BILANS SPATIALISES DE CARBONE, D'AZOTE ET DE PHOSPHORE D'UN TERROIR DE SAVANE OUEST-AFRICAINE– I. STOCKS D'ELEMENTS ET STRUCTURE D'UN SYSTEME AGROPASTORAL*

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Résumé étendu

La viabilité des systèmes agropastoraux de savane ouest-africaine dépend largement de la gestion des ressources organiques endogènes car celles-ci satisfont les besoins locaux en nourriture, en fourrage et en bois, et maintiennent la qualité du sol. C'est pourquoi les stocks de carbone, d'azote et de phosphore du sol (horizon 0-20 cm ; mesure de P assimilable uniquement) et de la biomasse végétale (aérienne et souterraine jusqu'à 40 cm de profondeur) ont été évalués dans les différents systèmes de gestion de l'espace (SGE) et types de concessions pour un terroir du Sud Sénégal à la fin de la saison des pluies.

Le système agricole se caractérisait par une densité de population égale à 33 hab. km^{-2} et une charge animale de 51 unités de bétail tropical (UBT ; 1 UBT = 250kg de poids vif) par kilomètre carré. Les jachères, les cultures vivrières (céréales pluviales et riz) et de rente (arachide, coton) ont représenté 46, 25 et 17 % des 258 ha gérés par le village. Des contrastes importants ont été trouvés entre exploitations, en particulier en terme de disponibilité du bétail. La vaine pâture et le parcage de nuit pourraient de ce fait conduire à des transferts de fertilité déséquilibrés entre les champs des petits éleveurs et ceux des gros éleveurs.

Le village avait une organisation en auréoles concentriques avec un gradient positif d'intensification et de production alimentaire depuis la savane vers le village. Des relations claires sont apparues entre distribution spatiale de C, N et P et les fonctions agro-pastorales des SGE et des exploitations, tandis que la diversité à toutes les échelles apparaissait comme un pilier du fonctionnement du système. L'auréole de case était principalement consacrée à la production alimentaire ; elle couvrait 8 % de la surface et représentait 5, 7 et 14 % des stocks de C, N et P de l'ensemble du terroir villageois. L'auréole de brousse entourant l'auréole de case s'étendait sur 73 % du terroir et hébergeait 66 à 71 % des stocks de C, N et P du village. Le bas-fond (rizière) couvrait 6 % de la surface et stockait 9 % du carbone et 16 % de l'azote et du phosphore.

Les stocks de C, N et P dans la végétation et le sol étaient de 29,7, 1,52 et 28,6 10^{-3} t ha^{-1}. Les principaux lieux de stockage du carbone étaient le sol (52 %), la biomasse aérienne ligneuse (22 %), les souches (8 %) et les racines épaisses (Ø>2mm) (8 %).

Dans les conditions de la croissance démographique actuelle (2,5 %), les pertes simulées de carbone dues à l'expansion de l'espace cultivé, devraient conduire à une émission de 0,26 tC ha^{-1} an^{-1} pendant les 15 prochaines années, ce qui est beaucoup plus faible que les valeurs rapportées dans les zones tropicales plus humides, mais indique une crise agroécologique possible dans les prochaines décennies.

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* Cette communication a été précédemment publiée dans une version modifiée et étendue en tant que chapitre d'une thèse soutenue en 2000 (Manlay, 2000). Cette thèse est téléchargeable en français et en anglais à l'adresse suivante : http://www.engref.fr/thesemanlay.htm. Une version modifiée de cette communication est également sous presse dans *Agricultural Systems*.

SPATIAL CARBON, NITROGEN AND PHOSPHORUS BUDGET OF A VILLAGE TERRITORY IN THE WEST AFRICAN SAVANNA – I. ELEMENT POOLS AND STRUCTURE OF A MIXED-FARMING SYSTEM*

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Abstract

The viability of mixed farming systems in West African savannas relies largely on the management of endogenous organic resources. Assessment of the organic balance at both plot and village territory scales is needed as an indicator of this viability. Distribution of carbon (C), nitrogen and phosphorus in soil and plant biomass was thus quantified for a village in southern Senegal across the different land use systems (LUS) and farm holdings. The village exhibited a ring-like organisation, including a compound ring, a bush ring, and lowland paddy fields, with positive gradients of intensification and food production from the savanna to the dwellings. Marked contrasts were found between holdings, especially in livestock availability. Clear relationships were evidenced between the spatial distribution of C and nutrients and the agricultural functions of LUS and holdings, while multi-scale diversity appeared to be the main factor that ensured the functioning of the system. Intensification schemes at the village level aimed at increasing organic resources and their cycling efficiency must thus take into account their impact on this diversity.

