CHAPTER 3.

CARBON, NITROGEN AND PHOSPHORUS ALLOCATION IN AGRO-ECOSYSTEMS OF A WEST AFRICAN SAVANNA.

III. THE PLANT AND SOIL COMPONENTS UNDER CONTINUOUS CULTIVATION

Biomass assessment in a compound maize field

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ABSTRACT

Patterns of carbon (C), nitrogen (N) and phosphorus (P) allocation in the plant-soil system (down to 40 cm deep) were compared at harvest among six plots cropped with groundnut, four with millet, two with maize and two with rice in a mixed-farming system of southern Senegal. The storage of C in the plant-soil system averaged 25.0±0.6, 27.4±1.0, 34.9±6.5 and 71.9±9.6 t ha^{-1} in the groundnut, millet, maize and rice fields respectively. Nitrogen storage amounted to 2.00±0.11, 2.03±0.15, 2.83±0.5 and 6.16±2.20 t ha^{-1} in these fields. Amounts of P (total P in plant + available P in soil, noted P_{OD}) were 5.8±1.1 in groundnut plots, 47.6±9.2 in millet ones, 153.4±35.9 in maize ones and 147.2±100.4 kg ha^{-1} in rice fields. Ninety per cent of C and P and 95 % of N of the whole ecosystem were stored in the soil.

High storage values found for rice plots were attributed to the clayey texture of the soil and to seasonal flooding. Lowest values for C, N and P_{OD} found in the soils of the bush ring (groundnut crops), as compared to those of the compound ring (millet and maize crops), stemmed from land management. The bush ring plots rely only on fallowing for the maintenance of their soil properties. Continuous cultivation together with higher amounts of C, N and P_{OD} in soils of the compound ring were possible thanks to higher organic and nutrient inputs originating from crop residue recycling, manuring and, in the maize plots, to the spreading of household wastes. In the compound ring the amount of C stored seemed to depend more on the chemical richness of organic inflow, than on the amount of C input. However the effect of land management (bush *vs.* compound ring) on soil properties was restricted to the 0-20 cm layer (except for P), and the better soil status in the compound ring relied on nutrient depletion of the bush ring.

On a global change perspective, the potential of managing West African savannas (WAS) to directly mitigate the anthropogenic emission of green house gas was found to be limited, due to low potential for C sequestration in both soil and plant.

On a methodological point of view, soil carbon status may be considered as a relevant indicator for the fertility of agroecosystems of the WAS belt, provided that it encompasses its biotic components, and that characterisation of quality and dynamics of soil organic matter (assessment of seasonal variations, and C flows) are taken into account.

KEY WORDS

Carbon, Groundnut, Maize, Millet, Nitrogen, Phosphorus, Plant biomass, Rice, Savanna, Senegal, Soil

3.1. INTRODUCTION

Because of seasonal violent rainfall, coarse-textured and chemically poor soils, low access to motorization and to external inputs (fertilizer, energy, pesticides), the sustainability of farming systems of the West African savanna belt heavily relies on the way peasants cycle organic matter produced on-site. Crop-livestock integration associated with semi-permanent cultivation have proved to be relevant under low population density conditions (Ker, 1995). The corollary, widespread organisation of the villages is a compound-centred, ring management scheme (Pélissier, 1966; Ruthenberg, 1971; Prudencio, 1993). At least three rings are usually distinguished:

(1) the savanna ring, which is seldom appropriated and only partly integrated to the farming system. It provides the population with wood throughout the year, and it is an essential rangeland for livestock during the cropping period.

(2) the bush ring, subjected to semi-permanent cultivation, dominated by cash crops.

(3) the compound ring, where crop-livestock integration is fully achieved. Continuous cultivation is sustained by manuring, usually through night corralling and day straying on drift pasture, and by recycling of household wastes throughout the dry season.

The vicinity of a lowland, which can be continuously cropped, because of chemically rich soils and seasonal flooding, sometimes disrupts the radial symmetry of this general scheme.

In these still largely self-sufficient systems, endogenous organic production supplies farmers with economic goods (grain, meat, wood). It is also an essential means of production, since (1) replenishment of soil fertility during fallowing relies on the building and initiation of important stocks and fluxes of carbon in the ecosystem (2) livestock, which provides labour power and manure to fields under continuous cultivation, is fed forage.

Soil organic status as defined by the carbon and nitrogen concentration has often been considered as a reliable indicator for soil quality. This is due to the positive effects of organic matter on soil properties, i.e. physical (structure, stability, porosity), chemical (exchangeable cations, cation exchange capacity or CEC, pH) and biological (energy substrate for soil fauna and microflora) (Tiessen *et al.*, 1994; Herrick and Wander, 1998; Kay, 1998; Feller *et al.*, 2000). The role of carbon is even more important in sandy soils with low clay-activity of the West African savanna, because it (1) acts as a substitute for clay for CEC build up (2) protects soil against climate harshness (3) remains an essential mediator of nutrient supply in traditional cropping systems with low chemical inputs (Jones and Wild, 1975; de Ridder and van Keulen, 1990; Asadu *et al.*, 1997). Carbon versatility arises from the fact that soil organic matter (SOM) consists of various carbon functional pools differing in their chemical constitution and turnover. Physical (size-fractionation) methods exist, that enable isolation of these pools (Feller *et al.*, 2000).

Growing needs for land call for a shift in traditional practices, which in the current context would lead to annual losses of more than 20 to 25 kg of nitrogen (N) and 2.5 kg of phosphorus (P) in the fields of sub-Saharan Africa (van der Pol, 1992; Stoorvogel *et al.*, 1993a). There is much evidence that N and P availability acts as the main chemical factor limiting crop yield in West African savannas (WAS) (Mokwunye and Hammond, 1992; Bationo *et al.*, 1998), but past experience shows that their supply to plant should be organically mediated (Pieri, 1989). Although much pleads for the conservation of multi-purpose improved savanna fallows, most of the intensification will likely rely on a better management of biogeochemical nutrient cycles through crop-livestock integration, mulching and agroforestry in the compound ring (Vierich and Stoop, 1990). Indeed, sub-Saharan Africa accounts for less than one per cent of the world fertilizer consumption while harbouring one tenth of the world population, and outlooks indicate little improvement in the access to fertilisers in the coming years (FAO, 1998a; UNDP, 1999).

