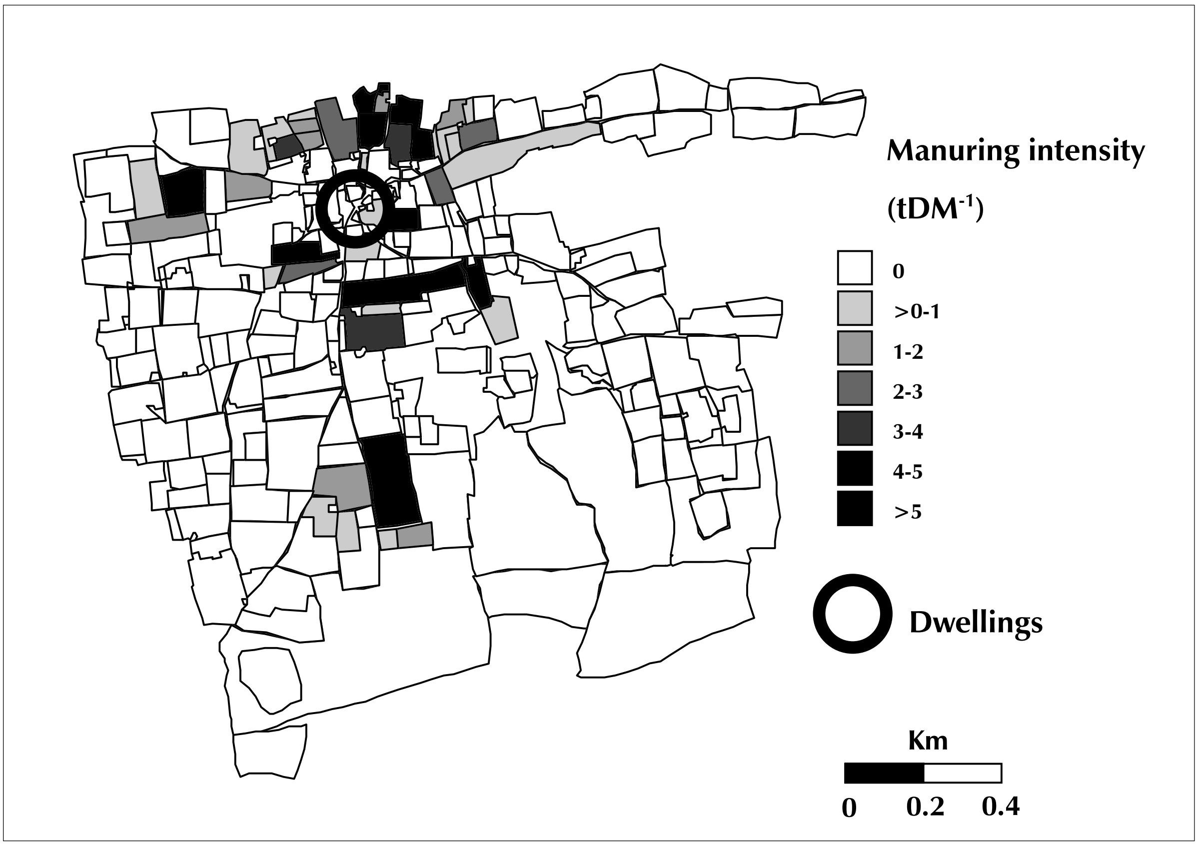


Figure 5.5 Manuring intensity from night corralling in the village of Sare Yorobana during the 1996-1997 dry season. See Appendix 2 for data.

Table 5.5 Input of dry matter to fields from manuring during night corralling as influenced by the plant species planned for cropping.

