
PART

II

ORGANIC · STATUS · OF
AGROECOSYSTEMS · OF
A · WEST · AFRICAN · SAVANNA

THE VILLAGE TERRITORY
SCALE

CHAPTER 4.

CARBON, NITROGEN AND PHOSPHORUS

SPATIALIZED BUDGET OF A VILLAGE TERRITORY

OF THE WEST AFRICAN SAVANNA.

I. THE STOCKS



Millet field at harvest

Chapter 4. CARBON, NITROGEN & PHOSPHORUS SPATIALIZED BUDGET OF A VILLAGE TERRITORY OF THE WEST AFRICAN SAVANNA – I. THE STOCKS.

ABSTRACT

Mixed farming systems of West African savannas greatly rely on availability of organic matter to supply local needs for food, forage and wood and to sustain soil quality. Hence amounts of C, N and P in soil (0-20 cm layer; available P measured only) and plant biomass (above- and below-ground down to 40 cm deep) as related to agro-social organisation were assessed for a village territory of southern Senegal at the offset of the rainy season.

Main features of the agricultural system were human density equal to 33 inhabitants km⁻² and stocking rates being 51 tropical livestock units (TLU; 1TLU = 250 kg of live weight) per square kilometre. Fallows, staple (rainfed cereals and rice) and cash (groundnut, cotton) crops represented 46, 25 and 17 % of the 258 ha owned by the village. Important contrasts were found between holdings, especially about livestock availability. As a result, common grazing and night corralling would lead to possible unbalanced fertility transfers from fields of small cattle owners to those of big holder.

The village exhibited a ring-like organisation with positive gradient of intensification and food production from the savanna to the dwellings. The compound ring was mostly devoted to food production; it covered 8 % of the acreage and accounted for 5, 7 and 14 % of the amounts of C, N and P of the whole village territory. The bush ring surrounding the compound ring spread over 73 % of the village and stored 66-71 % of C, N and P of the village. The lowland (rice fields) accounted for 6 % of the surface and 9 % of C and 16 % of N and P stocks, the rest of the village being covered with a palm grove.

Amounts of C, N and P in plant and soil averaged 29.7, 1.52 and 28.6 10⁻³ t ha⁻¹. Main C pools were soil (52 %), woody above-ground biomass (22 %), stumps (8 %) and coarse ($\varnothing > 2$ mm) roots (8 %), the rest of it consisting of fine roots, above-ground herbaceous biomass (crop and advents) and litter.

Under current demographic annual growth rate (2.5 %), simulated C depletion due to expansion of cropped areas should lead to a net release of 0.38 tC ha⁻¹ y⁻¹ during the next 31 years, which is far less than figures usually recorded under wetter tropical conditions, but indicates possible agro-ecological crash within the next decades.

KEY WORDS

Plant biomass, Carbon, Mixed-farming system, Nitrogen, Phosphorus, Savanna, Soil, Stock

4.1. INTRODUCTION

Most of traditional farming systems in West Africa, and especially those of the savanna share two main features (Ruthenberg, 1971):

- low requirements of exogenous inputs (fertiliser, energy, pesticide), often enabling only extensified agriculture, and remaining on the use of fallowing and manuring,
- high social cohesion, leading to common land tenure and rules of land management and sometimes allowing for spatially restricted intensification.

While experiencing an annual growth rate of 2.7 % of its population, sub-Saharan Africa has been decreasing its consumption of chemical fertilisers since the early nineties (Naseem and Kelly, 1999). To overcome energy, fertiliser and labour shortage, peasants have generally organised their village territory according to a ring-like scheme that is a general feature of self-sufficient mixed-farming systems (Mazoyer and Roudard, 1997). From their compounds to peripheral areas peasants have set a decreasing gradient of agricultural intensification and land tenure control, usually allowing for the distinction of three main rings (Pélissier, 1966; Ruthenberg, 1971; Prudencio, 1993):

- the compound ring. It is devoted to continuous cultivation, thanks to intensified practices of management of fertility, through manuring and spreading of household wastes. This ring ensures food safety and is cropped prior to any other land use system (LUS),
- the bush ring. It experiences less stable cropping systems and harbours both cash and staple crops. Semi-permanent agriculture mixes with more or less continuous cropping depending on soil initial properties, need for food and cash, and livestock availability. Fallows are short to long and constitute a reservoir of land that can be easily cleared depending on various factors such as labour availability,
- the forest or savanna ring, which has not been cropped for several decades and is submitted to common land tenure. This ring acts as a source of forage, wood and other ligneous by-products.

On the wettest fringe of the West African Savanna (WAS) belt, these mixed-farming systems have been mainly sustained by the proper management of organic matter (OM), thanks to the establishment of vertical transfers such as those occurring during fallow, and horizontal fluxes set by livestock during day straying and night corralling.

Endogenous OM (locally fixed carbon) has been managed by people as a multi-purpose tool for decades and can thus be viewed as a resource. The organic matter pool is a continuum of carbon forms from live biomass to humified compounds. It provides people with food, fuel wood and construction materials. It supplies livestock with forage. It conveys nutrients and energy to the soil while ensuring the integrity of the structure of the soil ecosystem. In heavily leached, coarse textured, low-activity clay ferruginous soils

that prevail in the WAS, these functions are of utmost importance, since soil organic matter drives many of chemical, physical and biological properties (Jones and Wild, 1975; de Ridder and van Keulen, 1990; Asadu *et al.*, 1997; Feller and Beare, 1997). However, such practices have proved to fit to a weak demographic context only (van der Pol, 1992; Floret *et al.*, 1993). For a few decades, WAS have experienced fast increase of their population. This, together with unsecured national land tenure policy, results in growing needs for land, wood and forage, calling fallowing and even manuring into question (Dugué, 2000). The reduction of the fallow period and of the available peripheral rangelands during the cropping period, the exhaustion of woody vegetation, the decrease of the return of crop residues to the soil together with the privatisation of land tenure and thus of organic resources, all these factors threaten the reproducibility of traditional organic practices.

The assessment of the organic resource at the field scale is a first step toward the definition of new viable agricultural systems. In a village of the WAS belt of southern Senegal, it has brought some understanding about the role of organic matter in sustaining the productivity of local agroecosystems (Chapters 1, 2 and 3). It has been shown that fast increase of the storage of plant biomass can occur in fallow, and provide farmers with goods, as well as improve soil chemical properties (carbon, nitrogen, cation exchange capacity, pH, and magnesium). However, such an evolution relied chiefly on stump maintenance and, although most of plant biomass and soil characteristics would not evolve beyond 10 years of fallow, long breaks of fallow were necessary for stump encroachment. On the other hand, the chemical status of the compound ring was much better than that of the bush ring; the amount of carbon inputs alone did not fully account for the increase of the SOM content, which relied also on the quality (biochemistry, nutrient content) of organic matter returned to the plots (stover, manure, household waste).

However, more information –especially about the sustainability of the farming system- may be retrieved from carbon (C), nitrogen (N) and phosphorus (P) dynamics when shifting from the plot to the village territory scale (Landais and Lhoste, 1993; Izac and Swift, 1994; Krogh, 1997). Reasons for this are:

- functional connection between the land use systems (bush and compound rings), through livestock management for instance,
- mostly common practices for the management of fertility, as well as land tenure, at least at the scale of the holding,
- plot carbon and nutrient budgets needed to be weighted by their surface, soil inherent properties, and cropping history for more accurate estimate.

Increasingly populated WAS are likely to shift towards mining agriculture (van der Pol, 1992), and, unless better access to chemical inputs is possible, the sustainability of these agricultural systems in the coming years may still be assessed through the accurate estimate of carbon and nutrients stored on site at the village scale. As mentioned by Stoorvogel *et al.* (1993a), this kind of fieldwork is still lacking.

The aims of this study were to (1) describe the social, functional and spatial organisation of a mixed-farming system in the way it drives OM production and C, N and P storage (2) give global budgets of C, N and P of a village territory (cropped fields, fallows aged less than 18 years, and palm grove) of southern Senegal as related to land use and management of fertility (3) estimate future trends in the storage of carbon in this territory under different scenarios related to agriculture efficiency and evolution of farmers needs.

4.2. METHODS

4.2.1. Site characteristics

The study was held in Senegal, in the village of Sare Yorobana, Region of High Casamance, Department of Kolda. Sare Yorobana belongs to the district of Dioulacolon and is located 12°49'N and 14°53'W. The village was chosen for its representativeness of the mixed-farming systems encountered on the southern fringe of the region, although high variability with regard to population density, herd ownership and agricultural practices, is the rule in High Casamance (Fanchette, 1999b).

A detailed description of the site climate, soil and vegetation can be found in Chapters 1, 2 and 3.

The climate is tropical subhumid with rainfalls occurring mainly from May to October and averaging 960 mm per annum in the 1978-1997 period (Figure 4.1) (Service de la Météorologie Nationale, station of

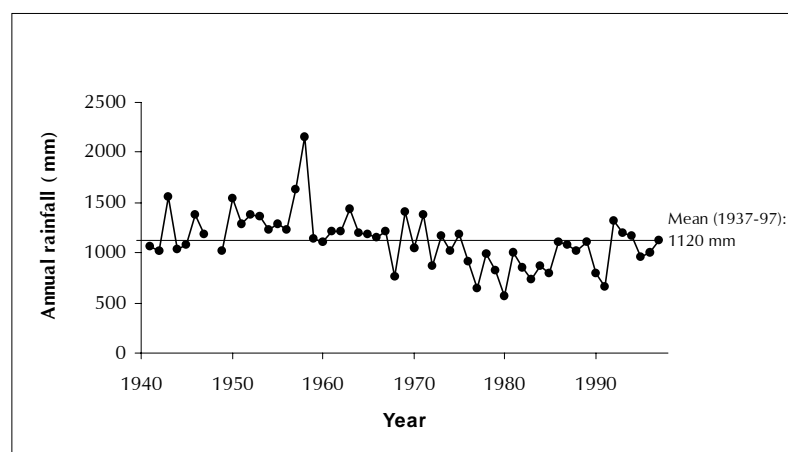


Figure 4.1 Mean annual rainfall over the last 60 years (Service de la Météorologie Nationale, station of Kolda). See data in Appendix 28.

Kolda).

The landscape is quite flat, and the typical toposequence is made of a plateau, a glaxis and a seasonally flooded lowland. Both plateau and glaxis share tropical ferruginous, sand-loamy soils (Baldensperger *et al.*,

1967), also described as ferric (plateau) and haplic (glacis) Lixisols (FAO, 1998b). The lowland harbours hydromorphic silt-clay-loamy soils (typical Gleysols). Soil properties do not depend on land management in layers deeper than 20 cm (Chapters 2 and 3). Soil C, N and available P (measured following Olson's method modified by Dabin 1967, and noted P_{OD}) contents average respectively 5.1 (C), 0.39 (N) and $2.3 \cdot 10^{-3}$ (P) g kg⁻¹ in fallows, 4.1 (C), 0.33 (N) and $2.2 \cdot 10^{-3}$ (P) in cropped fields of the bush ring, 5.9 (C), 0.49 (N) and $13.7 \cdot 10^{-3}$ (P) g kg⁻¹ in the compound ring, and 15.2 (C), 1.4 (N), and $21.6 \cdot 10^{-3}$ (P) g kg⁻¹ in the rice (*Oryza sativa* L.) fields of the lowland.

The village of Sare Yorobana belongs to the most ancient nucleus of Fulani (Peulh) settlement in the region of High Casamance (Pélissier, 1966; Fanchette, 1999b). Before the independence war held against their Mandingue masters in the mid-19th Century, a distinction had already been made among Peulh people between the nobility –the first, authentic Peulh migrants- and those whom they had enslaved during the wars held against other ethnic groups with the help of the Mandingues. These slaves were progressively culturally integrated in the Peulh ethnic group, but formed a new caste, that of the captives (Pélissier, 1966). Although slavery was abolished a long time ago, hierarchy still remains between noble and captive lineages; mixing seldom happens between them.