Keywords

Carbon; Mixed-farming system; Nitrogen; Phosphorus; Plant biomass; Savanna; Soil

Résumé

La viabilité des systèmes agropastoraux de savane ouest-africaine dépend largement de la gestion des ressources organiques endogènes. L'établissement du bilan organique à l'échelle de la parcelle et du terroir est donc nécessaire comme indicateur de cette viabilité. La distribution du carbone, de l'azote et du phosphore dans le système sol-plante a donc été quantifiée dans un terroir du Sud Sénégal à la fin de la saison des pluies. Le village avait une organisation concentriques comprenant une auréole da case, de brousse et une rizière de bas-fond, avec un gradient positif d'intensification et de production alimentaire depuis la savane vers le village. Des relations claires sont apparues entre distribution spatiale du carbone, de l'azote et du phosphore et les fonctions agro-pastorales des systèmes de gestion de l'espace et des exploitations, tandis que la diversité est apparue à plusieurs échelles comme le pilier du fonctionnement du système. Les stratégies d'intensification à l'échelle du terroir visant à augmenter les ressources organiques et l'efficacité de leur recyclage doivent donc également être évaluées selon leur impact sur cette diversité.

Mots-clés

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

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* This communication was previously published in a modified and extended version as part of a PhD thesis defended in 2000 (Manlay, 2000) which is downloadable in English and in French at: http://www.engref.fr/thesemanlay.htm. A modified version of the paper is also in press in*Agricultural Systems.*

1. Introduction

Most traditional farming systems in the West African savanna (WAS) share two main features (Ruthenberg, 1971): (1) low requirements in exogenous inputs, often only enabling extensive agriculture, (2) high social cohesion, leading to communal land tenure and management and allowing for spatially restricted intensification.

To overcome energy, fertiliser and labour shortages, peasants have generally organised their village territory in a ring-like scheme. From the compounds to peripheral areas there is a decreasing gradient in agricultural intensification and land tenure control, which usually allows the distinction of three main rings (Pélissier, 1966; Ruthenberg, 1971; Prudencio, 1993): (1) a compound ring, devoted to continuous cultivation, thanks to manuring and spreading of household wastes, (2) a bush ring under less stable, semi-permanent cropping patterns of both cash and staple crops, (3) a forest or savanna ring, uncropped for several decades and under common land tenure.

On the wettest fringe of the WAS belt, farmers have used endogenous organic matter (OM) as a multi-purpose tool for decades and it can thus be considered 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. In the sandy, ferruginous soils that prevail in the WAS, soil organic matter controls many specific chemical, physical and biological properties (Jones and Wild, 1975; de Ridder and van Keulen, 1990; Feller and Beare, 1997).

However, such practices have only proved operational where the population density is low (van der Pol, 1992). Rapid population growth in the WAS and unsecured national land tenure policies have resulted in an increasing need for land, wood and forage, which calls into question organic fertility management practices such as fallowing and manuring and instead favours mining agriculture (Ker, 1995).

Assessing organic resources at the field scale is the first step towards defining new viable agricultural systems. However, more information - especially concerning the sustainability of the farming system – can be obtained by studying carbon (C), nitrogen (N) and phosphorus (P) dynamics at the village territory scale rather than at the plot scale (Landais and Lhoste, 1993; Izac and Swift, 1994; Krogh, 1997). The reasons for this are: (1) the functional connection between the land use systems (LUS) (bush and compound rings), (2) communal control of fertility management practices and of land tenure, at least at the level of the holding, (3) the need for accurate carbon and nutrient budgets representative of each LUS, as inferred from plot budgets, and weighted by area, soil properties, and cropping history.

Where better access to chemical inputs is impossible, quantifying carbon and nutrients budgets at the village territory scale is the first step towards assessing the sustainability of agricultural systems in the WAS. First, the distribution of carbon and nutrients in each spatio-functional unit must be analysed and this is the concern here. Second, amounts of organo-mineral resources must be compared with their use (Manlay *et al.*, this volume). These two preliminary studies are also relevant in the context of global change, for they help estimate the capacity of savanna farming systems to mitigate anthropogenic gaseous carbon emissions.

The aims of the present work were to (1) analyse the social, functional and spatial organisation of a mixed-farming village territory in southern Senegal to determine the influence it has on OM production and C, N and P storage (2) assess the global C, N and P budgets of this system related to land use and fertility management (3) predict changes in the carbon balance in the coming years.

2. Methods

2.1. Site characteristics

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

A description of the site with its tropical sub-humid climate (960 mm of mean annual rainfall during the 1978-1997 period, occurring from May to October), smooth topography, soil distribution, and Sudanian-like native vegetation can be found in Figure 1 and Manlay (2000).

2.2. Characterisation of the farming system

2.2.1. Spatial organisation

Although extensive cattle husbandry frequently spreads well beyond the village boundaries, only the territory owned by the community (in accordance with customary law) was considered in this study. Mapping was initiated in 1996 and updated in 1997. Fields (whether cropped or not) were identified as land tenure units, while plots referred to land management (one field comprising at least one plot, usually several, with in-between plot boundaries moving from one year to another). Fallows less than 18 years old were mapped; fixing boundaries for older stands was almost impossible. Rice (*Oryza sativa* L.) fields were mapped as a whole due to the highly complex land tenure.