	Millet(x maize)	Maize	Millet	Sorghum	Cotton	Groundnut	Fallow	All plots
Mean spatial density (tDM ha^{-1})								
Compound	3.92 ±1.28	2.57 ±1.22	1.58 ±0.44	1.10 ±0.53	0.24 ±0.16	0.02 ±0.01	0.01	0.93 ±0.24
(n)	(12)	(6)	(18)	(14)	(11)	(16)		(19)
Village	4.10	4.02	2.28	1.91	0.35	0.03	0.01	0.59
Absolute values (tDM)								
	24.6	12.8	69.0	9.0	3.0	1.2	1.5	121.2
(%)	(20.3)	(10.6)	(56.9)	(7.4)	(2.5)	(2.5)	(1.2)	(100)

±: standard error.
See data in Appendix 45.

Total faecal excretion amounted to 239 tDM, of which 121 t were dropped during night tethering. Corresponding C, N and P flows were 98 tC, 7.5 tN and 610 kgP (Figure 5.1b, Figure 5.2b, Figure 5.3b). Overall dung deposition happened mainly (85 %) in the bush and compound ring; in these rings carbon inputs from manure offset C intake (input: output ratio = 1.4); it was not the case for the savanna ring and rice fields, in which only a third of C loss was recovered (Figure 5.1b, Table 5.2). The same trends were recorded for N and P, with P inflows compensating for half of the losses (Figure 5.2b, Figure 5.3b).

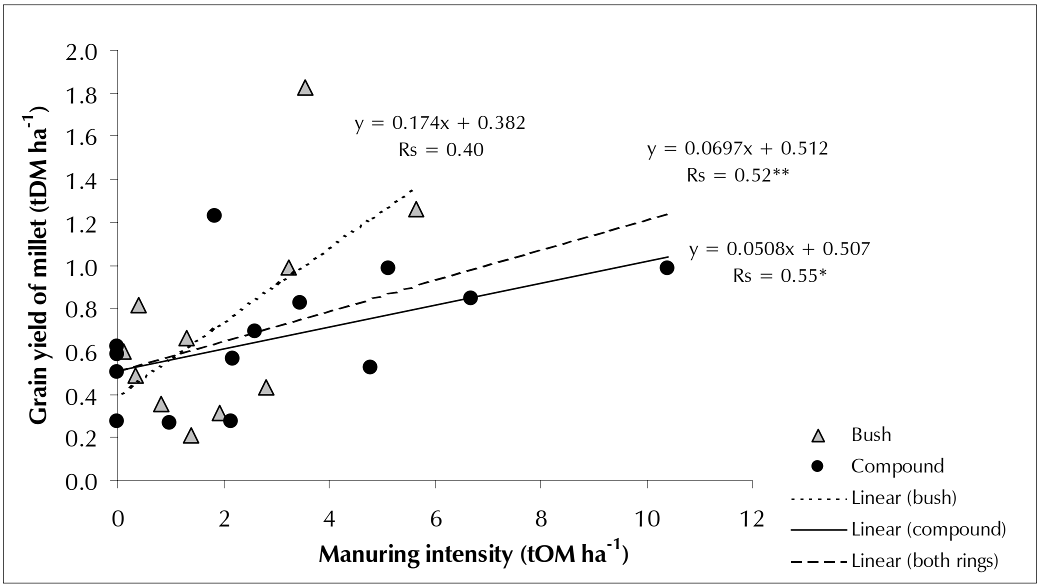


Figure 5.6 Millet yield as related to manuring practices in the compound and bush rings.
p{$R_{Spearman}$=0}: *<0.05; **<0.01. See Appendix 47 for data.

Impact of manuring on millet yield was noticeable for plots of both rings, but significant for those of the compound ring only (Figure 5.6). However, the slope of the regression was higher for the fields of the bush ring than for those of the compound ring. Pooling all data yielded a highly significant relationship between manuring intensity and grain yield.

5.3.1.3. Other anthropogenic fluxes

Wood consumption per permanent habitant was estimated to 280 kgDM per year (320 kgDM when including the needs for temporary workers employed during the cropping season).