4.2.2. Characterisation of the farming system

4.2.2.1. Spatial organisation

Although extensive cattle breeding largely spreads beyond the village boundaries, only the territory owned by the community (according to customary law) was considered in this study. Mapping was initiated in 1996 using a teodolith. It was updated in 1997 using a compass. Fields (whether cropped or not) were identified as land tenure units, while plots referred to land management (one field comprising at least one plot, mostly several, with in-between plot boundaries moving from one year to another). Fallows were mapped only when the age of abandonment was less than 18 years; fixing boundaries for older fallows was indeed almost impossible, due to vegetation regrowth and unreliable indications from farmers, which evidenced the weak appropriation of such plots. The rice fields owned by the village were mapped as a whole due to high complexity of land tenure. A global positioning system was used to fix the boundaries of the palm grove.

The co-ordinate database was managed with the Atlas Geographic Information System (SMI, 1993), with which topological variables were computed (surface, distance to the dwelling).

A systematic characterisation of plot history and management was made through on-field enquiries with farmers. Cropping history, ownership, usership, and reasons for fallowing were investigated. The local typology applying to rainfed fields was also investigated. Roughly speaking, this typology distinguishes between (1) fields under continuous cultivation of cereals (the compound fields, or *bambe* in the local terminology), crops being mainly pearl millet (*Pennisetum glaucum* L.), maize (*Zea mays* L.) and sorghum

(*Sorghum bicolor* L. Moench) (2) and the fields under semi-permanent cultivation (the bush fields, called *kene* and *segueli*), bearing groundnut (*Arachis hypogea* L.) and cotton (*Gossypium hirsutum* L.). Although the criteria put forward to classify plots as belonging to the compound or to the bush ring changed between farmers, enquiries on cultural past indicated that compound fields could be well defined as those having been continuously cropped with cereals during the last 10 years.

These enquiries enabled to compute the cropping intensity or CI (defined as the proportion of years during which the plot has been cropped for the last 10 years) of each plot.

4.2.2.2. Social organisation

In the local societies of Casamance as is the case in most of those of the WAS, social cohesion and decision making are not established at the household level, but at the farm holding level (Pélissier, 1966; Achterstraat, 1983). A holding is understood here as a community of neighbouring people, related or not to each other, sharing the same staple crop fields, granary, and, most often, herd. A multivariate analysis was carried out to establish an agro-social typology of farm holdings of Sare Yorobana, on the bases of population structure (total size, feed need “FU”, labour power “WU”), means of production (animals “TLU”, equipment “Equ”, surface owned “OS” and employment of seasonal workers “Sea”) and land use (share between food crop “%foodS”, cash crop “%cashS” and fallow “%fallowS”).

Every holding was investigated for the structure of its permanent and seasonal population (size, age). These bulk data were used to compute the “population-to-feed” variable “FU” (expressed in “feed units”); for this purpose, we chose to assign 0.5 unit to any inhabitant aged less than 15, and one unit to any adult (“Adu”). The “working force” variable “WU” (expressed in working units) was computed by assigning the following weights according to age and sex of the population of the holding (derived from FIA-SLE, 1990): (1) people aged 15-59: female=0.5; male=1 (2) people aged less than 15: female=0.2; male=0.5. Production means investigated were: livestock availability “TLU” expressed in tropical livestock unit (1 TLU = 250 kg of live weight or LW), ownership of ploughs, hoes and sowers (pooled in one equipment variable “Equ”) and employment of seasonal workers “Sea”. Some of the variables were “normalised” after being divided by population variables (“Adu”, “WU” or “FU”). Farm typology was made using Principal Component Analysis (PCA) with ADE 4 Software (Thioulouse *et al.*, 1997). The data set consisted of 16 lines (holdings) and 10 columns (simple and mixed variables described above; see the legend of Figure 4.5 for a complete listing of variables and abbreviations). Spearman correlations were computed using SAS Software 6.14, proc CORR (Hatcher and Stepanski, 1994).

4.2.3. Carbon, nitrogen & phosphorus storage for the village territory

4.2.3.1. On-field measurement of harvested plant biomass

The harvested biomass (cereal panicle, groundnut pod, cotton grain) was weighed on site at harvest time, plot by plot when possible. A sample from each plot was brought back to the laboratory for the determination of the water content (drying at 60 °C to constant weight). Results in each plot were expressed in dry matter harvest yield.

4.2.3.2. Dry matter, carbon, nitrogen & phosphorus storage in other components of plant

biomass

Regression relationships were used to estimate full plant biomass storage of each plot. The harvest yield in cropped plots, and the age of crop abandonment in fallow fields were easily measured variables, that were thus used as predictors for the estimate of plant biomass for (1) stover, herbaceous advents, crop roots down to 40 cm deep in cropped plots (2) tree and grass layers, litter, stump, fine and coarse roots in fallows (down to 40 cm). Linear regressions were established for crops, using data from Chapter 3 and from four added field plots, two being cropped with millet intercropped with maize (MIxMA01 and MIxMA02), and two being cropped with sorghum (SO01 and SO02) (see locations in Appendix 1). Methods for sampling and measure of biomass yields were strictly equivalent to those presented in Chapter 3. Proc REG and F-test were performed with SAS software 6.14. Non-linear regression relations (logistic-like functions) were used in fallow fields to predict C, N and P storage in plant biomass as functions of length of fallow (Chapter 1). When regressions were not statistically satisfactory, mean amounts of biomass reported in both previously cited works were used.

Some of the plant biomass components of cropped fields could not be related to harvest yield. This was the case for above- and below-ground biomass (AGB and BGB) of woody advents. This one was rather estimated to be related to cropping intensity (CI), in the following manner based on field observations: $CI > 0.75$: woody AGB, coarse root and stump biomass equal to 0; $CI \leq 0.75$: $AGB = 0.32 \text{ t ha}^{-1}$, coarse root biomass = 3.38 t ha^{-1} , stump biomass: 7.48 t ha^{-1} (derived from Chapter 1). Because the choice of the threshold value for CI was made from qualitative observations, a test of sensitiveness was applied by re-computing total amounts of plant biomass at the village scale after modifying the threshold value for CI by less or more than 10 %.

C, N and P contents from Chapters 1 and 3 were then applied to convert DM amounts into C, N and P values.

Due to the lack of data for the palm grove and some of the sorghum and cotton biomass components, literature review was also used (see Table 4.5).

4.2.3.3. C, N and P_{OD} storage in soils

C, N and P_{OD} contents were computed from measures reported for 25 plots of the village (crop and fallow) from Chapters 2 and 3. Figures for soil stocks were computed down to 20 cm only, since C, N and P values are only slightly influenced by land use below this depth (except for P in the compound ring; see Chapters 2 and 3). Criteria considered for soil stock values were: ring of management, vicinity of a dwelling, land use (fallow, rice) and cropping intensity (see Table 4.1).

Table 4.1 Settings of C (in t ha⁻¹), N and P_{OD} (in kg ha⁻¹) stored in soil (0-20 cm layer) for the calculation of budgets at the village scale, as related to land use (in the case of fallow and rice), ring of management, vicinity of a compound, and cropping intensity (CI).

Land use	Fallow	Rice	Other			
			Compound		Bush	
Ring			Yes	No	Yes	No
Adjoining a compound:						
CI = <0.5:						
C (t ha ⁻¹)	15.4	41.2	21.3	14.5	12.9	11.7
N (kg ha ⁻¹)	1282	3796	2000	1175	989	989
P (kg ha ⁻¹)	7.2	56.3	77.8	17.9	6.4	6.4

Source: Chapters 2 and 3.

4.2.3.4. Establishment of a simplified agropastoral budget

The self-sufficiency of each holding, with regard to its needs for forage and manure during the 1996-1997 dry season, was computed. The following hypotheses were made: (1) intake: 15.4 kgDM per kilo of metabolic weight (MW) (Ickowicz *et al.*, 1998) (2) mean faecal production during night corralling: 8.74 kgDM kgLW⁻¹ (ibid.) (3) annual minimal need of manure of a cereal crop: 2.5 tDM ha⁻¹ (de Ridder and van Keulen, 1990; Berger, 1996). The amount of available forage of a holding was defined as the sum of the biomass of stover and weeds in cropped fields, and of the herbaceous biomass of the fallow plots belonging to the holding.

4.2.4. Prediction of the evolution of the carbon status of the village

To predict how the organic status of the village territory may evolve during the next decades, a simplified representation of its dynamics was made using a spreadsheet relating C storage to land use, which in turn was linked to manure availability and human needs. Initialisation was made for year 1997 as a simplified representation of the territory from data presented here and in Chapter 5. Initial simplifications consisted mainly in pooling millet, sorghum and maize in a single land use label “rainfed cereal” and considering groundnut as the only cash crop (cotton fields being replaced by groundnut fields). The following assumptions were made for the basic static model, with figures derived from the actual situation in 1997 (this chapter and Chapter 5):

- annual growth of the population set to 2.5 % (UNDP, 1999),
- constant need for food and cash: 180 kg of cereal grain, 210 kg of groundnut pods, expressed in kg of DM grain per year and per inhabitant,
- constant yield of groundnut (1.29 tDM pod ha⁻¹),

- constant production of flooded rice (13 tDM; steady surface and yield),
- yield of rainfed cereal as a linear function of manure availability (as evidenced for millet in Chapter 5). The regression parameters were set to slope = 0.0659 ton of DM grain per ton of OM manure applied during night corralling, and intercept = 0.664 t ha⁻¹. These values were computed according to the fact that mean DM rain yield of cereal in all manured plots reached 0.795 t ha⁻¹ in 1997 for an available amount of manure of 1.99 tDM ha⁻¹ of manure, while non-manured plots yielded only 0.664 t ha⁻¹. Considering the works of Gueye and Ganry (1981) and Fernandes (1999), a threshold was set to 6 tDM of manure ha⁻¹, beyond which yields could not increase,
- constant ratio of the surface of fallows aged less than 10 years (labelled as “Young fallows”) to that of rainfed cropped plots (0.56 in 1997),
- in case of land shortage, priority given to the satisfaction of food need, then to cash need,
- constant TLU availability per capita equal to 1.55,
- constant forage availability (no modification of zootechnical performances as compared to 1997).

The palm grove was not considered in the model, since no direct measures of amounts of carbon were made on it, and because it is not likely to be cropped in the coming years due to poor chemical soil status.

From the “control” scenario described above, four alternative scenarios were built by crossing:

- increase of the cereal yield (“Y”) as a result of improved cultural practices (purchase of chemical inputs, genetically improved plant material ...). Two levels of increase were tested: 30 and 100 %,
- increase of the standard of living of people (“S”), that is a 30 % raise of the need for cereal and groundnut per capita, resulting in a 30 % increase of the TLU availability per human being.

Output variables followed were land use distribution (among cereal fields, groundnut fields, old fallows -aged more than 10 years-, young fallows) and C storage in the plant-soil system (above-ground biomass, below-ground biomass and plant biomass+soil).

4.3. RESULTS

4.3.1. Spatial organisation of the farming system

The village of Sare Yorobana spreads over 256 ha (add 2 ha for dwellings and farm gardens), of which 46 % are fallows, 25 % are staple crops and 17 % are cash crops (Table 4.2). Land use and management rely on both geomorphology and distance to the village (Figure 4.2; Figure 4.3).

Table 4.2 Surface distribution (ha) of land use with respect to ring of management and geomorphology in the village of Sare Yorobana.

Use	Bush ring		Compound ring	Palm grove	Rice field	Total
	Plateau	Glacis				
Millet x maize	0.0	0.4	5.6			6.0
Maize	0.6	0.8	1.8			3.2
Millet	10.6	12.1	10.6			33.2
Sorghum	1.4	2.3	1.0			4.7
Cotton	5.6	1.2	1.8			8.7
Groundnut	25.8	9.1	0.7			35.6
Fallow	100.0	16.7	0.0			116.7
Palm				31.9		31.9
Rice					16.2	16.2
Total	144.0	42.6	21.5	31.9	16.2	256.2

“Millet x maize” stand for millet intercropped with maize.