In a global change perspective, agricultural activities are a major source of greenhouse gas (GHG) emission (Schimel, 1995). In Senegal like in other parts of the world, agriculture would be responsible for a fourth of anthropogenic GHG release (Sokona, 1995). Although mitigation of gaseous carbon emissions ought not to be a priority for fragile economies of dry tropical Africa, carbon sequestration might well enhance the sustainability of agricultural ecosystems of the sub-region (Woomer *et al.*, 1998).

In African smallholder agriculture, there is thus a growing need for an exact quantification of carbon (C), nitrogen and phosphorus budgets, in relation to land use management. Nutrient balances for cropping systems of dry West Africa at a national scale have been established by Stoorvogel *et al.* (1993a). These authors reckon that comprehensive local studies such as those achieved by Stoorvogel *et al.* (1993b) are still too few to validate the kind of model they used. On the other hand, most studies dealing with the management of soil fertility in permanent to semi-permanent cropping systems in the sub-region were done in research centres (Pieri, 1989; Bationo *et al.*, 1998), where environmental conditions (homogeneity of soil features, rational experimental design) are suitable for a proper estimation of the parameters responsible for the efficiency of a practice. Results of on-farm studies are less documented; however, the effect of a practice on soil status and plant biomass yield might well be alleviated as a result of soil heterogeneity, pest hazard and constraining agricultural timetable. Meanwhile, carbon sequestration studies in sub-Saharan Africa are scarce due to the economic context (Woomer *et al.*, 1998). Tiessen *et al.* (1998) provide a synthesis for semi-arid Senegal which, excepting the work of Diouf (1990), emphasises (1) the lack of comprehensive and accurate carbon and nutrient budget in a given place in connection to land use management (2) the paucity of estimates of turn-over rates of soil organic matter in different management systems.

This work is the third and last part of an attempt to quantify C, N and P allocation in agroecosystems of a West African savanna. Previous parts focused on the allocation in plant biomass (Chapter 1) and soil (Chapter 2) under semi-permanent cultivation.

The aims of the study were (1) to provide detailed C, N and available P budgets of some cropped plant-soil agroecosystems (2) to assess the relationships between SOM content and other soil physical and chemical properties, cropping intensity (bush *vs.* compound field), and the management of organic inputs (fallow, manure, household waste) (3) to appraise the functional complementarity between continuous and semi-permanent cultivation cropping systems (4) to discuss the way soil organic status may be used as an indicator of both soil quality and of sustainability of the cropping systems of the WAS.

3.2. METHODS

3.2.1. Site characteristics

The village of Sare Yorobana (12°49'N – 14°53'W) lies in the region of Kolda, High Casamance, south Senegal. The climate is tropical dry. Mean annual rainfall was 960 mm during the past 20 years and occurred from May to October; temperature averaged 28 °C (Service de la Météorologie Nationale, station of Kolda). Mean annual potential evapotranspiration was 1570 mm between 1977 and 1988 (Dacosta, 1989). The study was held during years 1996 and 1997. Ring–like, compound-centred management of the village consists of three main land use systems:

(1) The up-slope plateau, still covered with vast areas of mixed dry forest, savanna and old fallows, woody vegetation being dominated by resprouting Combretaceae. Bush fields at the edge of the plateau are devoted to the cropping of a groundnut (*Arachis hypogaea* L.) local cultivar of the Virginia type. Soils are sandy, ferruginous (Baldensperger *et al.*, 1967), also referred to as ferric Lixisols (FAO, 1998b; see description in Chapter 2 and Appendix 4).

(2) The mid slope glacis, mainly covered with food crops such as late pearl millet (*Pennisetum glaucum* L.), maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench). Permanent crops are usually manured mostly during night tethering at rates depending on the owner's herd size. Plots adjoining the compounds receive household wastes too. Glacis soils are haplic Lixisols (see description in Appendix 4). Soil features are: texture similar to that of the soil found on the plateau, with slightly less clay accumulation in deepest layers; less pronounced acidity (6.3±0.1 in water); C, N and available-P contents of respectively 7.5±1.0 (4.3±0.4) g kg^{-1}, 0.65±0.11 (0.37±0.04) g kg^{-1} and 16.3±6.4 (11.1±3.8) µg kg^{-1} in the 0-10 (0-40) cm layer; CEC reaching 3.7±0.5 (2.5±0.2) meq 100g^{-1}, with high cation saturation.

(3) The lowland, dedicated to rice (*Oryza sativa* L.) and palm plantation. Annual flooding and soil texture explain the good chemical status of the soils of this unit. Soils are Gleysol (FAO, 1998b), with silt-clay-loamy texture in the subsurface layer, turning to loamy to silt-clayey below 30 cm (see description in Appendix 4). Fairly high C, N and available P_{OD} contents of respectively 16.9±1.0 (12.3±1.1) g kg^{-1}, 1.5±0.1 (1.1±0.2) g kg^{-1} and 12.2 (25.7) µg kg^{-1} in the 0-10 (0-40) cm layer, CEC averaging 10 (8.8)

meq 100g^{-1}, with saturation (S) below 50 (37) % are the other main soil characteristics. Like in the two other land use systems, soil bulk density was very stable, being slightly lower for lowland soils than for soils of the glacis and the plateau (1.4 *vs.* 1.5).

Settled Fulani (Peulh) people, who are primarily herdsmen, have integrated an extensive pastoralism - mostly cattle- to this diversified, partly continuous, partly semi-permanent, agriculture.

3.2.2. Sampling schemes

Sampling was performed at harvest time in 1996 and 1997. Apart from maize that reaches maturity in September, harvest occurs in November to December at the beginning of the dry season. Maximum standing crops are usually recorded at this time, which coincides with the return of livestock kept in the peripheral rangeland during the cropping period.