Wood harvest generated an important flow of DM (86 t) between the bush ring and the farmyard, corresponding to 32 tC, 200 kgN and 58 kgP (Figure 5.1c, Figure 5.2c, Figure 5.3c). But except for P, nothing was returned to the compound ring.

The number of bundles (NB) needed to roof a hut with a circumference C (in m) was estimated by the following relationship: NB = 0.289 * C^$^{1.664}$ (R^2=0.96; p{Fobs>Fth}<0.001), with mean bundle weight being 8.96±0.81 kgDM. Total herbaceous biomass stored on roofs of the village was estimated to

40.7 tDM. Turnover rate was 0.2 y^{-1}, thus leading to a yearly input of 30 kg of straw per capita to the compound ring.

5.3.1.4. Global carbon and nutrient balance

Livestock activity accounted for more than half of the anthropogenic outflows of C, N and P, the share of crop harvest being only 25 to 32 % (Table 5.6, Figure 5.1, Figure 5.2, Figure 5.3). The preeminence of animal activity was even higher when considering C and nutrient returns to the soil, since animals were responsible for 79-86 % of carbon and nutrient inputs. Wood and straw flows were significant for carbon transfers only.

Table 5.6 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 (%)	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 among LUS (Table 5.2). Highest carbon inputs per hectare occurred in fields cropped for food production in the compound ring (3.8 tC ha^{-1}) and in the bush ring (1.8 tC ha^{-1}). C input sources in the compound and bush rings were mainly dung deposition (45 and 55 % in the compound and bush rings respectively), crop residue recycling (22 and 45 %) and recycling of harvested crop biomass (25 and 0 %). Exogenous N and P inputs during the dry season originated mainly from manuring in both rings (69-100 % for N, 58-100 % for P). In the rice fields of the village the situation was slightly different, since 75 % of the C inputs stemmed from residue recycling.

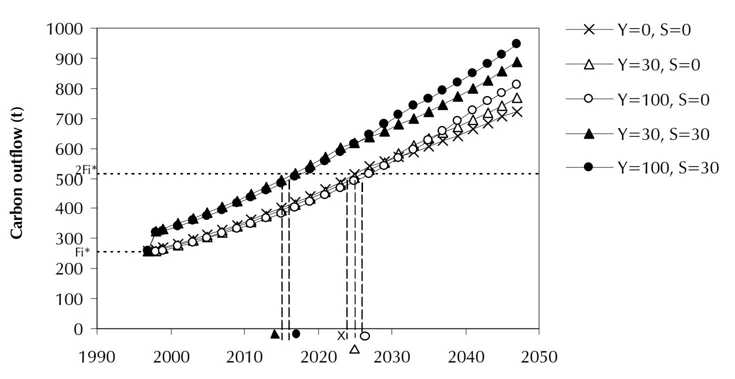
C uptake in the bush ring was related to crop harvest (39 %), browsing (37 %) and wood collecting (24 %). In the compound ring, browsing accounted for 67 % of the C withdrawal. In the rice fields, intake was well balanced between animals and humans beings.

N and P balances were strongly positive in the compound fields cropped with cereals: +117 kgN ha^{-1}, and +11.8 kgP ha^{-1}. Net N positive balance (+33 kg ha^{-1}) was recorded in the food crop fields of the bush ring too; P outputs were nearly compensated for by P inflows (-0.1 kgP ha^{-1}). All other land use units exhibited N and P deficits. Nutrient depletion was highest in the cash crops of the bush ring (-63 kgN ha^{-1}; -3.9 kg P ha^{-1}), followed by those of the compound ring, rice fields of the village, grass savanna and fallows (-5kgN ha^{-1}; -0.7kgP ha^{-1}). The N and P deficit of the bush ring rose to –13 kgN ha^{-1} and –1.3 kg P ha^{-1}.