Four land use systems owned by the village people (thus not including the forest and savanna ring) can be distinguished:

- (1) the bush ring, settled mainly on the plateau and covering 73 % of the surface owned by the village (SOV) (Table 4.2). This is the farthest ring from the dwellings. Only slightly more than 40 % is cropped, the rest being left to short to long fallows. The cash crops (mainly groundnut and cotton) cover 60 % of the crop share. Reasons for fallowing are various and lead to distinguish between two kinds of fallows. Fifty-nine per cent of these fallows result indeed from the moving of the dwellings from the edge of the plateau to the mid glacis as a result of lower annual rainfall since the early 80's. The other type of fallow is fully integrated to the farming system, since reasons put forward for their keeping were fertility management (55 %), and labour and seed shortage (35 and 23 %) (one or more reasons for fallowing being possibly cited by peasants).
- (2) the compound ring is located on the glacis only and represents less than 8 % of the surface of the village, but a third of the whole hectareage under cereals. The choice of the cereal is clearly driven by the proximity of the dwelling (Figure 4.3), the closest plots receiving maize, or millet intercropped with maize.
- (3) the palm (*Elaeis guineensis* Jacq.) grove is down-slope the glacis. It covers 12 % of the SOV.
- (4) the rice fields represent only 6 % of the SOV, but 26 % of the cereal belt. Because only women usually crop rice, water management is restricted to light embankments, especially on the driest fringe of this land use system.

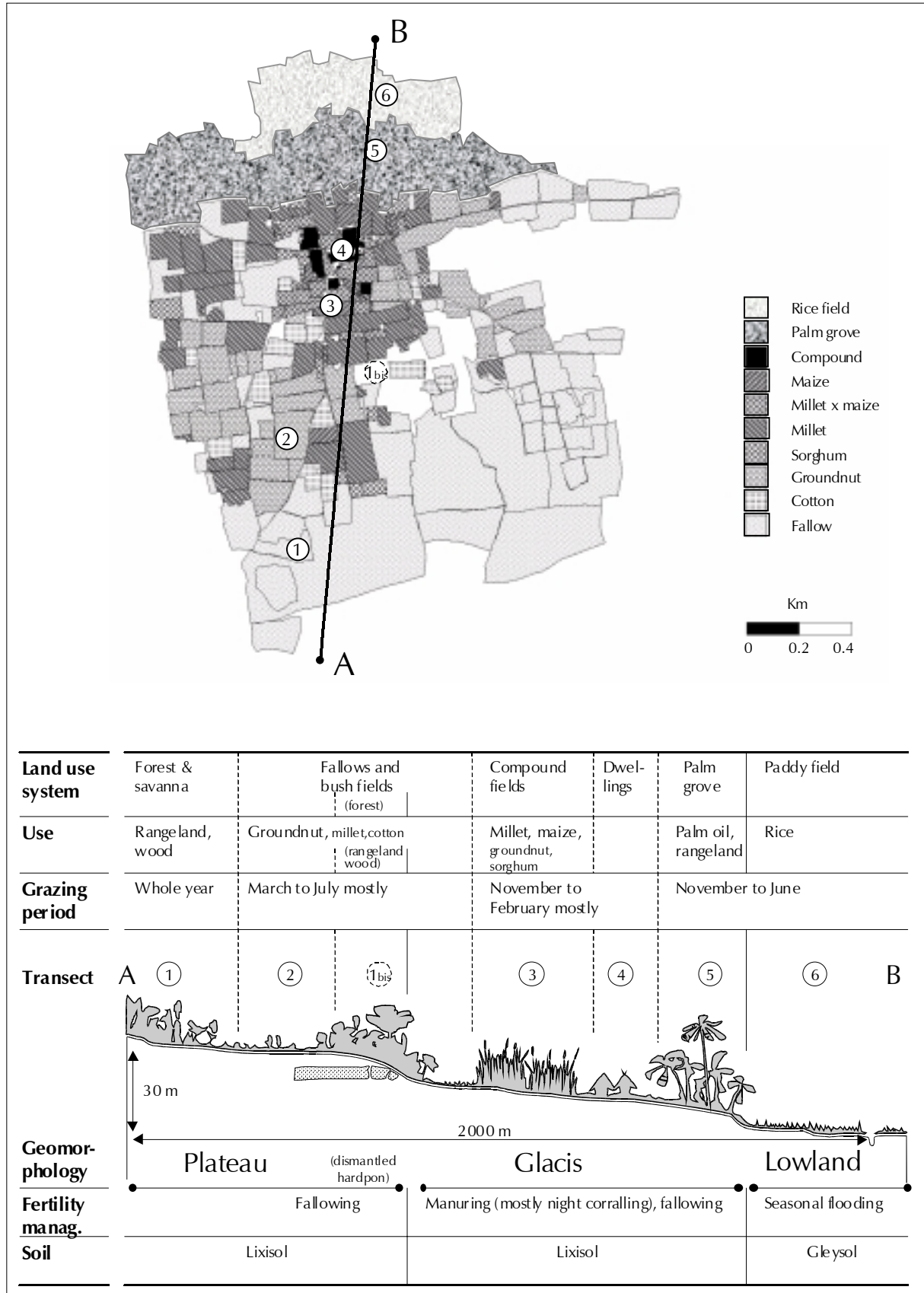


Figure 4.2 Spatial organisation and land use in the village of Sare Yorobana.

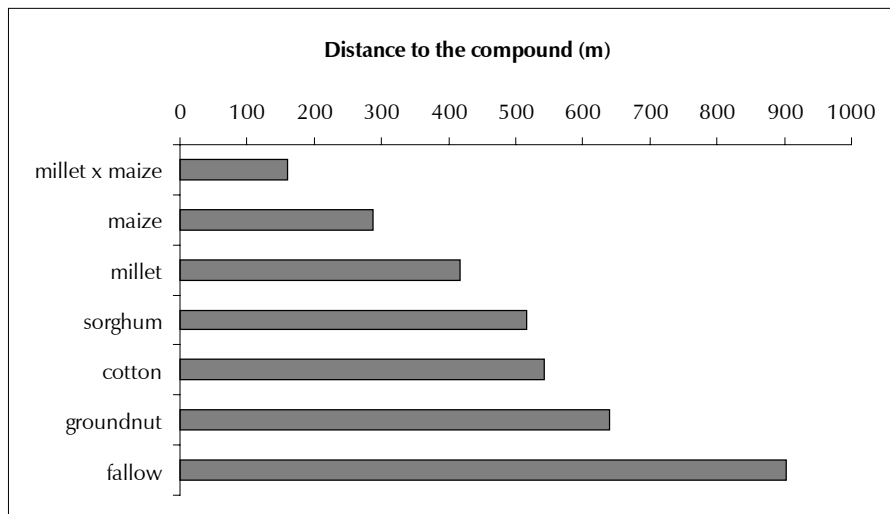


Figure 4.3 Spatial distribution of land use as illustrated by the distance of crops to the compound. See data in Appendix 29.

Fallowing and manuring are spatially dissociated among plots of the village (Figure 4.4). Most of the surface involved in the village cropping system seldom benefits from either fallowing or manuring. Most of plots experiencing regular fallowing were not manured, while only plots continuously cropped benefited from highest manure inputs.

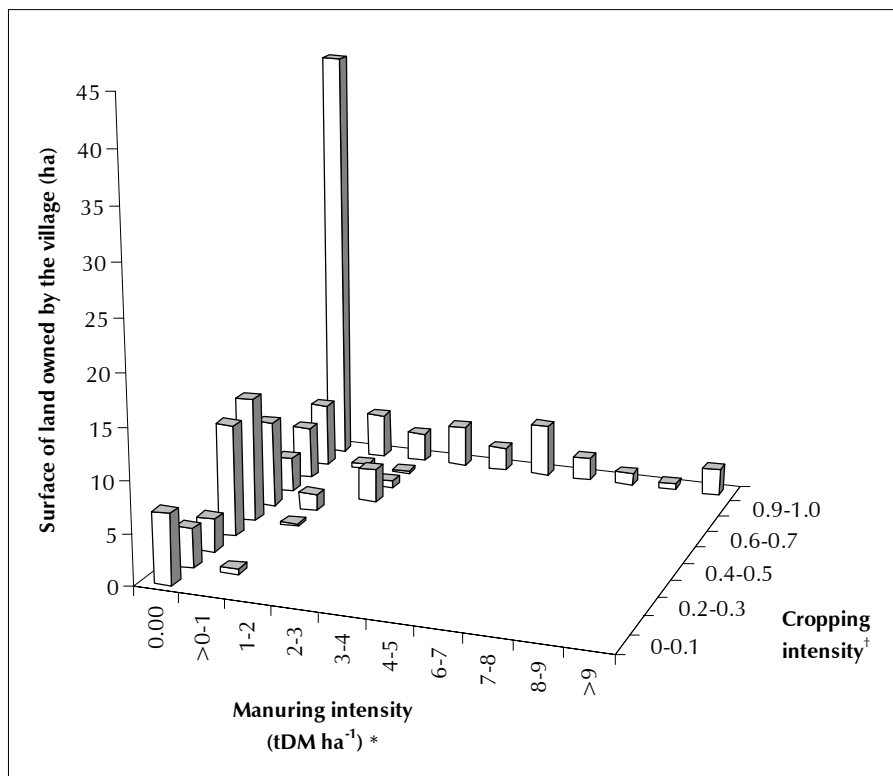


Figure 4.4 Spatial complementarity between cropping intensity and manuring in the mixed-farming system of the village of Sare Yorobana.

* applied during the 1996-1997 dry season (night corralling only).

† defined as the rate of campaigns during which the plot was cropped between 1987 and 1997

See data in Appendix 30.

4.3.2. Social organisation

The permanent population of Sare Yorobana reached 268 inhabitants in June 1997, of which more than a half was aged less than 15 (Table 4.3). Seasonal workers contributed to 15 % of the labour power. The village owned 415 TLU. Corresponding human density, with regard to the space owned by the village, would be 104 inhab. km⁻² and 162 TLU km⁻². However, vast areas of non-appropriated land remain on the plateau. Thus, previous density figures should be modified by taking into account the actual area exploited by the village, which goes well beyond that owned by people of Sare Yorobana (see Chapter 5). For instance, total surface explored by cattle during the dry season for the supply of its forage need is 812 ha; in these conditions, actual population density would average 33 inhab. km⁻² and 51 TLU km⁻².

Table 4.3 Elementary statistics characterising 16 holdings of the village of Sare Yorobana.

Variable	Unit	Mean ±SE	Median	Range	Village
Population	(h. beings)	15.9 ±2.3	13.5	3-32	268
- incl. adults :	(h. beings)	7.7 ±1	8.0	2-16	129
Labour power ⁽¹⁾	(working unit)	7.3 ±1	7.6	1.5-15.2	124
Livestock	(TLU) ⁽²⁾	26.0 ±8.2	14.3	0-99.6	415
Land management :	(%surface)				
- food crop		29 ±3	31	4-45	30
- cash crop		32 ±4	38	2-56	32
- fallow		39 ±7	29	6-93	38
Owned land ⁽³⁾	(ha)	8.8 ±1.5	7.6	1-22.6	144
Equipement ⁽⁴⁾		4.3 ±0.9	3.5	0-14	76
Yield					
- groundnut	(t pod/ha)	1.28 ±0.13	1.30	0.4-2.3	1.29
- millet (monocropped)	(t grain/ha)	0.91 ±0.13	0.83	0.3-2.1	1.13
- millet (mono- and intercropped)		1.03 ±0.12	0.91	0.4-2.0	1.12

(1) See 4.2.2.2. for definition

(2) Tropical Livestock Unit; 1 TLU = 250 kg of live weight

(3) by a holding (does not include oldest fallows owned collectively by the village)

(4) defined as the sum of the number of ploughs, hoes and sowers held by the holding.

See more data in Appendix 31.