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

Plot history and management were characterised through on-field enquiries with farmers. Cropping history, ownership, and usership were investigated, as well as local typology applying to rainfed fields. Roughly speaking, this typology distinguished (1) fields under continuous cultivation of cereals (the compound fields), 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), 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 varied between farmers, enquiries about cropping history indicated that compound fields could be defined as those that had been continuously cropped with cereals for the last 10 years.

2.2.2. Social organisation

In local Casamance communities - as is mostly the case in the WAS - social cohesion and decision making occur at the farm holding level, not at the household one (Pélissier, 1966; Achterstraat, 1983). A holding is defined here as a community of neighbouring people who share the same staple crop fields, granary, and, most often, herd. Production means investigated were: (1) human population size, (2) livestock availability expressed in tropical livestock units (1 TLU = 250 kg of live weight or LW), (3) owned surface.

2.3. Carbon, nitrogen and phosphorus storage for the village territory

2.3.1. On-field measurement of harvested plant biomass

Harvested biomass (cereal panicles, groundnut pods, cotton bolls) was weighed on site at harvest time, plot by plot when possible. Results for each plot were expressed as dry matter (DM) harvest yield (after measure of water content of each component).

2.3.2. Dry matter, carbon, nitrogen and phosphorus storage in other components of plant biomass

Regression relationships were used to estimate total plant biomass storage for each plot. The yield of the harvested component in cropped plots and the age of crop abandonment in fallow fields were used as predictors for the estimation of plant biomass for (1) stover, herbaceous advents, crop roots (down to 40 cm) in cropped plots (2) tree and grass layers, litter, stump, fine and coarse roots (down to 40 cm) in fallow stands. Linear regressions were established for crops, using data from Manlay *et al.* (2002c) and from four added field plots (millet intercropped with maize and sorghum). 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 (Manlay *et al.*, 2002a). When regression parameters had no statistical significance, mean values reported in both previously cited works were used. The yield of some plant biomass components of cropped fields could not be related to that of the harvested component and were estimated as explained in Manlay (2000). Because of the lack of data for the palm grove and some of the sorghum and cotton biomass components, data was also used from the literature (Manlay, 2000). Carbon, N and P contents from Manlay et al (2002-a,c) were then applied to convert DM into C, N and P values.

2.3.3. Carbon, nitrogen and available phosphorus storage in soils

Soil C, N and available P (Olsen method modified by Dabin 1967, noted P_{OD}) contents were computed from measurements from 25 plots across the village territory (crop and fallow) from Manlay *et al.* (2002-b,c). Figures for soil pools were computed down to 20 cm only, since C, N and P values were only slightly influenced by land use below this depth (except for P in the compound ring). Criteria used for computing element amounts in soil are given in Manlay (2000).

2.3.4. Establishment of a simplified agropastoral budget

The self-sufficiency of each holding with respect to forage and manure was computed for the 1996-1997 dry season. Hypotheses used about livestock intake, mean faecal production during night corralling, and minimum annual manure requirements for a cereal crop can be found in Manlay (2000). 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 herbaceous biomass in fallow plots belonging to the holding.

2.4. Prediction of changes in the carbon status of the village

To predict changes in the organic status of the village territory over the 1997-2012 period, 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 farmers' needs. Initialisation was made for year 1997 as a simplified representation of the territory from data presented here and in Manlay *et al.* (this volume). Main initial simplifications consisted in pooling millet, sorghum and maize in a single land use denoted "rainfed cereal" and considering groundnuts as the only cash crop. Other working hypothesis are detailed in Manlay (2000). Output variables were land-use distribution (among cereal fields, groundnut fields, old fallows - more than 10 years old - and young fallows) and C storage in the plant-soil system (above-ground biomass, below-ground biomass and plant biomass+soil).

3. Results

3.1. Spatial organisation of the farming system

Sare Yorobana extends over 256 ha, of which 46 % were fallow, 25 % under staple crops and 17 % under cash crops. Land use and management were clearly related to distance to the village and to geomorphology (Figure 1).

Four LUS owned by the village people (thus not including the forest and savanna ring) could be distinguished: (1) the bush ring, mainly settled on the plateau and covering nearly 75 % of the surface owned by the village (SOV); it was the farthest ring from the dwellings. Only slightly more than 40 % was cropped, the rest being under short or long fallow. Cash crops (mainly groundnut and cotton) represented 60 % of total crops, (2) the compound ring was limited to the glacis and represented less than 10 % of the total surface area of the village, but a third of the whole hectarage under cereals; the choice for the cereal sown was based on the proximity of the dwelling, the closest plots being planted with maize either in pure stands or mixed with millet, (3) the palm grove was down-slope from the glacis; it covered 12 % of the SOV, (4) paddy fields represented only 6 % of the SOV, but accounted for a fourth of the surface cropped with cereals; water management was restricted to light embankments, since only women usually grow rice.

When considering the total surface area explored by cattle during the dry season to meet their forage needs (812 ha; Manlay et al, this volume) densities averaged 33 inhab. km^{-2} and 51 TLU km^{-2}.