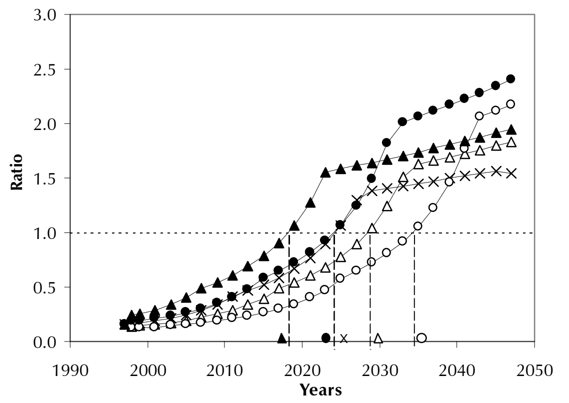
5.3.2. Outlook on future carbon outflows

A doubling of the carbon outflow is expected to happen in 28 years' time if no increase of the standard of living is expected (Figure 5.7a). When increasing this standard by 30 %, the doubling would happen in 20 years' time only. Modifying the food crop yield would have only little influence on C transfers.

The ratio of the C outflows to amounts of C stored in plant AGB would rise from 0.16 in 1997 to 1.55-2.40 in 50 years' time (Figure 5.7b). Slowest initial evolution would be recorded when hypothesising increase of cereal yield with steady standard of living. In the basic scenario, the 1:1 ratio would be reached in 27 years' time. Increasing cereal yield by 30 and 100 % would turn this value to 31 years' time. When considering a 30 % improvement of the standard of living, the outflow would equal the value of the stock in 21 to 27 years' time.



(a) Anthropogenic outflow



(b) Anthropogenic outflow:stock ratio

*Figure 5.7 Evolution of (a) anthropogenic carbon outflows (b) ratio of C outflow to amount of C stored in plant above-ground biomass of the territory of the village of Sare Yorobana for the 1997-2047 period as predicted by modelling (see description of the model in Chapter 4). Outflows considered are: harvested crop biomass, livestock uptake during the dry season, and wood and straw collecting. * Fi: initial flow. See Appendix 48 for data.*

5.4. DISCUSSION

5.4.1. Control of stocks over flows: livestock mediated transfers

5.4.1.1. Dry matter intake as influenced by organic matter quantity & quality

At the offset of the rains, herding of animals becomes looser, and cattle are left free to feed where desired at lowest metabolic costs. Preferential grazing on crop residues was already reported by Richard *et al.* (1991) on the study site, and by Dugué (1998b) in North Cameroon. Higher N content of maize stover and weeds of cropped fields than of fallow herbaceous layer in Sare Yorobana were found in Chapters 1 and 3. This has been frequently observed for most crops elsewhere in sub-Saharan Africa (Khombe *et al.*, 1992; Lamers *et al.*, 1996) and related to exogenous nutrient inputs to food crop fields (Powell, 1986; Buerkert *et al.*, 1997).

Available quantity of biomass obviously influences grazing trajectories of animals too, as demonstrated by the low frequentation of groundnut fields (Figure 5.4), in which the removing of haulms leaves only little edible biomass for livestock.

Not all the available plant biomass is put to value by animals left to common grazing. The DM “intake:available herbaceous biomass” ratio computed from results presented above and from Chapter 4 would be 53 % in the cropped fields of the bush ring, 61 % in those of the compound ring. Cereal leaves and weeds are eaten first, but much of crop stalks are left apart because of their poor feed value, tainting by urine, and trampling during browsing. As a result, frequentation of cropped rainfed areas drops quickly within the first two months of the dry season; later, animals prospect rather rice fields (where they can access limited grass regrowth throughout the dry season) and rangelands (fallow, savanna) (Richard *et al.*, 1991; Ickowicz *et al.*, 1998). The rate of intake in fallows of the village territory would be only 9 % of available dry matter. Fast decreasing feed quality of the herbaceous layer during the dry season (César, 1992), and uncontrolled fires removing large amounts of plant biomass may well account for this fact.