General sampling design was aimed at taking into account high field heterogeneity due to micro-local effects of stump, termite mounds, cropping history, and topography (Milleville, 1972). Fourteen fields were chosen for full C, N and P budget assessment. They represent the different types of land management along the toposequence: six bush fields cropped with groundnut (GN) (four in biennial rotation with fallow, the two others in irregular rotation with cereal and fallow); four compound fields devoted to permanent cropping of millet (MI) with various intensity of manuring during night corralling and day straying; two compound maize (MA) fields benefiting from household wastes and from the highest manuring rates; two seasonally flooded, down-slope rice (RI) fields (Figure 3.1; Appendix 1). Thorough inquiries among field owners were made to check that no mineral fertilizer had been used in the past ten years, and that history of agricultural practices had been similar among the fields sharing the same crop. In Sare Yorobana, groundnut, millet, maize, sorghum and rice are usually planted at respectively 0.2x0.4, 1.0x1.0, 0.5x0.5, 1.0x1.0 and approximately 0.1x0.1 m spacing.

In each field, four square subplots (16 m^2) each were randomly chosen. Vegetation was cleared. Stover/haulm, pod/panicle/ear and advent biomasses were weighed separately, and a sample of each kept for dry matter (DM), C, N and P assessment. At each subplot corner roots were sampled using a core auger (Ø: 5.6 cm). A pit was dug around the hole and soil was taken for further analysis. A 100-cm^3 cylinder was used for soil bulk density measurement. Root and soil sampling was done in 10 cm increments, down to 40 cm, root activity and influence of land use being very little below that depth (Siband, 1974; Chopart, 1980; Feller, 1995a).

3.2.3. Soil & plant analysis

Roots were hydro-pneumatically separated from the soil using a 1-mm sieve (Webb, 1995). All plant samples were oven-dried at 70 °C to constant weight for DM content determination. Roots were then hand-sorted in two diameter classes (diameter below and above 2 mm).

Soil samples were sieved (< 2 mm) and oven-dried at 105 °C for 24 hours. Samples from the same subplot were pooled for carbon content and bulk density determination, yielding four replicates per plot and per soil layer. Only two determinations were performed on fields MI02, GN01 and GN02. All other physical and chemical properties were analysed on one sample per plot, for all plots. All methods for plant (C, N and total P, noted P_t) and soil (C, N, P_{OD}, pH in H20 and in KCl, Ca, Mg, Na, K, CEC, S, five-fraction granulometry, pFs 2.5 and 4.2) analyses were described in Chapter 2. They are detailed in Page *et al.* (1989), except (1) C and N on soil fractions determined under wet combustion with a Fisons (Carlo Erba) Na2000 elemental analyser (2) soil available P, which was assessed with the Olsen method modified by Dabin (1967) and noted P_{OD} (3) Volumetric water content, measured at a suction equivalent to pF2.5 (0.322 atm) and pF4.2 (14.5 atm).

Amounts (t ha^{-1}) of C, N, P_{OD} and P_t stored in soil and vegetation were computed using DM storage or soil bulk density measures and C, N, P_{OD} and P_t contents reported in Table 3.1a,b and Table 3.2. Because of possible bias of soil storage data due to differences of bulk density between plots, statistics on soil elements storage were computed for soil equivalent masses (Ellert and Bettany, 1995). Size fractionation of SOM using wet sieving was performed on samples from the 0-10 and 10-20 cm layers, following a simplified method from Gavinelli *et al.* (1995). It allowed the soil fractions [0-50] and [50-2000] µm to be separated and their organic matter studied separately. In what follows, the C content of a fraction will refer to the quantity of C per mass unit of soil, while the C concentration of a fraction will be defined as the quantity of C per mass unit of fraction.

The abundance of clay+silt size fractions was estimated at the subplot scale, from the weight of the fraction 0-50 µm obtained by the fractionation method described above. Even though it is not strictly equivalent to the relative mass of the [0-50] µm size fraction (clay+silt) as assessed by the standard five-fractions method, where organic cements are removed by oxidation, the difference is very little (Feller, 1995a). The relative mass of the fine fraction [0-50] µm determined by this method was used as an indicator of fine texture at the subplot scale (see 3.2.4.).

3.2.4. Data analysis

All statistical analyses were done using SAS software 6.14 (Hatcher and Stepanski, 1994) except Principal Component Analyses (PCA) with ADE-4 software (Thioulouse *et al.*, 1997). Because Gleysols of paddy fields were too different from soils of the glacis and plateau, soil data from them were not included in the multivariate analyses and the analyses of variance (Anovas).

Multivariate analysis was performed using proc CORR for the computation of Spearman correlations (R_S). Correlation analyses were performed between soil variables (18 soil variables listed above, plus sand, silt, clay+silt and clay+fine silt contents, density, C:N; for layers 0-10 and 10-20 cm C content of fine and coarse fractions was added). PCA were computed for each soil layer on the correlation matrix of a table containing 12 lines as plot replicates and 24-26 columns as soil variables (those used in correlation analyses).

Two-ways Anovas were performed with proc GLM on ranks of data due to the small number of repeated measures and uncertainty about normality of distributions of data and residues (Potvin and Roff, 1993). As explained in Chapter 2, positive relations have been recorded between carbon and fine texture in soils of the West African savannas (Jones and Wild, 1975; Feller, 1993; Zech *et al.*, 1997). Thus, linking soil properties to soil management required that texture be introduced in the model as a covariate.

Two sets of Anovas were performed. One was aimed at relating soil properties to "cultivation intensity" (bush *vs.* compound fields) and used field plot replicates (texture covariate: relative weight of the clay+fine silt fraction, standard methodology). The second set of Anovas was performed on field subplot replicates to evaluate the effect of organic management of fertility on SOM status (texture covariate: relative weight of the [0-50] µm fraction measured without SOM destruction); five treatments were distinguished:

- bush fields: simply fallowed (BuFa), or slightly manured during night corralling of cattle (BuCor).
- compound fields: never manured (Com); manured without household wastes (ComCor); manured with household wastes (ComCorWa) (see Figure 3.1 for a more detailed description of the situations and quantified estimate of organic inputs).

In this second set of Anovas, pair-wise T-test (α=0.05) on least square (LS) means helped to identify management practices that had similar impact on soil C content and storage.