The village comprised 18 holdings. Among the 16 most typical ones, a wide range of values was found for all variables, including production means such as land, herd size (also illustrated on Figure 4.7), and equipment. Millet grain yield averaged 1.1 tDM ha⁻¹, and groundnut reached 1.3 tDM of pod ha⁻¹. The first principal component (PC) (relative inertia or RI: 40 %) of the PCA performed on variables characterising the structure of holdings was held mostly by availability of land (“OS”, “OS:Adu”) and livestock (“TLU”, “TLU:Adu”) on the positive semi-axis, by available labour power as related to food need of the holding (“PmWU:PmFU”) on the negative side (Figure 4.5). The second PC (RI: 25 %) was rather a gradient of cropping intensity, with the share of fallow (“%FallowS”) on the positive semi-axis, and the share of cash crops (“%cashS”) and livestock availability (“TLU”, “TLU:Adu”) on the negative side. Particularly significant correlations of Spearman were found between “TLU” and “OS” (+0.80***), “OS:Adu” and “SeaWU:totWU” (+0.67**), and “PmWU:PmFU” and “SeaWU:TotWU” (-0.58*) (Appendix 32). The third PC did not yield clear information (Appendix 34a).

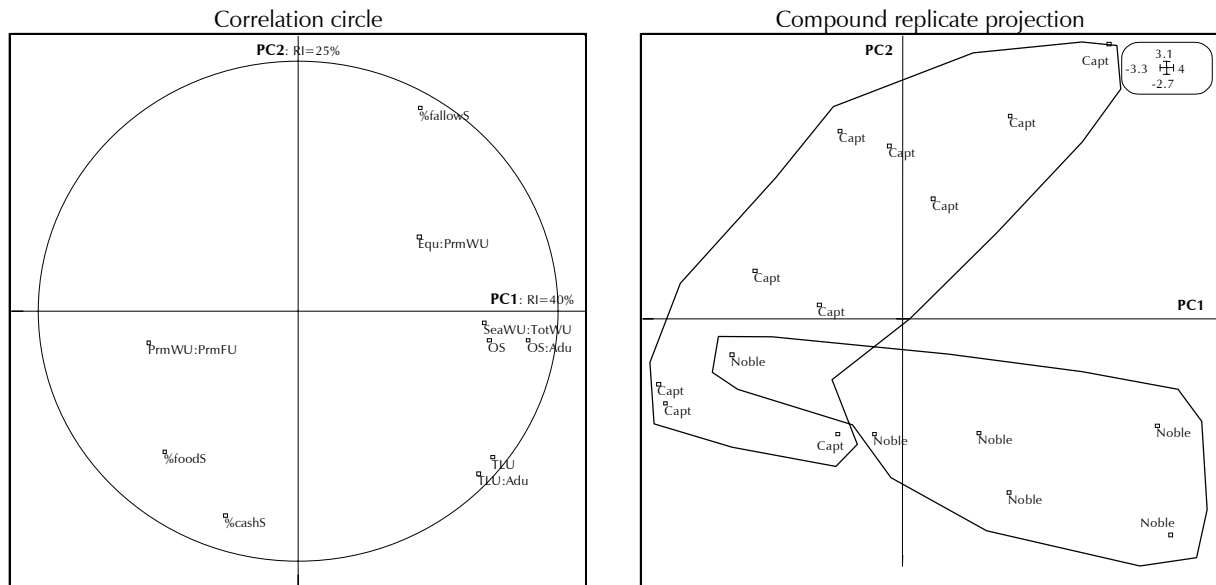


Figure 4.5 Principal component (PC) analysis of the structure of 16 out of the 18 holdings of Sare Yorobana: correlation circle of the variables and compound replicate projection (1st and 2nd PC).

“:” stands for “ratio”.

Adu: size of the adult population (aged 15 years or more). *Capt*: captive. *Equ*: equipment (see 4.2.2.2.). *OS*: owned surface. *PrmFU*: permanent feed unit (see 4.2.2.2.). *TLU*: size of the cattle herd (in tropical livestock units). *WU*: working unit (see 4.2.2.2.). *Prm/Sea/Tot*: permanent, seasonal, total population. *%fallowS*, *%foodS*, *%cashS*: respective shares of surface devoted to fallow, food and cash crop (in % of OS).

See Appendix 33 for data and Appendix 34 for projections on plane PC1×PC3 and for eigen values of principal components.

4.3.3. Dry matter, C, N & P storage at the village scale

4.3.3.1. Regression relationships between grain yield and plant biomass of the cropped fields

All crops exhibited highly significant ($p < 0.01$) regression relationships between panicle/pod yield and grain yield (Table 4.4). Relationships were highly significant between panicle or pod yield and stover production. But poor correlations were found between the former and weed yield, except in millet fields. However, a simplified, no-intercept regression had to be proposed for weed in millet crop, in order to make the model coherent (to avoid negative predicted yields for instance). Regressions on fine root biomass proved to be generally significantly positive in the 0-40 cm layer, but no linear model could be fitted to the root data of maize.

Table 4.4 Regression relations of yields between plant biomass components. Model: $Yield_{Component} = a * Yield_{Harvest} + b$.
 "Harvest" stands for (1) panicle of millet, sorghum and rice (2) ear of maize (3) pod of groundnut.

Component	a	b (t ha ⁻¹)	Mean (t ha ⁻¹)	F	R ²	n	Remark [†]
<i>Groundnut</i>							
Haulm	0.967	0.602	1.07	40.92 ***	0.61	28	
Advent bush	0.366	0.0183	0.353	1.8	0.06	28	Mean used
Weed	-0.00579	0.490	0.485	0.0	0.00	28	Mean used
Fine root	0.153	0.425	0.569	4.5 *	0.17	24	
Coarse root							Set to 0
<i>Millet</i>							
Stover	3.587	0.231	7.53	16.7 **	0.54	16	
Weed	0.770	-0.7477	0.818	10.3 **	0.42	16	Regression used: Weed = 0.628 * Panicle (F:14.7**)
Stover (if intercropped with maize)	3.310	0.1408	4.112	9.6 *	0.62	8	
Weed (if intercropped with maize)	-0.830	3.318	2.322	0.5	0.08	8	Mean used
Fine root	0.389	0.123	0.914	5.2 *	0.27	16	
Coarse root	0.173	-0.0764	0.275	0.5	0.03	16	Mean used
<i>Maize</i>							
Stover	0.812	0.877	3.43	53.3 ***	0.79	16	
Weed	-0.0152	1.245	1.175	0.0	0.00	8	Mean used
Fine root	-0.0170	0.397	0.319	0.4	0.06	8	Mean used
Coarse root	0.00041	0.0196	0.0215	0.0	0.00	8	Mean used
<i>Sorghum</i>							
Stover	3.404	1.146	9.80	6.9 *	0.54	8	
Weed	-0.337	2.124	1.27	1.2	0.17	8	Mean used
<i>Rice</i>							
Stover	0.624	1.462	3.306	16.8 **	0.74	8	
Weed	0.073	0.027	0.244	6.0	0.50	8	Mean used
Fine root	-0.591	5.026	3.277	12.5 *	0.68	8	Valid for 1.16 < Panicle < 5.38
Coarse root	-0.022	0.132	0.067	15.8 **	0.72	8	Valid for 1.16 < Panicle < 5.38

$p\{H_0: F=0\}$; * < 0.05; ** < 0.01; *** < 0.001.

Data used for regressions are in Appendix 35.

Fine roots: diameter ranging 0-2 mm. Coarse roots: diameter above 2 mm (stump not included)

† model used for calculation of plant biomass at the village territory scale in the present work.

4.3.3.2. Manageable stocks of DM, C, N & P at the village scale

The mean plant biomass (above- and below-ground down to 40 cm) stored in the village territory was 37.3 tDM ha⁻¹, of which 58 % were above-ground (Table 4.5). Great variations occurred between LUS. Lowest values per hectare were found in the compound ring. They were only 16 % of those found in the bush ring, with most striking differences below ground. Tree biomass accounted for approximately 61 to 77 % of the plant biomass and explained why highest figures for plant biomass were found in non-cropped plots (fallow, palm grove).

Table 4.5 Mean DM, C, N and P storage in a few agro-ecosystems of Sare Yorobana with respect to ring management and land use (plant biomass down to 40 cm deep, soil down to 20 cm deep).

a. Dry matter ($t\ ha^{-1}$)

Compartment	Bush ring						Compound ring					Palm grove	Rice field	Village
	Fallow	Groundnut	Cotton	Sorghum	Millet	Ring	Millet	Millet(x maize)	Maize	Cotton	Ring			
Tree	28.1	0.1	0.2	0.2	0.1	17.6	0.0	0.0	0.0	0.0	0.0	30.0 ⁽¹⁾⁽²⁾	0.0	16.6
Grass/herb. advent	3.6	0.5	0.0 [†]	1.3	0.7	2.5	0.7	2.3	1.2	0.0 [†]	1.1	3.0 ⁽³⁾	0.2	2.3
Harvest	-	1.3	1.2	0.7	1.1	0.4	1.1	1.0	1.2	0.9	1.1	-	1.3	0.5
Stover	-	1.8	1.5 ⁽⁴⁾	3.4	4.1	1.0	4.2	3.4	1.8	1.1 ⁽⁴⁾	3.5	-	2.3	1.2
Litter	2.1	0.0	0.0 [†]	0.0	0.0	1.3	0.0	0.0	0.0	0.0 [†]	0.0	2.1 ⁽⁵⁾	0.0	1.2
Total above ground	33.8	3.7	3.0	5.5	5.9	22.8	6.0	6.7	4.2	1.9	5.7	35.1	3.9	21.7
Stump	11.8	2.6	5.1	3.6	1.2	8.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.0
Coarse root	11.3	1.2	2.3	1.9	0.8	7.5	0.3	0.3	0.0	0.0	0.2	5.3 ⁽¹⁾⁽⁶⁾	0.1	6.1
Fine root	2.5	0.6	1.0 ⁽⁷⁾	1.0 ⁽⁸⁾	0.5	1.8	0.5	0.5	0.3	0.9 ⁽⁷⁾	0.6	14.7 ⁽¹⁾⁽⁶⁾	4.2	3.4
Total below ground	25.5	4.4	8.3	6.5	2.6	17.6	0.8	0.8	0.3	0.9	0.8	20.0	4.3	15.6
Total	59.3	8.1	11.3	12.0	8.5	40.4	6.8	7.5	4.5	2.8	6.5	55.1	8.2	37.4

b. Carbon ($t\ ha^{-1}$)

Compartment	Bush ring						Compound ring					Palm grove	Rice field	Village
	Fallow	Groundnut	Cotton	Sorghum [‡]	Millet	Ring	Millet	Millet(x maize)	Maize	Cotton ⁽⁹⁾	Ring			
Tree	10.6	0.0	0.1	0.1	0.0	6.6	0.0	0.0	0.0	0.0	0.0	13.8 ⁽⁵⁾	0.0	6.5
Grass/herb. advent	1.3	0.2	0.0	0.4	0.2	0.9	0.2	0.8	0.3	0.0	0.4	1.1 ⁽⁹⁾	0.1	0.8
Harvest	-	0.6	0.6	0.2	0.4	0.2	0.4	0.4	0.4	0.4	0.4	-	0.4	0.2
Stover	-	0.6	0.7	1.3	1.5	0.4	1.5	1.3	0.6	0.5	1.3	-	0.7	0.4
Litter	0.7	-	-	-	-	0.4	-	-	-	-	0.0	0.7 ⁽⁵⁾	-	0.4
Total above ground	12.5	1.4	1.4	2.0	2.1	8.5	2.2	2.4	1.4	0.9	2.1	15.6	1.2	8.4
Stump	4.3	1.0	1.9	1.4	0.5	3.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2
Coarse root	4.1	0.4	0.9	0.7	0.3	2.7	0.1	0.1	0.0	0.0	0.1	2.4 ⁽⁶⁾	0.0	2.3
Fine root	0.8	0.2	0.4	0.3	0.2	0.6	0.2	0.2	0.1	0.4	0.2	6.6 ⁽⁶⁾	1.3	1.4
Soil	15.4	12.1	11.9	11.8	11.7	14.1	15.2	16.8	18.1	14.5	15.9	9.9 ⁽¹¹⁾	41.2	15.4
Total below ground	24.7	13.7	15.2	14.2	12.7	20.5	15.5	17.0	18.2	14.9	16.2	18.9	42.5	21.3
Total	37.2	15.1	16.6	16.2	14.9	29.0	17.7	19.5	19.6	15.8	18.2	34.5	43.7	29.7

c. Nitrogen ($kg\ ha^{-1}$)