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

5.4.1.2. The human factor

As suggested by our results, the frequentation of land appropriated by the village is not random; it happens preferentially on plots owned by the holding that herds cattle, probably as a consequence of the memorisation of corralling sites by animals. This is particularly true for holdings with low “herd size:

owned surface" ratio (Table 5.4). These holdings also own the smallest herds (see Chapter 4). Thus, large herds transfer significant amounts of plant biomass and thus of fertility from the fields of farmers possessing few animals to those of owners of large herds, something already suggested in Chapter 4 from assessment of forage availability and need among all holdings of the village.

The more intensive exploitation of the forage resource on cropped fields than on uncropped ones is certainly driven by factors else than simple forage availability. For instance, farmers try to keep animals close to the dwellings where they are more easily overseen; and ponds used for water intake located down slope can be accessed only through the compound fields.

5.4.2. Control of flows over stocks: night corralling & cereal yield

The positive response of cereal yield to manuring which we evidenced here, has been clearly established in sub-Saharan Africa under controlled conditions (Pieri, 1989; de Ridder and van Keulen, 1990; Bationo and Mokwunye, 1991) or in farmers' fields (Powell, 1986; Derouw, 1998). Only trends could be evidenced for data of the bush ring, probably as a result from interactions with fallow practices. Though significant, millet response to manuring in the compound ring shows high variability. This indicates that factors such as residual effect of manure applied during previous years (de Ridder and van Keulen, 1990; Lupwayi and Haque, 1999), other inputs of fertilisers such as household waste spreading and dung drop during the day, agricultural practices and land use history may account for much of the cereal yields reported in Chapter 4. This is expected under any real farm condition.

The selectivity of farmers for manure application rates with regard to the following crop evidenced here is consistent with the varying response of local staple crops to organic fertilisation usually reported in the region (Kowal and Kassam, 1978; Pieri, 1989; Prudencio, 1993; Peters and Schulte, 1994; Derouw, 1998). All these studies indicate highest sensitivity of maize to manuring.

The great variability of manuring intensity between plots also illustrates unequal access to manuring between holdings. Although dung deposition during day straying might lessen such contrast, excessive manuring in some plots (see Chapter 4) may keep the village off optimum of food production. Indeed, cereal yield might not respond linearly to organic manuring at rates exceeding 5-6 t ha^{-1} (Gueye and Ganry, 1981; Bationo and Mokwunye, 1991; Fernandes, 1999), and high manuring rates (10 tDM ha^{-1} y^{-1}) leads to heavy leaching of C, N and P (Brouwer and Powell, 1998), and even to yield decline under dry conditions (Williams *et al.*, 1994; Probert *et al.*, 1995; Achard *et al.*, 2000). Increased weed encroachment is also reported as a drawback in manuring by peasants of Sare Yorobana and elsewhere in West Africa (Powell, 1986). But here manure is also said to be an efficient means to fight *Striga hermonthica* weed too; moreover, advent biomass is of high feed value.

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

5.4.3.1. On site recycling

As demonstrated above, common grazing leads to on-site recycling of half of herbaceous biomass produced on the cropped fields. From a pastoralist point of view, common grazing thus saves labour but not forage resource. On 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. Assessment of soil C, N and P status at the plot scale in various agroecosystems of the study site have pointed out the necessity of setting steady C flows through the soil to maintain soil quality (Chapters 2 and 3). Thus propositions aimed at improving manure availability and quality through herd expansion and stalling of cattle (Bosma *et al.*, 1999) should also take into account the energetic (carbon) cost of such practices for the farming ecosystem. Organic matter/energy loss is all the more likely to happen, since the return of manure from stall to field is often limited by transport means and labour availability (Schleich, 1986). Such a loss may seriously threaten the sustainability of traditional farming systems, since fast beneficial effects of on-site recycling of crop residues on soil quality by the doing of below-ground macrofauna for instance are now well documented (Mando, 1998; Mando and Stroosnijder, 1999).