3.2. Dry matter, carbon, nitrogen and phosphorus storage at the village scale

3.2.1. Manageable amounts of carbon, nitrogen, and phosphorus at the village scale

Carbon stored in plant biomass and in the 0-20 cm soil layer averaged 29.7 t ha^{-1} (41.1 t ha^{-1} when including carbon from the 20-40 cm soil layer) (Table 1). Sixty per cent of plant C was stored above ground. Vertical allocation was as follows (in %): soil (0-20 cm): 52; woody AGB: 22; stump: 8; coarse root: 8, the rest consisting of fine roots, herbaceous AGB (crop and weeds) and litter. AGB of cereal crops (not including pure maize and rice) reached 1.89 t C ha^{-1}, with a low harvest index (millet: 0.13). Spatial distribution was mainly in the uncropped area of the bush ring (60 %) (Figure 2). Highest carbon densities were found in rice fields (44 t ha^{-1}, 94 % in the soil) and in fallow stands on the plateau (39 t ha^{-1}, 40 % in the soil).

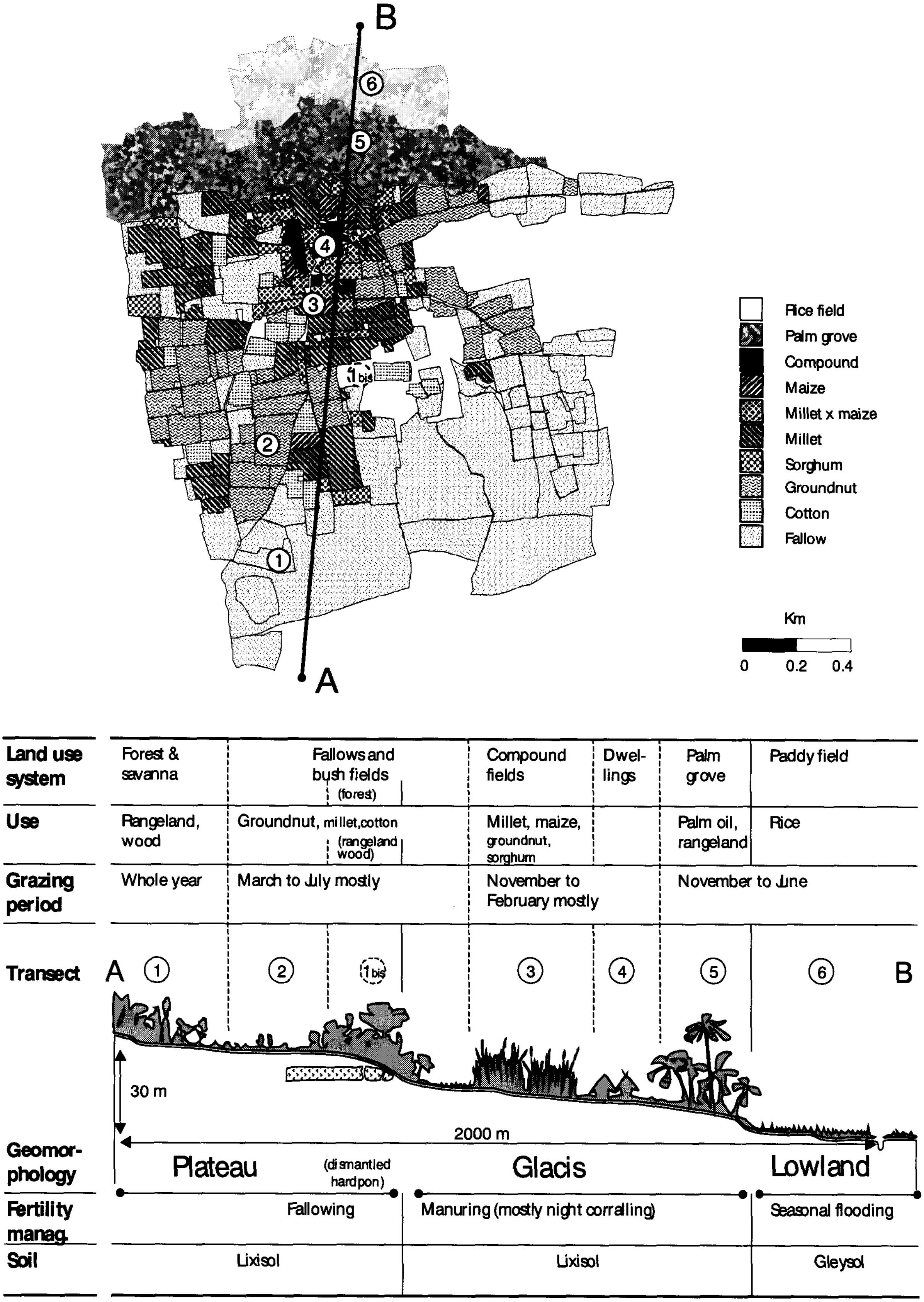

Figure 1 Spatial organisation and land use in the village of Sare Yorobana.

Table 1 Mean C, N and P amounts in some agro-ecosystems in Sare Yorobana with respect to ring management and land use.