Compartment	Bush ring						Compound ring					Palm grove	Rice field	Village
	Fallow	Groundnut	Cotton	Sorghum	Millet	Ring	Millet	Millet(x maize)	Maize	Cotton ⁽⁹⁾	Ring			
Tree	118	5	10	7	2	76	0	0	0	0	0	249	0	86
Grass/herb. advent	23	5	0	16	9	17	9	30	18	0	15	20	2	16
Harvest	-	37	21	8	13	10	14	12	14	15	14	-	8	9
Stover	-	31	26	9	11	8	11	9	15	18	12	-	9	8
Litter	11	-	-	-	-	7	-	-	-	-	0	11 ⁽⁵⁾	-	6
Total above ground	152	78	57	41	35	117	34	51	47	33	41	279	20	125
Stump	46	9	18	12	4	32	0	0	0	0	0	0	0	23
Coarse root	43	4	8	8	5	29	3	3	0	0	2	42 ⁽¹⁾	1	27
Fine root	20	10	10	10	6	16	6	5	4	9	6	118 ⁽¹⁾	32	29
Soil	1282	989	989	989	989	1173	1263	1451	1611	1175	1341	860 ⁽¹¹⁾	3796	1314
Total below ground	1391	1012	1024	1020	1003	1249	1272	1459	1615	1184	1350	1020	3829	1392
Total	1543	1090	1081	1061	1039	1367	1305	1510	1663	1217	1391	1300	3849	1517

d. Phosphorus ($kg\ ha^{-1}$)

Compartment	Bush ring						Compound ring					Palm grove	Rice field	Village*
	Fallow	Groundnut	Cotton	Sorghum	Millet	Ring	Millet	Millet(x maize)	Maize	Cotton ⁽¹²⁾	Ring			
Tree	13.8	0.5	1.0	0.7	0.2	8.8	0.0	0.0	0.0	0.0	0.0	nd	0.0	7.3
Grass/herb. advent	2.1	0.3	0.0	2.3	1.2	1.6	1.3	4.2	4.5	0.0	2.3	nd	0.5	1.6
Harvest	-	2.2	3.9	1.6	2.6	0.9	2.6	2.4	2.4	2.7	2.5	-	1.8	1.1
Stover	-	1.5	6.9	2.3	2.8	1.0	2.8	2.3	3.6	4.8	2.9	-	2.2	1.2
Litter	0.0	-	-	-	-	0.0	-	-	-	-	0.0	nd	-	0.0
Total above ground	16.0	4.6	11.7	7.0	6.8	12.3	6.7	8.9	10.5	7.5	7.7	0.0	4.5	11.3
Stump	3.2	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	nd	0.0	1.7
Coarse root	3.5	0.2	0.5	0.5	0.3	2.3	0.2	0.2	0.0	0.0	0.2	nd	0.1	1.9
Fine root	1.1	0.4	4.4	0.7	0.4	1.0	0.4	0.4	0.2	4.0	0.7	nd	2.3	1.0
Soil	7.2	6.4	6.4	6.4	6.4	6.9	24.3	37.9	49.5	17.9	30.0	nd	56.3	12.7
Total below ground	14.9	7.0	11.2	7.6	7.1	12.2	24.9	38.5	49.8	21.9	30.8	nd	58.6	17.3

Fine roots: diameter ranging 0-2 mm. Coarse roots: diameter above 2 mm (stump not included)

[†] set to 0

[‡] carbon content set to that of millet

* not including the palm grove

Sources: (1) Dufrene et al., 1990; (2) Jaffre, 1984; (3) Blanfort, 1991; (4) Déat et al., 1976; (5) Chapter 1; (6) Jacquemard, 1995; (7) Poulain, 1977; (8) Chopart, 1980; (9) carbon contents for all components taken from (6); (10) carbon content set as that of grass biomass of fallows aged 1 to 9 years from Chapter 1; (11) Baldensperger et al (1967) and Appendix 4; (12) all total P contents from (4).

Carbon storage averaged 29.7 t ha^{-1} (41.1 t ha^{-1} when including carbon from the 20-40 cm soil layer) (Figure 4.6a, Table 4.5). Observations made on DM plant biomass apply here too. Total storage amounted to 7607 tC. Vertical distribution in the main components was the following (in %): soil (0-20 cm): 52; AG woody: 22; stump: 8; coarse root: 8, the rest of it consisting of fine roots, above-ground herbaceous biomass (crop and advents) and litter. Spatial allocation happened mainly in the uncropped part of the bush ring (57 %), the palm grove (14 %), the cropped part of the bush ring (14 %) and the rice fields (9 %). Highest carbon density was found in the rice fields (43.7 t ha^{-1} , 94 % in the soil) and in the fallows of the plateau (38.5 t ha^{-1} , 40 % in the soil).

Mean amount of nitrogen was 1.52 t ha^{-1} , mainly stored in the soil (87 %) (Figure 4.6b). The second contributor was tree AGB, harbouring only 6 % of the total storage. Forty six per cent of the 389 tN stored in the village were located in the fallows of the bush ring, the main other sites being the cropped fields of the bush ring (21 %), the rice fields (16 %), and the palm grove (11 %). Highest values for N spatial density were found in the rice fields (3.85 t , 99 % in the soil) and in the fallow fields of both bush and compound rings (range: $1.46\text{-}1.56 \text{ t ha}^{-1}$, 82-88 % in the soil).

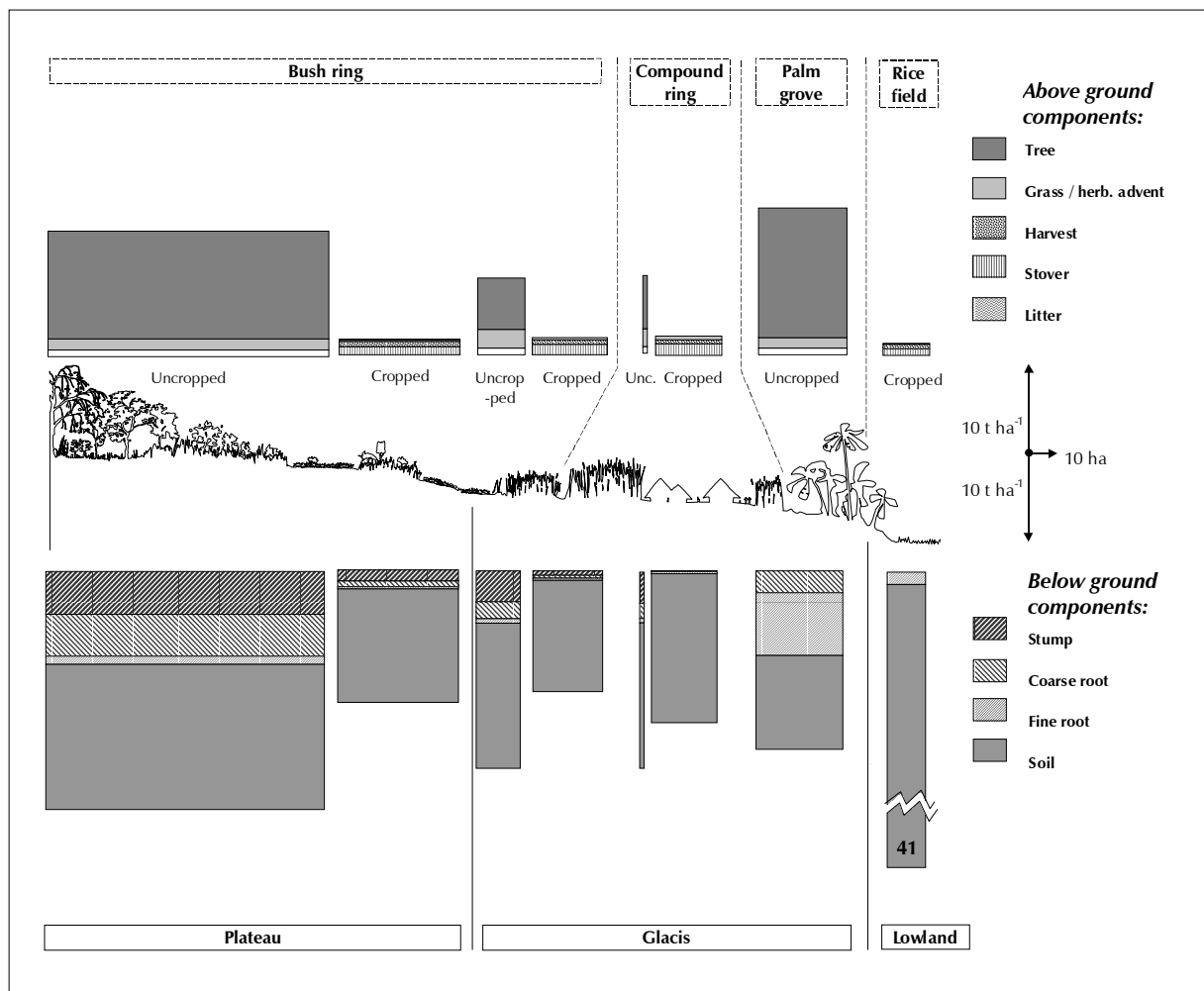


Figure 4.6a Carbon storage in plant biomass and soil of the territory of the village of Sare Yorobana with respect to geomorphology, ring and land use (cropped, non-cropped).

Horizontal scale: surface of the land use unit. Vertical scale: amount of the element per hectare. Thus, the amount for each component of each unit is proportional to the area of the corresponding rectangle. Fine roots: diameter ranging 0-2 mm. Coarse roots: diameter above 2 mm (stump not included). See Appendix 36a for data

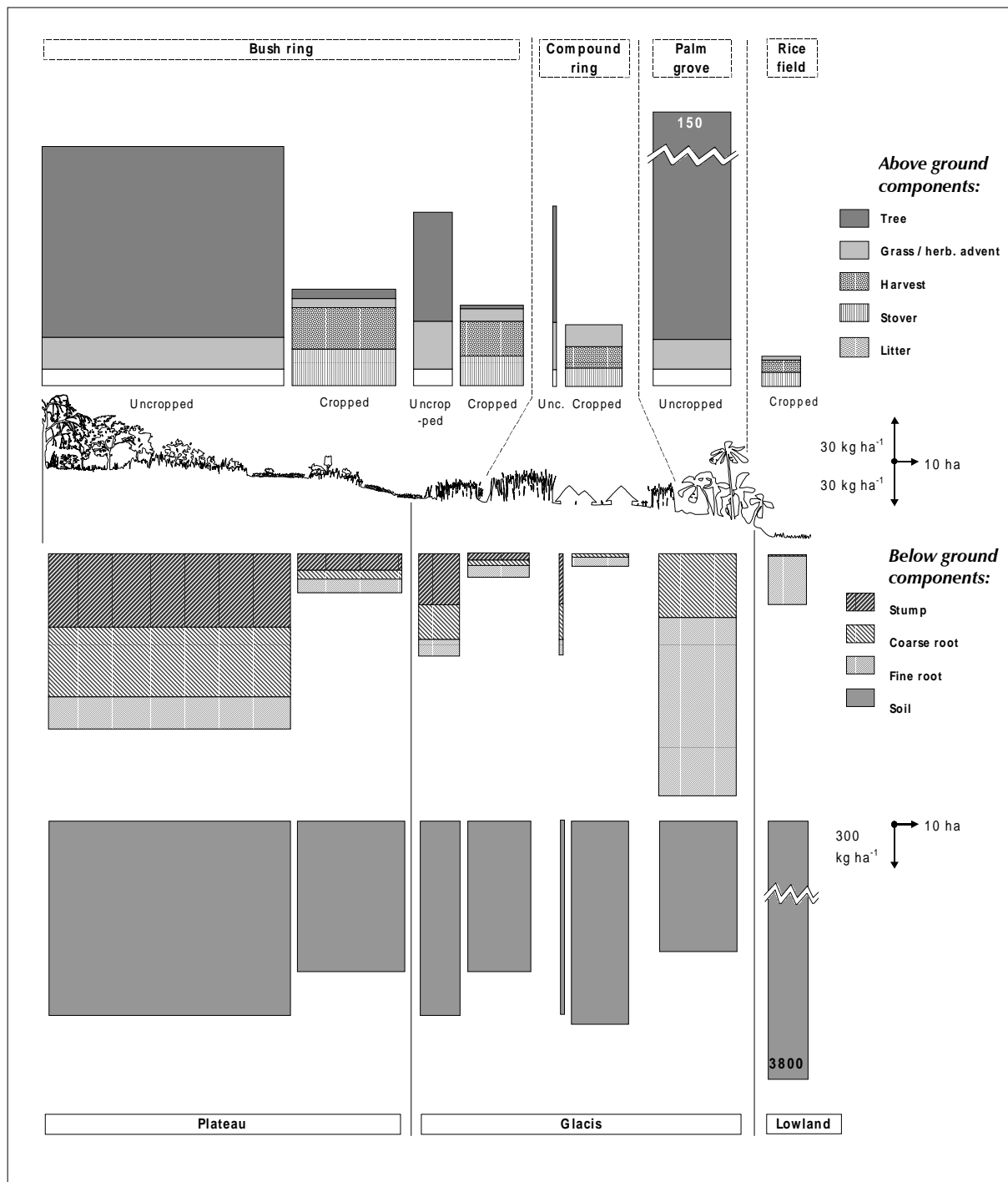


Figure 4.6b Nitrogen storage in plant biomass and soil of the territory of the village of Sare Yorobana with respect to geomorphology, ring and land use (cropped, non-cropped).