3.3. RESULTS

3.3.1. Amounts of C, N & P in biomass of cropped fields

Table 3.1 Biomass of groundnut (GN), millet (MI), maize (MA) and rice (RI): a. dry matter storage (tDM ha^{-1}). b. C, N and P_t content.

a.

Plot	Panicle / pod	Stover / haulm	Weed and woody advent	Fine roots per soil layer in cm 0-10	10-20	20-30	30-40	0-40	Coarse roots
GN01	0.66	1.52	0.32	0.19	0.15	0.11	0.07	0.52	5.18 +
GN02	1.18	1.86	0.39	0.20	0.17	0.10	0.07	0.53	3.02 +
GN03	0.73	1.14	0.75	0.25	0.16	0.12	0.08	0.61	3.13 +
GN04	1.24	1.75	1.66	0.33	0.18	0.11	0.07	0.69	2.99 +
GN05	0.67	1.18	1.14	0.21	0.09	0.08	0.05	0.44	2.95 +
GN06	1.12	1.51	0.82	0.29	0.18	0.10	0.07	0.63	3.03 +
MI01	1.41	4.38	0.27	0.32	0.19	0.08	0.11	0.70	0.24
MI02	1.85	6.28	0.39	0.34	0.23	0.12	0.09	0.78	0.10
MI03	2.43	9.82	1.32	0.53	0.32	0.16	0.09	1.09	0.03
MI04	2.44	9.62	1.29	0.70	0.24	0.07	0.07	1.08	0.73
MA01	3.66	4.71	1.38	0.16	0.05	0.05	0.04	0.30	0.01
MA02	5.61	5.21	0.97	0.17	0.06	0.05	0.05	0.34	0.03
RI01	1.30	2.16	0.09	2.91	0.87	0.33	0.26	4.38	0.10
RI02	4.61	4.45	0.40	1.55	0.36	0.15	0.12	2.18	0.03

+: computed by using a regression relationship linking coarse root biomass (in tDM ha^{-1}) as measured by full excavation (a) to that measured by the coring technique (b): $a=1.73*b + 2.95$; $R^2=0.6$; $p\{Fobs>Fth\}<0.05$; $n=9$ (see Chapter 1). Fine roots: diameter ranging 0-2 mm. Coarse roots: diameter above 2 mm (stump not included).

b.

Plot	Pod, panicle or ear m ±SE	Haulm or stover m ±SE	Herb/woody advent m ±SE	Roots fine m ±SE	Roots coarse m ±SE
C (g 100g^{-1}DM)					
Groundnut	45.2 ±0.8	33.6 ±0.2	35.7 ±0.3	34.1 ±0.5	38.0 +
Millet	35.3 ±0.1	37.0 ±0.6	35.2 ±0.3	35.1 ±1.0	35.1 ±1.0 ‡
Maize	35.6 ±0.4	35.1 ±0.3	26.4 ±1.5	34.4 ±1.0	34.4 ±1.0 ‡
Rice	32.2 ±1.0	30.7 ±1.2	32.6 ±0.1	29.8 ±0.2	29.8 ±0.2 ‡
N (g 100g^{-1}DM)					
Groundnut	2.87 ±0.10	1.70 ±0.06	0.83 ±0.06	1.66 ±0.03	0.35 +
Millet	1.23 ±0.09	0.27 ±0.03	1.30 ±0.08	1.04 ±0.04	1.04 ±0.04 ‡
Maize	1.21 ±0.18	0.80 ±0.01	1.58 ±0.11	1.31 ±0.08	1.31 ±0.08 ‡
Rice	0.63 ±0.05	0.41 ±0.01	0.91 ±0.01	0.76 ±0.07	0.76 ±0.07 ‡
P_t (g 100g^{-1}DM)					
Groundnut	0.17 ±0.01	0.08 ±0.00	0.06 ±0.00	0.07 ±0.01	0.02 +
Millet	0.24 ±0.01	0.07 ±0.00	0.19 ±0.03	0.07 ±0.00	0.07 ±0.00 ‡
Maize	0.20 ±0.05	0.20 ±0.01	0.39 ±0.02	0.08 ±0.00	0.08 ±0.00 ‡
Rice	0.14 ±0.04	0.10 ±0.02	0.21 ±0.02	0.06 ±0.01	0.06 ±0.01 ‡