Component	Bush ring						Compound ring				Palm grove	Rice field	Village
	fallow	ground-nut	cotton	sorghum	millet	ring	millet	millet x maize	maize	ring			
Carbon (t ha^{-1})													
Tree	10.6	0.0	0.1	0.1	0.0	6.6				0.0	13.8		6.5
Grass/weed	1.3	0.2		0.4	0.2	0.9	0.2	0.8	0.3	0.4	1.1	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	0.2
Stover	-	0.6	0.7	1.3	1.5	0.4	1.5	1.3	0.6	1.3	-	0.7	0.4
Litter	0.7					0.4				0.0	0.7		0.4
Stump	4.3	1.0	1.9	1.4	0.5	3.1				0.0			2.2
Coarse root	4.1	0.4	0.9	0.7	0.3	2.7	0.1	0.1	0.0	0.1	2.4	0.0	2.3
Fine root	0.8	0.2	0.4	0.3	0.2	0.6	0.2	0.2	0.1	0.2	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	15.9	9.9	41.2	15.4
Total	37.2	15.1	16.6	16.2	14.9	29.0	17.7	19.5	19.6	18.2	34.5	43.7	29.7
Nitrogen (kg ha^{-1})													
Tree	118	5	10	7	2	76				0	249		86
Grass/weed	23	5		16	9	17	9	30	18	15	20	2	16
Harvest	-	37	21	8	13	10	14	12	14	14	-	8	9
Stover	-	31	26	9	11	8	11	9	15	12	-	9	8
Litter	11					7				0	11		6
Stump	46	9	18	12	4	32				0			23
Coarse root	43	4	8	8	5	29	3	3	0	2	42	1	27
Fine root	20	10	10	10	6	16	6	5	4	6	118	32	29
Soil	1282	989	989	989	989	1173	1263	1451	1611	1341	860	3796	1314
Total	1543	1090	1081	1061	1039	1367	1305	1510	1663	1391	1300	3849	1517
Phosphorus (kg ha^{-1})													
Tree	13.8	0.5	1.0	0.7	0.2	8.8				0.0	nd		7.3
Grass/weed	2.1	0.3		2.3	1.2	1.6	1.3	4.2	4.5	2.3	nd	0.5	1.6
Harvest	-	2.2	3.9	1.6	2.6	0.9	2.6	2.4	2.4	2.5	-	1.8	1.1
Stover	-	1.5	6.9	2.3	2.8	1.0	2.8	2.3	3.6	2.9	-	2.2	1.2
Litter	0.0					0.0				0.0	nd		0.0
Stump	3.2	0.0	0.0	0.0	0.0	2.0				0.0	nd		1.7
Coarse root	3.5	0.2	0.5	0.5	0.3	2.3	0.2	0.2	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	0.7	nd	2.3	1.0
Soil (avail. P)	7.2	6.4	6.4	6.4	6.4	6.9	24.3	37.9	49.5	30.0	nd	56.3	12.7
Total	30.9	11.6	22.9	14.6	13.9	24.5	31.6	47.4	60.3	38.5	nd	63.2	28.6
Surface (ha)	117	35	7	4	23	187	11	6	2	19	32	16	256

Plant biomass and soil down to 40-cm and 20-cm depths respectively. Fine roots: diameter ranging from 0-2 mm. Coarse roots: diameter over 2 mm (stump not included). Sources: see details in Manlay (2000).

The mean amount of nitrogen was 1.52 t ha^{-1}, mainly stored in the soil (87 %) (Table 1). The second contributor was tree AGB, which contained only 6 % of the total stock. Fallows in the bush ring accounted for 46 % of nitrogen stored in the village, the other main spatial pool being cropped fields in the bush ring. Highest N spatial densities were found in rice fields (3.8 t ha^{-1}) and in fallow fields in both bush and compound rings (range: 1.5-1.6 t ha^{-1}).

Phosphorus (P_{total} in plant biomass plus P_{OD} in soil; palm grove not included) amounts showed somewhat different vertical and horizontal distribution patterns (Table 1). Mean stocks amounted to 28.6 kg ha^{-1} in the whole village territory. Main reservoirs were the soil (44 %) and tree AGB (26 %). Other components each accounted for less than 10 % of total amounts. Though low (4 %), the contribution of harvested biomass (panicle, ear, and pod) was four times higher when expressed in P than in C or N units. More than half of P was stored in fallows in the bush ring. Highest P spatial densities were found in rice (63.2 kg P ha^{-1}) and compound (38.5 kg P ha^{-1}) fields, and in fallows on the plateau (32.5 kg P ha^{-1}).