Horizontal scale: surface of the land use unit. Vertical scale: amount of the element per hectare. Thus, the amount of each component of each unit is proportional to the area of the corresponding rectangle. Fine roots: diameter ranging 0-2 mm. Coarse roots: diameter above 2 mm (stump not included). See Appendix 36b for data.

P (P_{total} in plant biomass plus P_{OD} in soil; palm grove not included) amounts showed somewhat different vertical and horizontal distribution patterns (Figure 4.6c). Mean stocks amounted to 28.6 kg ha⁻¹ in the whole village territory. Main reservoirs were the soil (44 %) and the tree AGB (26 %). The share of each of the other components did not exceed 10 %. Though remaining small (4 %), the contribution of harvested biomass (panicle, ear, and pod) was four times higher when expressed in P amounts than if computed in C or N values. Main storage was found in the fallows of the bush ring (56 %), in the rice fields (16 %) and in the cropped plots of the bush (15 %) and compound (14 %) rings. Highest P spatial densities were found in the rice (63.2 kgP ha⁻¹, 89 % in the soil) and compound (38.5 kgP ha⁻¹, 78 % in the soil) fields, and in the fallows of the plateau (32.5 kgP ha⁻¹, 22 % in the soil).

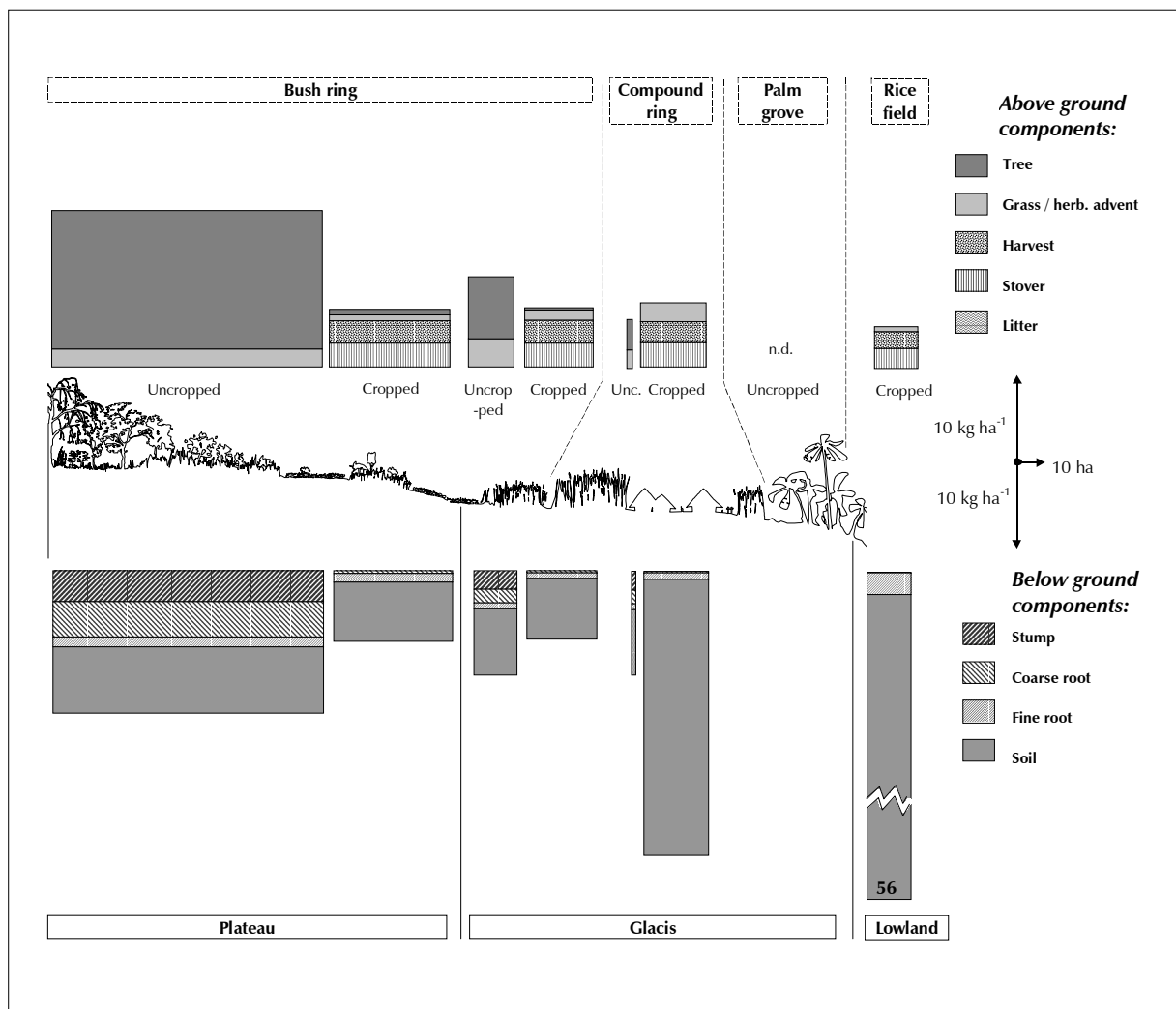


Figure 4.6c Phosphorus storage in plant biomass and soil of the territory of the village of Sare Yorobana with respect to geomorphology, ring and land use (cropped, non-cropped).

Horizontal scale: surface of the land use unit. Vertical scale: amount of the element per hectare. Thus, the amount for each component of each unit is proportional to the area of the corresponding rectangle. Fine roots: diameter ranging 0-2 mm. Coarse roots: diameter above 2 mm (stump not included). Soil: available P_{OD} only. See Appendix 36c for data.

4.3.3.3. A simplified agro-pastoral budget

The potential self-sufficiency rates of the needs for manure and forage of 17 holdings ranged widely and were related to the herd size (Figure 4.7). Six of them, each owning at least 30 TLU, could meet their need for manure during the 1997 cropping season. However, biggest livestock owners were not self-sufficient with regard to their need for forage. Finally, only five farm holdings produced enough manure and forage with regard to their needs.

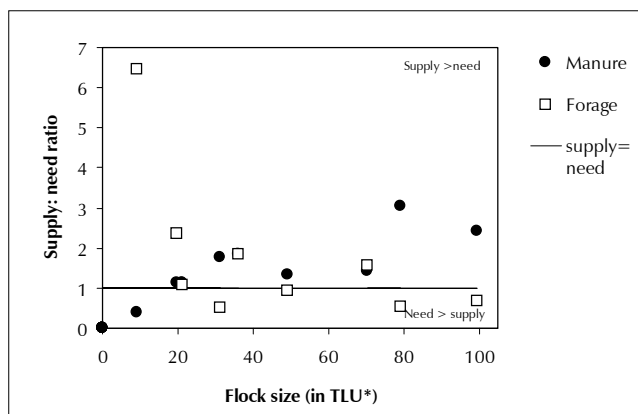


Figure 4.7 Self sufficiency in manure and forage availability in the holdings of Sare Yorobana as derived from a simplified agro-pastoral budget.

* Tropical livestock unit = 250 kg of live weight.
See Appendix 37 for data.

4.3.3.4. Impact of the relationship between cropping intensity and woody biomass on the carbon budget of the village

Diminishing by 10 % the initial threshold value (0.75) of the cropping intensity used to assess amounts of biomass of woody advents in cropped field did not modify by more than 7 % the different terms of the C budget of the cropped ring (Figure 4.8). However, increasing this value by 10 % led to a 15 % rise of the below ground biomass component, 7 % of the whole plant biomass component, and less than 1 % of the C stored in the whole cropped ecosystem. When including the non-cropped hectare, the variations did not exceed 2.5 %, whatever the hypotheses and the reservoir considered.

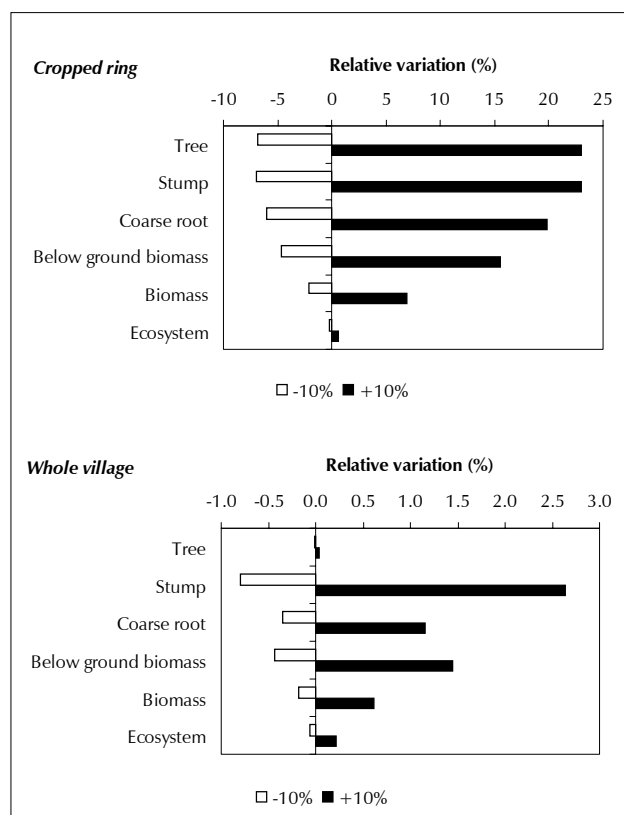


Figure 4.8 Analysis of sensitiveness of carbon storage calculation as related to the threshold value of cropping intensity driving woody advent biomass in cropped plots: impact of a variation of less or more than 10 % of this threshold value on C stock estimates.
See Appendix 38 for data.

4.3.4. Outlook on future C stocks

4.3.4.1. Land use

In the basic scenario, old fallows would disappear in 15 years' time (initial date: 1997), and no more fallow could possibly remain by 2027 (Figure 4.9). The surface of groundnut, and thus the satisfaction of cash needs, could be maintained during 48 years. A 100 % increase of the yield of cereals would allow the keeping of fallowing during 15 more years. Increasing both cereal yield and standard of living by 30 % would lead to a faster disappearance of fallows than in the basic scenario, while a 100 % increase of the cereal yield would compensate well for a 30 % increase of the farmers' incomes (Appendix 39).