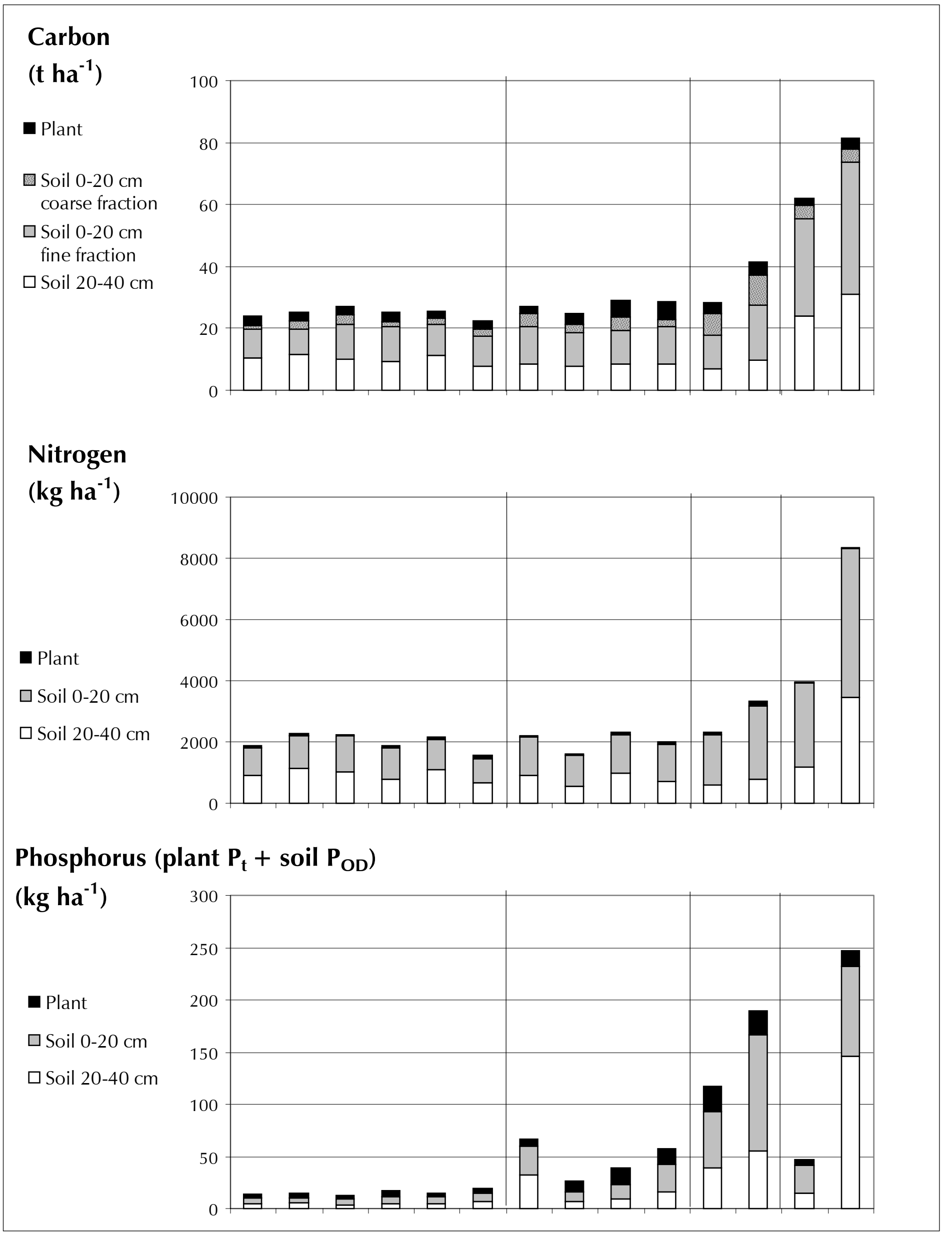
Groundnut: n=6; millet: n=4; maize: n=2; rice: n=2.
+: estimated as the mean value measured on coarse root biomass of three one-year old (see Chapter 1)
‡: extrapolated value from the content in fine root biomass.
Fine roots: diameter ranging 0-2 mm. Coarse roots: diameter above 2 mm (stump not included)
See data in Appendix 17.

Dry matter biomass of groundnut, millet, maize and rice fields amounted respectively to 7.2±0.4 (not including stumps, which biomass averaged 7.5±3.2, n=3, see Chapter 1), 11.6±1.0, 11.1±0.5 and 9.9±0.7 tDM ha^{-1} (Table 3.1a). Shoot:root ratios varied greatly, from 0.8 in the bush fields to 8.8 in the millet fields, 31.7 in the maize fields and 1.9 in the rice field. Woody and herbaceous advents accounted respectively for 26, 4, 11 and 8 % of the above-ground biomass (AGB).

C content averaged 34.3 gC $100gDM^{-1}$, with lowest values found for rice components, and highest ones for groundnut pod (Table 3.1b; Appendix 17). Mean N content of biomass was 1.16 gN $100gDM^{-1}$. Highest values were measured in groundnut AGB and fine roots, lowest values being recorded in millet and rice stover. P_t content averaged 0.14 gP $100gDM^{-1}$. Lowest and highest values were found in roots and AGB maize respectively.

C stored in groundnut, millet, maize and rice fields reached 2.71±0.14 (not including stumps, which amount of carbon averaged 2.83±1.22, n=3, see Chapter 1), 4.21±0.74, 3.81±0.38 and 3.02±0.52 tC ha^{-1} (Figure 3.1). Mean N amounts averaged 79.7±4.3 (groundnut), 69.1±13.4 (millet), 120.0±20.0 (maize) and 59.4±3.6 (rice) kg ha^{-1}. P in plant biomass in these cropped plots reached respectively 4.4±0.7, 12.3±2.1, 23.1±1.1 and 10.5±4.7 kg ha^{-1}.

Average exportation of N occurring at harvest reached 27, 25, 58 and 18 kg ha^{-1} respectively for groundnut, millet, maize and rice. Respective figures for phosphorus were 0.7, 2.4, 3.1 and 1.5 kg ha^{-1}. For groundnut, when including the haulm, an extra amount of N and P was exported, being respectively of 25 and 0.4 kg ha^{-1}.



Crop		Groundnut						Millet				Maize		Rice	
Plot coding		GN01	GN02	GN03	GN04	GN05	GN06	MI01	MI02	MI03	MI04	MA01	MA02	RI01	RI02
Position on toposequence															
Plateau		●	●	●	●	●	●								
Glacis								●	●	●	●	●	●		
Lowland														●	●
Management of fertility															
Crop ring		Bush field						Compound field						Paddy field	
Management coding$^{(1)}$			BuFa			BuCor		Com		ComCor		ComCorWa			
Flooding														●	●
Household wastes$^{(2)}$ (tOM ha^{-1})												2.5	5.6		
Manure$^{(3)}$	night					0.5	0.4			2.5	4.7	4.7	10.0	0	0
(tOM ha^{-1})	day	0.0	0.1	0.0	0.0	0.7	0.2	0.1	0.4	1.3	0.9	0.9	0.3	nd	nd
	total	0.0	0.1	0.0	0.0	1.2	0.5	0.1	0.4	3.8	5.6	5.6	10.3	nd	nd
Fallow rotation			●	●	●										

Figure 3.1 Plant and soil carbon, nitrogen and phosphorus storage in main cash and food crops along a typical toposequence in Sare Yorobana, southern Senegal.
nd: not determined.
(1) used in 3.3.5. .
(2) unpublished data for the dry season 1997-98, assuming the spreading of wastes in a 30-m width-band round the compounds.
(3) data for the dry seasons 1995-96 (day straying) and 1996-97 (night corralling) derived from Chapter 5.
See data in Appendix 18, Appendix 19 and Appendix 24.