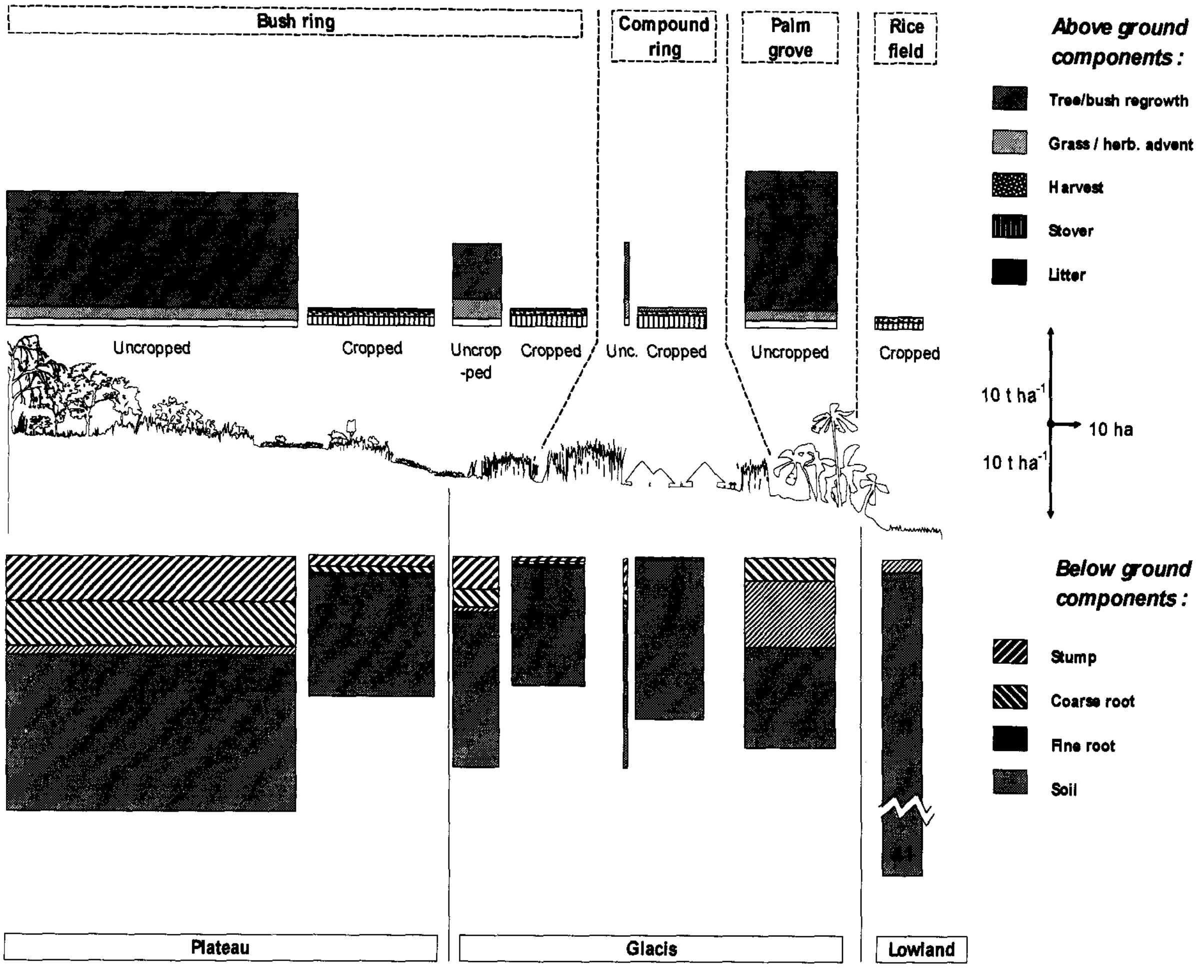

Figure 2 Carbon storage in plant biomass and soil of the territory of the village of Sare Yorobana with respect to geomorphology, ring and land use (cropped, non-cropped). Horizontal scale: surface area of the land use unit. Vertical scale: amount of the element per hectare. Thus, the amount of each component of each unit is proportional to the area of the corresponding rectangle. Fine roots: diameter ranging from 0-2 mm. Coarse roots: diameter over 2 mm (stump not included).

3.2.2. A simplified agro-pastoral budget

Self-sufficiency in manure and forage in the 17 holdings varied considerably and was related to herd size (Figure 3). Six of the holdings, each owning at least 30 TLU, were able to meet their need for manure in 1997, but the biggest livestock owners were not self-sufficient in forage. And only five holdings produced both enough manure and forage.

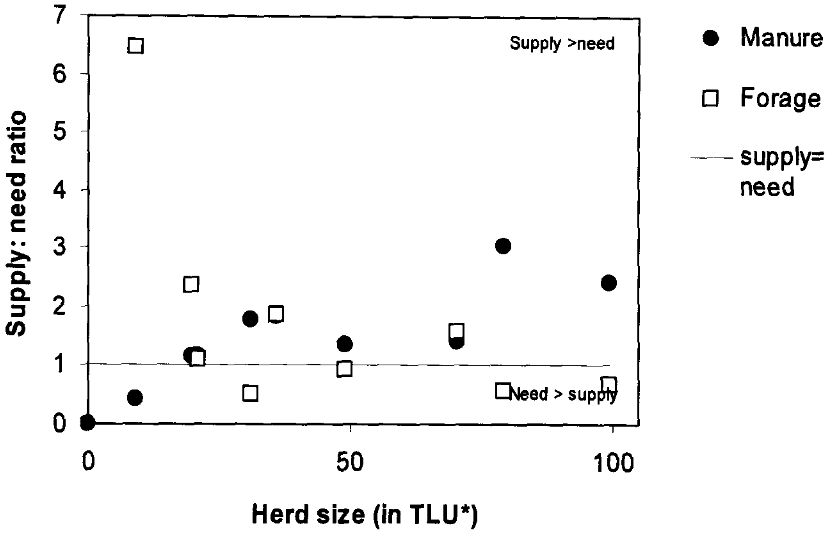

Figure 3 Self-sufficiency in manure and forage availability in holdings of Sare Yorobana as derived from simplified agro-pastoral budgets. * *Tropical livestock unit = 250 kg of live weight.*