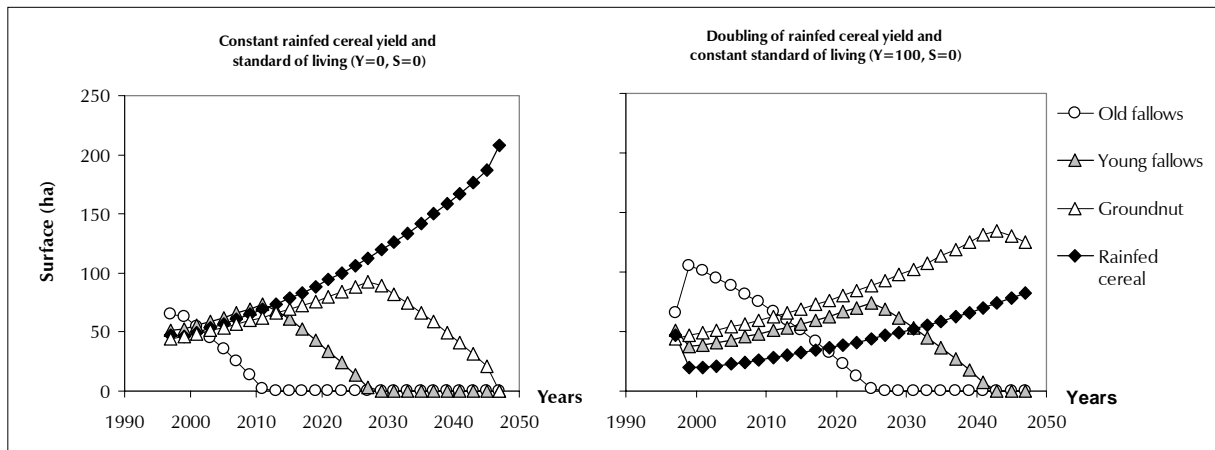


Figure 4.9 Evolution of land use in the village of Sare Yorobana for the 1997-2047 period as predicted by a static model (see description in text).

Young fallows: aged 0-9 years. Old fallows: aged 10 years or more. See Appendix 39 for data.

4.3.4.2. Carbon storage in the village territory

Carbon stocks in plant AGB and BGB as well as in the whole village territory should record sharp drops during the next few decades (Figure 4.10). In the basic scenario (no change in either crop performance or food and cash needs), amounts of carbon in AGB might decrease by 75 % in 31 years' time, leading to a loss of 0.19 tC ha⁻¹ y⁻¹. Beyond this point a slight increase should be recorded, with 0.02 tC ha⁻¹ y⁻¹ being fixed during 17 years before equilibrium is reached. Carbon in BGB may fall by 84 % in 2046. The annual loss would be 0.20 tC ha⁻¹ y⁻¹ during the coming 15 years, dropping to 0.09 tC ha⁻¹ y⁻¹ during the next 16 years. The total C losses of the system (including soil) would amount to 38 % till 2028, with a slight increase being recorded beyond this point. This would mean a decrease of 0.38 tC ha⁻¹ y⁻¹ during 31 years, with only 0.04 tC withdrawn from the soil. Increasing cereal yield or the standard of living by 30 % would

not change the level of total C stocks beyond 37 years' time, but it would change the speed at which a steady state is reached, and thus the rate of C release. For instance, in the five scenarios, annual C losses of

the plant-soil system during the 1997-2012 period would be (in tC ha⁻¹ y⁻¹):

- control: 0.50,
- yield +30 %: 0.29,
- yield +100 %: 0.03,
- yield +30 % with standard of living +30 %: 0.58,
- yield +100 %, standard of living +30 %: 0.39.

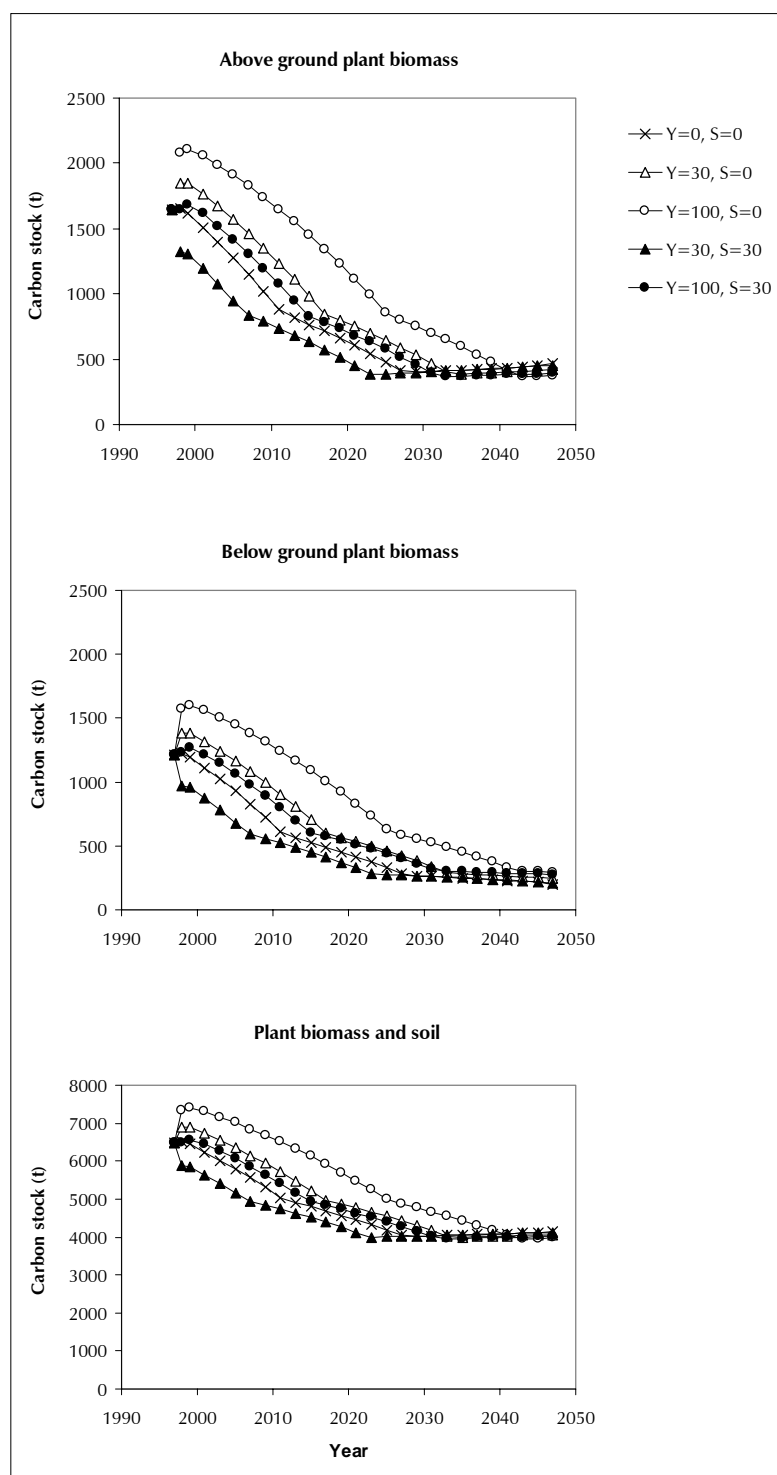


Figure 4.10 Evolution of carbon storage in the plant-soil system (soil: layer 0-20 cm considered only) of the territory of the village of Sare Yorobana for the 1997-2047 period as predicted by modelling (see description in text).

“Y” stands for relative increase (%) of cereal yield as compared to value in 1997.

“S” stands for relative increase (%) of standard of living as compared to value in 1997.

See Appendix 40 for data.

4.4. DISCUSSION

4.4.1. Social organisation & dynamics of the farming system

As a result of Peulh history as well as of different knowledge (Peulh people are pastoral people) livestock is owned mainly by the noble caste (Pélissier, 1966; Fanchette, 1999b). Two other social features, influencing the functioning of the farming systems in noble holdings, and subsequent to a higher education standard than in captive lineages, are: higher cash need, and frequent migration of young people to the town. Supplying high food and cash needs with limited agricultural power are subsequent constraints for to the reproducibility of noble lineages' farming system. These constraints are usually overcome with the help of livestock ownership, which enables: (1) high manuring potential and thus good cereal yield at a low working cost (2) good supply of animal labour power, which is crucial at certain moments of the agricultural timetable such as ploughing, sowing and weeding (3) minimum working capital allowing for better equipment and employment of seasonal work force. Captive lineages rather rely on high permanent labour power, and on the practice of fallowing (which is spatially complementary of manure; Figure 4.4). Manure deposition during day straying is a limited compensation offered by biggest livestock owners to herdless holdings. Some evidence of the agronomic value that farmers give to such an implicit deal is brought by the firm ban maintained on removing crop residue from the plot of a neighbour in order to feed one's own herd at the farmyard. The deal remains unfair on a nutrient point of view, because big cattle owners maintain the wealth of their livestock -that is, their capital and means of production- at low cost, thanks to the existence of a resource created by the work of those who own only a few animals, if any (Figure 4.7). This has also been reported by Dugué (1985) in a drier region of West Africa.

However, the balance of power between the holdings who own the forage and those who have the animals may be reversed in the future. The privatisation of land and of organic resources usually observed under growing human density invariably call into question the practice of straying and can lead to reduced cattle ownership (Lericollais and Milleville, 1993; Dugué, 1998b). Any developing program aimed at intensifying animal husbandry, through stalling for instance, should take into account its potential for modifying the traditional rules set for the common management of organic matter at the village scale.

4.4.2. Interrelations between agroecological functions of the land use systems, and their carbon, nitrogen & phosphorus status at the onset of the dry season

Each of the four main land use systems identified in the village of Sare Yorobana (bush and compound rings, palm grove, and rice fields) plays one or more specific roles in the farming system defined by the village. These roles are revealed by spatial organisation of land use and C, N and P vertical and horizontal distributions.

4.4.2.1. The bush ring

Because it is the farthest ring from the dwellings and because it has the less secured land tenure, the bush ring receives little attention for the management of its fertility, as testified by scarce manuring (see Chapter 5). The fertility of the plots relies almost on fallowing, which replenishes the soil with energy and nutrients, thus enhancing biological activity, and controls weed and pest hazards. Improvement of soil quality can happen quickly after crop abandonment, provided that long breaks of fallows are maintained, in order to save the resprouting ability of the woody vegetation. However, fallows are not necessarily linked to soil fertility problems. Those plots that do not result from the moving of dwellings down-slope some 20 years ago, may also act as reserves of land, until more labour and seeds are available in the holding. The bush ring harbours only a third of the staple crops, but nearly all of the cash crops (groundnut, cotton) (Table 4.2). Cash crops are managed privately by each household and not in common by the holding. The bush ring is the largest carbon reservoir of the village, not only because it is the widest LUS, but also because of great amounts of above-ground and below-ground woody biomass (Figure 4.6a). This biomass represents the main source of fuel wood for the village. Good forage resources can be found in young fallow only. However, tree green fodder of oldest fallows is of high qualitative value at the end of the dry season, when grass biomass contains nearly no more nitrogen (Richard *et al.*, 1991). The feed value of crop residues (quantity, quality) relies on the kind of plant considered (as roughly indicated by the amounts of nitrogen in crop biomass; see Table 4.5). The cereals provide high volumes of low quality, while groundnut haulms, though reaching low yields as compared to millet, are rich in nitrogen (Figure 4.6b). They are thus harvested and used as a feed complement for ovines and calves and oxen during the dry season. The adoption of cotton, introduced in 1997 in Sare Yorobana at the expense of groundnut, might conflict with the animal breeding activity, since cotton residues are of low nutrient value, and even toxic due to the application of chemical compounds for crop protection.