3.3.2. Amounts of carbon, nitrogen & phosphorus in cropped soil

Soil organic carbon (SOC) content averaged 6.42±1.10 and 5.18±0.87 g kg^{-1} for the 0-20 and 0-40 cm layers respectively (Table 3.2). Mean N contents were 0.56±0.11 and 0.45±0.09 g kg^{-1} in these layers. P contents averaged 9.88±3.20 and 9.23±3.35 in the 0-20 and 0-40 cm layers, with wide variations between plots. Mean soil C, N and P_{OD} contents ranked as follow: rice > maize > millet > groundnut (layers 0-20 and 0-40 cm). Little variation between plots was recorded for bulk density, being equal to 1.50 kg dm^{-3}.

Table 3.2 Soil C, N, P_{OD} content, C:N ratio and modified [0-2000] µm bulk density of groundnut (GN) millet (MI), maize (MA) and rice (RI) fields.

a. C (g kg^{-1})

Plot	Soil layer (cm)				
	0-10	10-20	20-30	30-40	0-40
GN01	3.93	3.19	3.09	3.87	3.52
GN02	4.40	3.30	3.55	4.12	3.84
GN03	5.07	4.28	3.40	3.41	4.04
GN04	5.02	3.75	3.30	2.85	3.73
GN05	4.20	3.77	3.92	3.60	3.87
GN06	4.31	3.70	2.66	2.55	3.31
MI01	6.97	3.53	2.67	2.98	4.04
MI02	5.22	3.61	2.85	2.26	3.48
MI03	6.58	3.78	2.43	3.02	3.95
MI04	5.96	3.71	2.62	2.75	3.76
MA01	8.54	3.74	2.31	2.12	4.18
MA02	11.98	6.66	3.64	2.59	6.22
RI01	14.59	10.38	7.69	6.81	9.87
RI02	19.17	16.51	13.37	10.07	14.78

b. N (g kg^{-1})

Plot	Soil layer (cm)				
	0-10	10-20	20-30	30-40	0-40
GN01	0.33	0.30	0.26	0.33	0.31
GN02	0.38	0.36	0.35	0.40	0.37
GN03	0.41	0.35	0.32	0.35	0.36
GN04	0.37	0.32	0.27	0.25	0.30
GN05	0.35	0.31	0.35	0.37	0.35
GN06	0.29	0.24	0.23	0.22	0.25
MI01	0.52	0.31	0.26	0.32	0.35
MI02	0.40	0.26	0.18	0.19	0.26
MI03	0.53	0.32	0.30	0.32	0.37
MI04	0.52	0.28	0.24	0.22	0.32
MA01	0.78	0.33	0.20	0.18	0.37
MA02	1.13	0.53	0.28	0.21	0.54
RI01	1.19	0.74	0.41	0.30	0.66
RI02	1.84	1.87	1.55	1.07	1.58

c. P_{OD} (mg kg^{-1})

Plot	Soil layer (cm)				
	0-10	10-20	20-30	30-40	0-40
GN01	1.7	1.9	2.0	1.3	1.7
GN02	2.3	1.1	2.0	1.9	1.8
GN03	2.4	1.4	0.8	1.2	1.5
GN04	2.9	2.0	1.6	1.6	2.0
GN05	2.6	1.9	1.7	1.1	1.8
GN06	3.2	2.5	2.3	2.0	2.5
MI01	9.4	8.4	8.5	12.5	9.7
MI02	3.4	3.0	2.3	2.1	2.7
MI03	5.9	4.0	2.9	2.8	3.9
MI04	10.9	7.0	6.2	3.7	7.0
MA01	22.9	13.4	12.4	13.2	15.5
MA02	45.4	30.7	19.4	15.5	27.8
RI01	10.1	8.3	5.1	3.8	6.8
RI02	14.4	53.4	66.9	43.8	44.6

d. C/N

Plot	Soil layer (cm)				
	0-10	10-20	20-30	30-40	0-40
GN01	11.9	10.6	11.9	11.7	11.5
GN02	11.6	9.2	10.1	10.3	10.3
GN03	12.4	12.2	10.6	9.7	11.3
GN04	13.6	11.7	12.2	11.4	12.3
GN05	12.0	12.1	11.2	9.7	11.2
GN06	14.9	15.4	11.6	11.6	13.5
MI01	13.4	11.4	10.3	9.3	11.5
MI02	13.1	13.9	15.8	11.9	13.5
MI03	12.4	11.8	8.1	9.4	10.8
MI04	11.5	13.2	10.9	12.5	11.9
MA01	10.9	11.3	11.6	11.6	11.2
MA02	10.6	12.6	13.0	12.6	11.6
RI01	12.3	14.1	18.9	22.9	15.0
RI02	10.4	8.8	8.7	9.4	9.3

e. Bulk density (fraction [0-2000]µm) (kg dm^{-3})

Plot	Soil layer (cm)				
	0-10	10-20	20-30	30-40	0-40
GN01	1.47	1.50	1.50	1.50	1.49
GN02	1.51	1.35	1.60	1.41	1.47
GN03	1.54	1.54	1.50	1.51	1.52
GN04	1.53	1.39	1.66	1.31	1.47
GN05	1.52	1.52	1.50	1.52	1.51
GN06	1.52	1.50	1.49	1.46	1.50
MI01	1.55	1.49	1.51	1.55	1.53
MI02	1.50	1.54	1.53	1.54	1.53
MI03	1.45	1.54	1.55	1.56	1.52
MI04	1.44	1.58	1.56	1.58	1.54
MA01	1.45	1.55	1.53	1.55	1.52
MA02	1.43	1.54	1.57	1.58	1.53
RI01	1.38	1.50	1.64	1.66	1.54
RI02	1.37	1.24	1.30	1.35	1.32

Modified bulk density is the weight of the soil fraction [0-2000] µm fraction (dry sieving) per unit of volume. This modified bulk density has been used for the calculation of amounts of soil elements.