3.3. Outlook on future carbon stocks

Carbon stocks in plant AGB and BGB, and in the whole plant-soil system, should decline sharply over the next 15 years (Figure 4). Amounts of carbon in AGB will have decreased by 50 % in 15 years' time, resulting in a loss of 0.26 t C ha^{-1} y^{-1}. The loss would amount to 0.20 t C ha^{-1} y^{-1} for BGB. Carbon loss for the whole system (including soil) would amount to 24 %, but soil contribution to C depletion of the village system would be only 0.02 t C ha^{-1} y^{-1}.

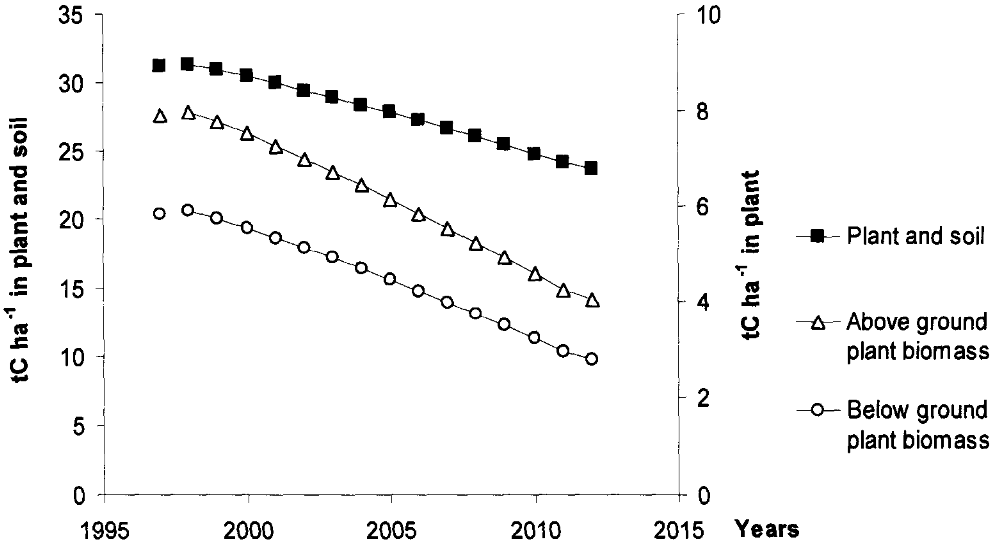

Figure 4 Predicted changes in carbon storage in the plant-soil system (only soil layer considered: 0-20 cm) in the village territory of Sare Yorobana for the 1997-2012 period. See description of model in text.

4. Discussion

4.1. Social organisation and dynamics of the farming system

Agro-pastoral budgets testify to complementary relationships between holdings owning small or large numbers of cattle (Figure 3). Livestock-mediated organic matter exchanges generated by browsing of crop residues and manure deposit during the day are subject to strict common rules, such as the strict ban on removing crop residue from a neighbour's plot in order to feed one's own herd in the farmyard. Nevertheless, organic transfers lead to misbalanced nutrient exchanges, due to the absence of night corralling agreements between holdings, *de facto* leading to nutrient concentration in compound fields of big cattle owners (Dugué, 1985), who maintain their animal wealth - i.e., capital and means of production - at low cost, with the help of a resource created by the work of others.

4.2. Land use systems: agro-ecological functions and carbon, nitrogen and phosphorus status

4.2.1. The bush ring

The bush ring is the farthest ring from the dwellings and has poorly secured land tenure; it therefore receives little attention for the management of its fertility, as testified by scant manuring (Manlay *et al.*, this volume). Highest C, N and P densities (per ha) recorded in the plant biomass illustrate the three main agro-ecological functions of the bush ring: (1) supply of livestock with forage, farmers with wood and crop harvest, (2) replenishment of soil fertility thanks to fallowing, (3) source of nutrients for the compound fields thanks to organic transfers mediated by livestock and crop and wood harvest (Manlay *et al.*, this volume).

4.2.2. The compound ring

Positive gradients of investment in fertility and labour - and in land tenure security - from the bush to the compound ring have been widely reported throughout West Africa (Prudencio, 1993; Peters and Schulte, 1994). The compound ring ensures a secure supply of food to peasants. Intensified fertility management enables steady production of food in the form of cereals, mainly through organic practices (manuring during night tethering and day straying, spreading of household waste, recycling of cooking stove ashes). As a result, amounts of available soil P are much bigger in the compound ring than in any other LUS, except rice fields (Figure 2c).