4.4.2.2. The compound ring

Positive gradients of investment in fertility and in labour, and of land tenure security, are set from the bush to the compound ring, as have been observed by Prudencio (1993) in Burkina Faso and Peters and Schulte (1994) in Gambia. The main function of the compound ring is to ensure food safety to peasants. The steady grain food production is enabled by intensified management of fertility, mainly through organic practices such as manuring during night tethering and day straying, household waste spreading, but also through the recycling of cooking stove ashes. A careful choice is made at sowing between three cereals (maize, millet and sorghum) to overcome the tide-over period at the end of the dry season “*when food reserves are at low ebb and energy demand is highest*” (Prudencio, 1993). Maize has the shortest growing cycle, and highest nutrient requirements. It is thus sown closest to the dwelling, where soil chemical properties are at their best, and care of plants is easiest (Figure 4.3). Choosing pure cropping or intercropping with millet depends on previous manure application. At the beginning of the dry season, amounts of C and N in the soil are slightly higher in the compound ring as compared to the bush ring. This is probably a consequence of previous massive decomposition of organic inputs during the wet season. However, below-ground storage of P of the compound ring is much more important than in any other LUS, except rice fields (Figure 4.6c). This results from the settlement of organic matter flows from the peripheral areas to the compound ring in the form of cattle dung, crop and wood harvest (see Chapter 5). Like in the bush ring, crop residues and weeds represent major pools of N and P, as compared to their biomass. Their high nutrient content explains to a certain extent why they are the forage most browsed by livestock, and why they are grazed prior to any other LUS at the beginning of the dry season.

4.4.2.3. The palm grove

Though spatially restricted, the palm grove harbours an important amount of construction wood and forage. However, due to the poor chemical status of the soil, this forage is of low quality, and it is available only during the dry season. The palm trees provide oil, and their use for wood need is thus restricted. This LUS is not likely to be converted to cropping later, due to soil constraints (chemical fertility and sensitivity to erosion), but orchards may slowly replace the ageing palm grove.

4.4.2.4. The rice fields

With the palm grove, this LUS disrupts the traditional concentric pattern of land use recorded in most of the farming systems of the West African savannas. The rice fields represent the other staple safe of the village. Every year they provide a steady food production at relatively low costs in labour and fertility management, thanks to high inherent soil fertility and free supply of water and nutrients during seasonal flooding. However, the paddy production for home-consumption is available only in December because of the long growing cycle of local rice varieties. Low N and P, and high silica content make rice stover a low-quality forage; but small grass regrowth occurring during the few weeks after the offset of the rains,

thanks to close watertable, explain why rice fields are much frequented by livestock during the dry season (see Chapter 5).

4.4.3. The limited current carbon storage capacity of the village farming system

Comparing the amounts of C found in this work with other anthropized savanna sites is difficult, because of the paucity of studies held at similar, intermediate scales, and because of the wide range of values of depth down to which C values were computed. For instance, Woomer *et al.* (1998) report carbon amounts to average 70 t ha⁻¹ in farming systems of the East African Highlands, which is 2.4 our finding. The ratio is only 1.6 when comparing mean AGB (8 tC ha⁻¹ in our study). However, the relevance of the comparison is limited by the lack of data about sampling depth, land use, vegetation composition and soil properties given by Woomer and his colleagues. The quantity of carbon stored in the plant biomass of non-cropped plots of the village territory (21.7 tC ha⁻¹) compares poorly with the values reported by Tiessen *et al.* (1998) in savannas and dry forests of the world (50 t C ha⁻¹). However, Woomer (1993) reports figures similar to ours for the plant biomass of Miombo dry woodlands (27 tC ha⁻¹) and broadleaved dry savanna (22.4 tC ha⁻¹) of southern Africa, and our findings amount to 62 % of the mean estimate given by Adams (1997) for preanthropogenic savanna ecosystems. Our figures for C stored in plant biomass were unsurprisingly higher than those reported by Tiessen *et al.* (1998) in drier, more degraded savannas of Central Senegal (2.8-5.6 tC ha⁻¹ in non-cropped ecosystems, 0.7-5.1 tC ha⁻¹ in cropped fields, assuming carbon content of the plant biomass to be 40 %).

Values found for low carbon sequestration capacity of sandy soils of Sare Yorobana remain low, as compared to those reported under other dry –not mentioning wet- tropical climates of the world and the . This suggests limited perspectives to improve quantitatively the carbon status of the Sudanian agro-ecosystems. Fastest and highest carbon storage may occur in woody biomass. The carbon stocks still remaining in savannas are the main reservoirs of easily available energy, nutrients, construction material and other economic goods. Fixing people in savannas through a better management of these reservoirs should be a promising strategy in order to refrain migrations towards more fragile carbon deposits such as wet forests (Brown and Lugo, 1990).

The common social organisation of labour and land use, the current national tenure politics and the need for land in West Africa might impede the efficiency of management programs aimed at replenishing the carbon resource, as compared to what could be expected in East Africa (Woomer *et al.*, 1998). The evolution of land tenure toward more secured land title should help replenish plant biomass and thus carbon and nutrient stocks of the farming systems of High Casamance as well as of sub-Saharan Africa, for the following reasons (Izac, 1997a): (1) it should refrain people from clearing fallows and extensifying their crops, just for the purpose of extending their right of use over more land, as the national land tenure

laws often enable them like in West Africa (2) it should stimulate the perennial investments favouring carbon sequestration by ensuring the farmers they will benefit later from the products (wood, forage, fruits) and services (soil fertility, shade) provided by improved planted fallow, live hedges, orchards, dispersed trees in fields, or investments for soil conservation.

4.4.4. Future evolution of the carbon stocks

Carbon storage would exhibit three stages of evolution linked to the dynamics of land use according to simulations (Figure 4.9 and Figure 4.10). Fast initial decrease of C amounts (9-25 years) would result from the conversion of old fallow stands to young ones and subsequent drop of C stored in tree and fine root biomass. Meanwhile soil would contribute little to the variation, and, only for plots of young fallow replaced by cash crop (Chapter 2). The slope of the curve of total C should then increase; it would remain negative, since young fallows would disappear for the benefit of cash and staple crops, implying clearing of natural secondary vegetation, stump and root decay, and soil organic carbon mineralization. The third step of evolution corresponds to the replacement of cash crops by food crops. The light increase of C amounts should result from higher plant biomass storage in standing crop of cereal than in that of groundnut, and from the better soil status of manured cereal fields, since manure availability per unit of cropped surface increases.

Significant lessening of C depletion could result from improvement of cereal yield within realistic limits, according to our results. However, such an improvement relies mostly on subsidising fertilizer prices and on rural investment policies, that is, on decisions implemented at scales on which peasants have no control. The standard of living of people results more on local choices, and could greatly influence the C budget of the farming system. Of course, given the current socio-economic and demographic context in the WAS and the omnipotence of C as a resource for local populations, C depletion in the region should be firstly considered as an indicator of loss of health and viability of agricultural systems (Woomer *et al.*, 1998).

However, on a global change perspective, land use change in the WAS should not account for much of global anthropogenic atmospheric C release (Houghton, 1995). Early values of net C release simulated here (0.03 to 0.58 tC ha⁻¹ ya⁻¹) during the first ten years are rather higher than those estimated by Woomer (1993) for a range of similar cropping systems for dry tropical southern Africa (0.07-0.17 tC ha⁻¹ ya⁻¹). Yet, they are much lower than rates of C release estimated under wet tropical conditions such as those of southern Cameroon (1.2 tC ha⁻¹ y⁻¹ between 1973 and 1988 according to Kotto-Same *et al.*, 1997), the discrepancy stemming mainly from differences of C amounts in initial plant biomass. Accuracy of these comparison obviously relies as much on patterns of C sequestration at the plot scale as on the respective cropped and uncropped shares of territory in the areas considered.

More refinement of the model would be needed for more accurate interpretation of the simulation results, which lack realism particularly during the transient phase following initial modification of cereal yield.

Taking into account spatial and functional complexity needs a shift to a more flexible tool such as object-oriented modelling (see Chapter 5 for further discussion).

4.4.5. Methodological considerations on assessment of carbon and nutrient budgets at the village scale

Carbon and nutrient budgets still lack at the village scale in Africa (Prudencio, 1993; Stoorvogel *et al.*, 1993a). One of the main constraints to any assessment of this kind is methodological. Traditional agriculture in West Africa still relies on the diversification of planted species and farming practices, and the conservation of agro-ecological niches (Olasantan, 1999). The heterogeneity of soil (inherent and biologically induced), vegetation physiognomy, and crop yields imply cautious, intensive sampling schemes, and the use of regression relationships linking variables easily measurable on field to the amount of an element in plant and soil components. Establishing regression relationships is labour- and credit-consuming. Hence the following discussion about the relevance of applying our findings to other subregions of sub-Saharan Africa.

4.4.5.1. Assessment of carbon, nitrogen and phosphorus storage in cropped fields

Several factors influence production of crop and weed, that may restrict the application of regression relationships established in crops to other places in other years (Powell, 1984). Among these are: cultivar origin, soil properties, climate, and pest or weed occurrence. However, no significant influence of pest or special weed such as *Striga hermonthica* was noticed in all subplots. Climatic data indicated normal rainfall during the years of measurements (Figure 4.1). Ferruginous sandy soils on which all crops except rice were grown are common in the subregion, and make the use of the relations possible over wide areas. Intraspecific variability may more seriously limit extrapolation of our findings. However, varieties (or mixes of varieties in the case of traditional food crops) sown in areas with close soil and climate conditions, are expected to remain phenotypically similar to each other, because traditional, low-input cropping patterns remain quite stable in the subregion. Under comparable soil and climate conditions, Egharevba (undated) reports values of biomass partitioning of pearl millet very close to our findings. Powell (1984), in a north-Nigerian savanna with soils similar to ours, established regression relationships between components for maize, millet, sorghum and groundnut. The ratio of the slope values obtained from the regression of stover on panicle/pod yield in our study and in Powell's was: maize: 1.0; millet: 1.1; sorghum: 1.6; groundnut: 1.3. In the case of groundnut, Larbi *et al.*(1999) have reported a high variability of cultivars in the way they partition biomass between their plant components. But we can not give any definite interpretation for the discrepancy observed on sorghum. However, estimates presented here should be tested in other study sites before applying them to the assessment of organic budgets for other sites.

The estimate of woody advent biomass in crops is difficult. Quantifying the dynamics of resprouting bushes during the cropping phase is a difficult task, because (1) it relies on cultural history, clearing methods and cultural practices (2) below-ground biomass is difficult to assess and exhibits weak correlation with above-ground woody biomass due to repeated clearing of vegetation during cropping (3) other studies on biomass production from stumps seriously lack (Bohringer *et al.*, 1996). Defining empirical rules linking woody biomass in crops to a variable easily measurable such as cropping intensity as we did can thus be only very intuitive and controversial. However, the test of sensitiveness indicates that modifying the threshold value of cropping intensity by more or less than 10 % only slightly influences the carbon storage of biotic components of the whole village ecosystem (Figure 4.8).

4.4.5.2. Assessment of carbon, nitrogen and phosphorus storage in fallow plots

The application of the relationships linking the amount of dry matter, carbon, nitrogen and phosphorus to the age of fallow as established in Chapter 1 and used here, to other secondary successions of the subregion should be validated by field measures. Although Combretaceae formations on Lixisols are widespread in West Africa, woody biomass dynamics after crop abandonment relies very much on plot history and, again, on cropping intensity. In Sare Yorobana, the dynamics of woody biomass and of the soil carbon, nitrogen and phosphorus status is strongly driven by the maintenance of woody stump and their resprouting capacity. Under higher population density, the reduction of the fallow period should lead to stump exhaustion, and thus to lower vegetation regrowth.

4.4.5.3. Definition of spatial boundaries for the assessment of carbon, nitrogen and phosphorus stocks of the village

Vertical limits were set to a 40-cm depth for roots and to a 20-cm depth for soil in our study. Literature and clay accumulation in the subsurface indicate that rooting activity is limited below the layer, while previous studies held on site shows that most soil chemical properties are independent from land management below 20 cm. These limits might well apply to Lixisols in general, but may not fit to other soil orders. Woomer *et al.*(1998) for instance report that deep rooting activity is found in soils of East Africa, and that land management influences soil carbon storage down to 1.20 m deep.

Less clear here is the way horizontal limits should be defined for the assessment of the carbon and nutrient budgets of such a village agroecosystem as Sare Yorobana. As shown in Chapter 5, the viability of the animal breeding system relies heavily on the use of organic resources not owned by the village, but which are grazed during the wet (full time) and dry (part-time) seasons.