5.4.3.2. Spatial organic transfers, C inputs and nutrient balances

The bush ring is the main carbon source for the village, in the form of food, wood and forage. But due to the extension of this ring, C outflows yet represent only 8.9 % of the carbon stored in above-ground biomass, not including litter (see Chapter 4). Inside this ring, C depletion is high in the cropped fields (75 % of C-AGB) and low in the fallow (3.2 % of C-AGB). High values are also recorded for the food crops of the compound field (65 %) and rice fields (68 %). But C redistribution benefits to the compound ring at the expense of other rings (Table 5.2). Carbon inputs in food crops of this ring (3.8 tC ha^{-1} y^{-1}) are much higher than amounts usually recommended to compensate for soil organic carbon mineralization, which assumes a relative rate of mineralization of soil organic matter to be 0.06 y^{-1} (de Ridder and van Keulen, 1990; Berger, 1996). Mean actual C amounts computed for the 0-20 cm layer of six plots from this ring was 17.7 tC ha^{-1}, while that of old fallows was 15.5 tC ha^{-1} (Chapters 2 and 3). Under the reasonable hypothesis that SOC storage of cropped plots would equal those of old fallows some 20 years ago (when the village moved to its current location) actual SOM decomposition rate would be 0.21 y^{-1} (neither decay nor exsudation of roots was taken into account). This suggests that estimates usually accepted in the literature are much too weak for sandy soils of the region.

Considering nutrient dynamics, N and P outflows were well balanced between rainfed cropped fields and other land use systems, but these cropped fields represented 74 % of the N and P sinks, of which nearly all benefited to staple crops, resulting in positive N and P balance. Thus, the current system acts as an impluvium for carbon and nutrient elements, since it taps organic resources from the peripheral areas to the rainfed food crops. By this way, ring like organisation scheme enables sustainable continuous cultivation of cereals at relatively high yields on 7 % of the surface owned by the village. In the compound ring (8 % of the territory) of a village of the Sahelian zone, N and P inputs were reported to amount to 7.7 kgN ha^{-1} and 1.1 kgP ha^{-1} under a stocking rate of 12 TLU ha^{-1} (Buerkert and Hiernaux, 1998). This is less than our findings (+87 kgN ha^{-1}; +8.3 kgP ha^{-1}), even taking into account the difference in stocking rate, and it indicates possible impact of climate on potential nutrient transfers by livestock.

In semi-arid Burkina Faso, Krogh (1997) showed to what extent nutrient balance of farming systems relies on the spatial scale considered. Most of N and P balances of staple fields were negative. This was not the case at the village level, since outputs due to harvest were kept within the boundaries of the village. Our work yielded the same kind of results: the nutrient balance in the bush ring was negative, but that of the village territory was positive when integrating N and P stored in septic tanks. However, our conclusion differs from Krogh's, because we think that a distinction has to be made between geographic and functional balances: N and P excreted by human beings will not be recycled and are lost for the cropping system.

From a nutrient point of view, the system as a whole might be considered close to sustainability. However, one of the major prerequisites is high livestock availability, through which most of C, N and P flows to the village occur. 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 switching to more intensified farming patterns such as fertilised ley and improved fallow (Hoefsloot and VanDerPol, 1993), forage availability quickly impedes the maintenance of animal husbandry in crowded areas. Another condition driving the sustainability of the farming system of Sare Yorobana is thus good land availability. The keeping of wide peripheral rangelands (1) ensures forage availability during the cropping period, thus avoiding the seasonal –and most of time definitive- migration of livestock as largely 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 (3) compensates for nutrient losses of the system at a low mineral depletion rate. Reporting good carbon and chemical status of soils of the compound ring in villages under various climates of Burkina Faso, Prudencio (1993) concludes that the evolution toward more permanent cultivation systems will mine the fertility of fields of the outer ring, but not that of the chemically well endowed soils of the compound ring. From what is presented here, we cannot strictly subscribe to his point of view, since soil quality of plots neighbouring the compounds relies on organic mining flows from the bush and savanna rings. Intensification is likely to reduce the surface of nutrient sources, weaken the biological mechanisms of mineral repletion and questions the maintenance of the means to transfer these nutrients to the staple crop area (Giller *et al.*, 1997).