C stored in soil amounted to 22.3±0.7, 23.1±0.7, 31.1±6.1 and 68.7±9.1 tC ha^{-1} in the 0-40 cm layer of groundnut, millet, maize and rice fields respectively, 55 % (groundnut) to 73 % (maize) being stored in the 0-20 cm layer (Figure 3.1; see Table 3.2 for detailed calculation). N averaged 1.92±1.10 (groundnut), 1.96±0.15 (millet), 2.71±0.48 (maize) and 6.10±2.20 (rice) t ha^{-1}, with vertical distribution similar to C. Amounts of P_{OD} were 11.3±0.8, 35.4±9.6, 130.2±37.0 and 136.7±96 kgP ha^{-1}, 57 % being contained in the 0-20 cm soil layer.

Carbon storage in the plant-soil system amounted to 25.0±0.6, 27.4±1.0, 34.9±6.5 and 71.7±9.6 t ha^{-1} in the groundnut, millet, maize, and rice fields respectively. Ninety per cent of C and P, and 95 % of N of the whole ecosystem were stored in the soil.

3.3.3. Soil organic matter status as related to other soil properties

Correlation analysis exhibited the following statistically significant ($p\{R=0\}<0.05$) links between variables:

- 0-10 cm layer: C, N and P contents were positively linked ($R_S=+0.79^{**}$ to $+0.95^{**}$) (Appendix 20a). pH (in water and KCl), Ca, Mg, K, CEC and S were related to C, N and P ($R_S=+0.62^{*}$ to $+0.98^{***}$). The correlations of these chemical properties with the C content of the [0-50] μm fraction (mean R_S: +0.85) were higher than with that of the [50-2000] μm fraction (mean R_S: +0.74). Fine elements (clay+fine silt) were correlated with pF2.5 ($R_S=+0.67^{*}$) and pF4.2 ($R_S=+0.88^{*}$) only. On the positive semi-axis, C (total and in fractions), N, CEC, Ca, Mg, K and P_{OD} were the main contributors to the first principal component (PC) (relative inertia or RI: 45 %) of the PCA, with sand and bulk density on the negative side (Figure 3.2a). MA fields were located on the positive side of the axis, and GN fields on the negative semi-axis, MI plots being neatly isolated near the origin (Figure 3.2b). The second PC (RI: 18 %) was held by texture; MA, MI and GN plots held no particular position along this PC (see Appendix 21 for projections on the plane PC1 x PC3),
- 10-20 cm layer: fine texture was negatively correlated to P, pH, Ca, Mg, Na and S ($R_S=-0.62^{*}$ to -0.68^{*}), while C (total and in fractions) and N were not linked to any other variable (Appendix 20b). PCA indicated that the main contribution to the first axis (RI: 42 %) was brought by Ca, P_{OD}, Mg and pH (and C and CEC to a lesser extent) (Figure 3.2c). Plot location along this axis was similar to that along the first PC in the upper layer (Figure 3.2d). The second PC (RI: 20 %) was driven by texture again, but did not segregate MA, MI and GN clusters (see Appendix 21 for projections on the plane PC1 x PC3),
- 20-30 cm layer: C was positively related to N ($R_S=+0.67^{*}$) and CEC ($R_S=+0.69^{*}$) (Appendix 20c). N, pH and exchangeable bases increased in the same way as fine elements, while P_{OD} decreased. In the PCA, the main PC (RI: 44 %) was held by fine texture and pFs on the positive side, by pH on the other side (Appendix 21). MA plots were associated to high pH, GN to fine texture. Interpretation of the second PC was difficult and yielded no clear information,

- 30-40 cm layer: C was positively related to N (R_S=+0.96***) and negatively to P_{OD} (R_S=-0.64*). C, N, CEC and pFs were positively correlated with fine elements (R_S=+0.92*** to +0.96***), while P, C:N, pH and S showed trends opposite to Clay+fine silt content (R_S=-0.59* to –0.64*) (Appendix 20d). Information from the PCA was the same as the one detailed in the 20-30 cm layer (Appendix 21a).