4.2.3. The palm grove

Though spatially restricted, the palm grove represents an important source of construction wood and forage. But the feed value of the herbaceous biomass is poor and is not available during the cropping season. Palm trees are grown to provide oil, and their use to meet wood needs is thus restricted. The palm grove is unlikely to be converted to cropping at a future date, due to high soil constraints (chemical fertility and the risk of erosion), but here and there orchards are gradually replacing ageing palm groves.

4.2.4. Rice fields

Rice fields represent a source of steady food production with only little investment in labour and fertility management, thanks to high inherent soil fertility and a free supply of water and nutrients during seasonal flooding. However, paddy production for home-consumption is available in December only because of the long growing cycle of local rice varieties. Rice stover is of low foraging quality, but the limited grass re-growth attracts livestock during the dry season.

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

Few carbon budgets have been assessed at the micro-regional scale for dry Africa, and sampling schemes often differ from one to another, limiting possible comparisons of soil data. Furthermore, the present study was solely concerned with soil layers whose organic status would only be affected by land management, and consequently assessment of C stored in the whole soil component was not made.

The mean amount of C in plant biomass in Sare Yorobana (14 t C ha^{-1}) was similar to that found for farming systems in the East African highlands (12.6 t C ha^{-1}, Woomer *et al.* 1998). Figures for uncropped areas of the village territory compared with those of dry woodlands and savannas in South Africa (22.4-27.0 t C ha^{-1}, Woomer 1993). Yet they remained much lower than those reported for dry savannas and forests (50 t C ha^{-1}, Tiessen *et al.* 1998), reflecting both local soil restrictions (Manlay *et al.*, 2002b) and the intensity of disturbances caused by human activities such as biomass clearing or burning.

The fast carbon depletion of the village system predicted by the model (Figure 4) results from the conversion of old fallow stands to young ones, and from young fallows to cropping and the subsequent drop in C stored in woody and in fine root components. At the same time, soil will contribute little to the variation, and will only occur in young fallow stands replaced by cash crops. Later, the rate of carbon depletion in the village territory is expected to decrease, as the quantity of biomass to be cleared from remaining ecosystems is much lower than that of mature fallows.

From the perspective of global change, modifications in land use in Sare Yorobana - like in the rest of the WAS - should not account for a high proportion of global anthropogenic atmospheric C release (Houghton, 1995). Early in the simulation period, values for net C release (0.48 t C ha^{-1} y^{-1}) for the village during the next 15 years are certainly higher than those estimated by Woomer (1993) for a range of similar cropping systems in dry tropical southern Africa (0.07-0.17 t C ha^{-1} y^{-1}). Yet they remain less than a twentieth of those estimated for wet tropical forests in southern Cameroon (Kotto-Same *et al.*, 1997), the discrepancy mainly stemming from different initial C amounts in plant biomass.

In Southern Senegal, communal social organisation of labour and land use, national tenure policies and the need for land might impede the efficiency of management programmes aimed at replenishing the carbon resource, as compared to what could be expected in East Africa (Woomer *et al.*, 1998). A better securisation of land title should help replenish plant biomass and thus carbon and nutrient stocks of the farming systems of High Casamance by (1) dissuading people from clearing fallows and extending crop production merely for the purpose of extending their right of use over more land, (2) stimulating perennial investments favouring carbon sequestration (Izac, 1997).

5. Conclusion

From a local agro-ecological point of view, there is a perceptible invariance about diversity as a lead factor influencing the functioning of the farming system at all spatial and functional scales. Plot studies stress the role of tree- and fauna-induced heterogeneity in the ability of savanna-derived natural fallows to replenish soil fertility. The present work shows that diversity is managed at the farm-holding level through the maintenance of various land use systems that play different roles related to specific carbon and nutrient distribution in plant and soil components.

The village community is itself a mosaic of contrasted types of holdings, especially with regard to livestock availability. Past experience suggests that sustainable patterns of intensification at the plot scale are those that enhance diversity or heterogeneity. This should be applied at the village and farm-holding levels by promoting corralling agreements to avoid unbalanced manuring rates. However, any development programme aimed at intensifying animal husbandry - stalling for instance - should take into account their potential ability to modify the traditional rules set for the communal management of organic matter, and thus the balance of power between holdings.

Analysis of spatial and functional diversity provides some understanding of the structure of the system. Diversity initiates matter and energy flows – including anthropogenic uptakes - whose study is indispensable in assessing the sustainability of the system.

From the perspective of global change, the most easily manageable carbon stocks still remaining in savannas are the main reservoirs of easily available energy, nutrients, construction material and other economic goods. Since the need for cropped land leaves little hope for their conservation, global environmental considerations in intensification schemes should aim at settling people in savannas through the more efficient use of these reservoirs to prevent migrations towards more fragile carbon deposits such as wet forests (Brown and Lugo, 1990).

A significant reduction in C depletion could result from intensification of production schemes, albeit within realistic limits. For instance, mineral fertilizers stabilise soil organic matter and slow down deforestation. However, such improvements rely mainly on the subsidisation of fertilizer prices and on rural investment policies, and these decisions are taken at levels over which peasants have but little control.

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