5.4.3.3. Other C, N and P flows

Only organically mediated C, N and P inputs and outputs are reported here. Actual C inflows to the soil should also take into account root exsudation and decay, and litter production in fallows. C transfers through erosion, runoff and leaching should remain limited. Assuming such water-mediated C flows to be 20 and 84 kgC ha^{-1} y^{-1} in fallow and cropped fields respectively (Roose and Barthes, accepted), C transfers would amount to 10.6 t ha^{-1} on the whole surface owned by the village, which is less than 2 % of the flows mediated by plant biomass. Factors affecting N and P balances not taken into account in our study are: atmospheric deposition, nitrogen biological fixation, 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 kgN and –1.5 kgP ha^{-1} y^{-1}, and biological N and P accumulation in fallow to +2.0 kgN and +0.87 kgP ha^{-1} y^{-1}. Applying these figures to the village, final nutrient balance of the system would be –4kgN and –1 kgP ha^{-1} y^{-1}, which is closer to equilibrium than the findings of these authors (-14 kgN and –9kgP ha^{-1} y^{-1}).

5.4.4. Future trends in the use of the carbon resource

5.4.4.1. Evolution of the carbon flows

Although the current ratio of carbon amounts redirected by farmers for their needs to that stored on AGB of the village territory is low (approximately 16 %), it is likely to increase quickly during the coming years as a result of growing need for cropped land. Whatever the option considered about cereal yield and standard of living, all scenarios indicate fast exhaustion of the carbon stocks, as well as increased needs for organic matter, mainly forage. Land use intensification expected to happen in Sare Yorobana within the next few decades could easily lead to land saturation in the same way as it was experienced by the Sereer farming system in Central Senegal during the 1965-1985 period, and, more recently, throughout the Sine-Saloum region, not far from High-Casamance. Coexistence of continuous cultivation and animal husbandry is another potential pattern of evolution for the agricultural system. However, it requires drastic changes of farming practices, land tenure status, as well as increased chemical inputs, and thus the existence of financial and technical advisory structures (Dugué, 1998a).

5.4.4.2. Methodological considerations: limits of the model

The C flow: C stock ratio as defined in the simulation here could be seen as a first step towards building an accurate carbon-based indicator of the viability of the farming system. Viability is understood here as the aptitude to provide products (food, forage, livestock, wood…) and means of production (livestock, manure, household wastes) in a given range of values, for a given initial state (here 1997), under various scenarios (demographic growth, crop yield, goals defined by peasants). At this step of the modelling approach, we restrict to the concept of viability, which refers to an objective mathematical concept. Main refinements of the model should include (1) representation of human (means of production, needs) diversity (2) representation of spatial heterogeneity and constraints (3) integration of multiple scales of space and time, (4) autonomisation of actors (holding individual strategies, animal choice for feeding trajectory during the day, vegetation dynamics) as well as their socialisation (for instance, common decisions for land management, vegetation dynamics as influenced by plant biomass intake by human/animal). The adoption of a flexible, object-oriented programming tool and the creation of a multi-agent system for the formalised representation of carbon dynamics at the village scale would be a more accurate tool than the spreadsheet (Manlay *et al.*, 2000a). Only then could modelling be used to assess the evolution of the organic status of the village farming system and thus evaluating its sustainability as understood in the pragmatic meaning of Izac and Swift (1997a).