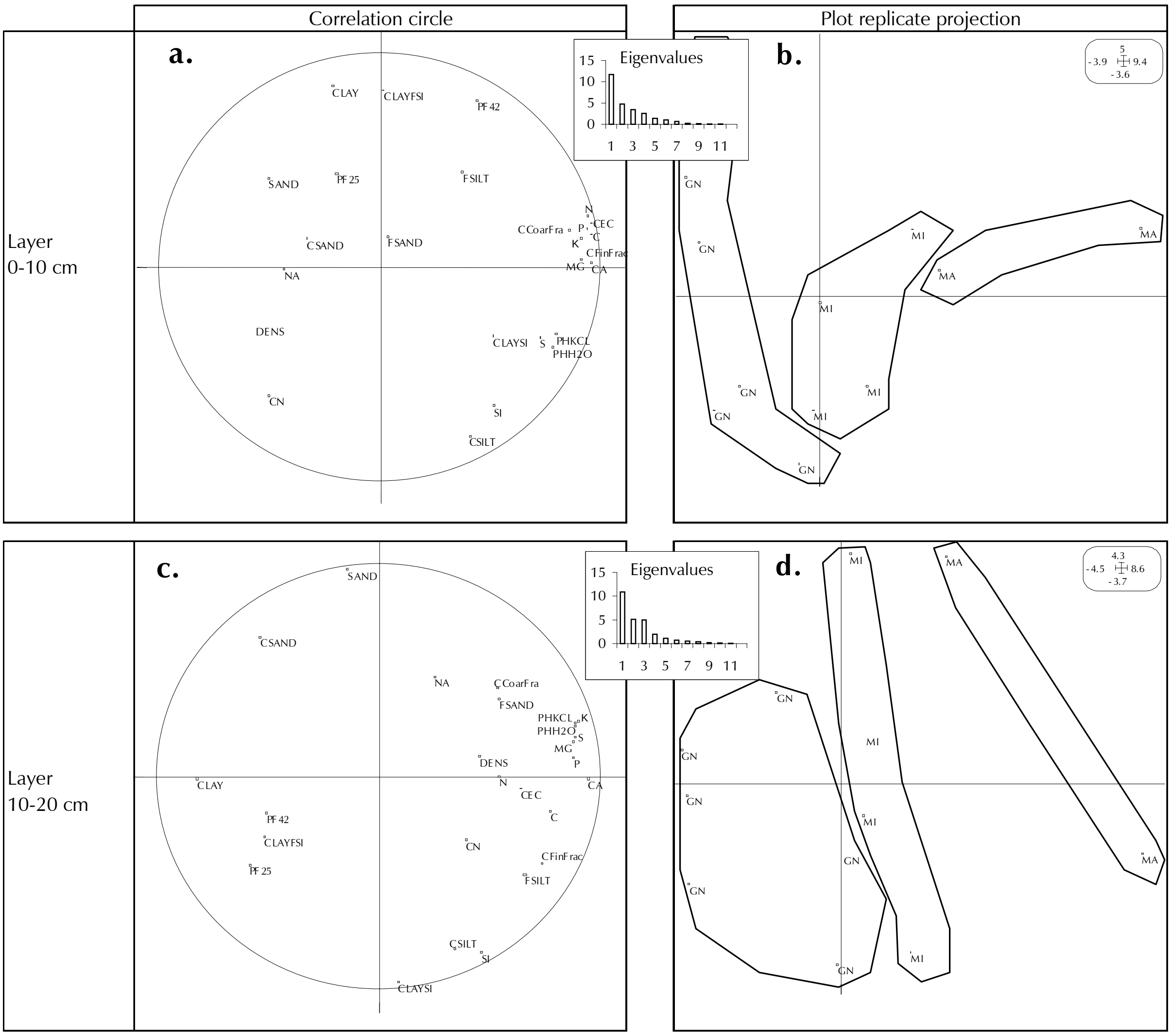


Figure 3.2 Principal components (PC) analysis of the soil properties of 12 cropped plots. Correlation circles of the variables and projection of the plot replicates on plane PC 1x PC2: a,b: layer 0-10 cm; c,d: layer 10-20 cm.

Coding of variables: C: carbon. CA: calcium. CCoarFra: carbon content of the [50-2000] µm fraction. CEC: cation exchange capacity. CFinFrac: carbon content of the [0-50] µm fraction. CLAY: clay. CLAYFSI: clay+fine silt. CLAYSI: clay+silt. CN: C:N ratio. CSAND: coarse sand. CSILT: coarse silt. DENS: bulk density. FSAND: fine sand. FSILT: fine silt. K: potassium. MG: magnesium. N: nitrogen. NA: sodium. P: available phosphorus. PHH2O: pH in water. PHKCL: pH in KCl. PF25 and PF42: volumetric water content determined at a suction equivalent to pF2.5 and pF4.2. S: saturation rate. SAND: sand. SI: silt.

Coding of plot replicates: GN: groundnut crop. MI: millet crop. MA: maize crop.

See eigen values in Appendix 21b.

3.3.4. Influence of cropping intensity on soil organic status & other soil properties

3.3.4.1. Chemical and physical properties

Clay+fine silt content was higher in the bush than in the compound fields, especially below 20 cm (26 *vs.* 20 %) (Table 3.3a). However, cultivation intensity did not influence physical properties, except bulk density in the layers 10-20 and 30-40 cm. All chemical properties (including C, N and P_{OD}) were significantly improved in the 0-10 cm soil layer of the compound fields (Table 3.3b). This was still the case for P_{OD}, pH, Mg, K and S in other deeper layers. Texture was found to influence N, pH and Na in upper layers. For the 20-40 cm layer, texture effect was recorded on all chemical properties, but P_{OD}, Ca, K and S. Consequently, higher C, N contents and CEC values were found in the deepest layers of bush plots than in those of compound plots.

Table 3.3 Effect of cultivation intensity and texture (clay+fine silt content) on soil properties.

a. physical properties.

Layer	Bush fields	Compound fields	F		
(cm)	Mean (±SE) (n=6)	Mean (±SE) (n=6)	Cult. Intens.	Texture	Overall
Clay + fine silt content (%)					
0-10	11.3 ±1.2	10.6 ±1.0	0.1		
10-20	17.1 ±1.3	14.5 ±0.9	2.3		
20-30	22.5 ±2.5	18.0 ±1.2	1.3		
30-40	29.4 ±4.3	21.6 ±2.3	1.8		
0-40	20.1 ±2.0	16.2 ±1.0	2.3		
pF2.5 (gH_20 100 g^{-1}soil)					
0-10	6.95 ±1.02	6.03 ±0.44	0.0	7.3 *	3.7
10-20	8.02 ±1.13	5.82 ±0.59	0.1	15.2 **	8.9 **
20-30	8.80 ±1.42	6.28 ±0.78	0.1	45.2 ***	26.1 ***
30-40	11.35 ±2.03	7.58 ±0.99	0.7	134.0 ***	83.6 ***
0-40	8.78 ±1.2	6.43 ±0.61	2.1	55.9 ***	30.0 ***
pF4.2 (gH_20 100 g^{-1}soil)					
0-10	2.70 ±0.34	2.82 ±0.37	0.5	33.1 ***	16.6 **
10-20	4.03 ±0.46	3.03 ±0.23	0.1	24.9 ***	16.4 **
20-30	5.35 ±0.75	3.78 ±0.28	2.1	36.0 ***	24.9 ***
30-40	7.30 ±1.22	4.82 ±0.66	0.9	184.2 ***	114.6 ***
0-40	4.85 ±0.64	3.61 ±0.26	0.3	134.0 ***	79.5 ***
Bulk density (kg dm^{-3})					
0-10	1.52 ±0.01	1.47 ±0.02	5.1	2.6	3.6
10-20	1.47 ±0.03	1.54 ±0.01	5.2 *	0.3	2.7
20-30	1.54 ±0.03	1.54 ±0.01	0.7	0.1	0.4
30-40	1.45 ±0.03	1.56 ±0.01	23.9 ***	0.4	13.3 **
0-40	1.50 ±0.01	1.53 ±0.00	12.2 **	0.2	6.9 *

p{Ho: $F_{obs}>F_{th}=0$}: $^{*}<0.05$; $^{**}<0.01$; $^{***}<0.001$.
See data in Appendix 22.

Table 3.3 (continued) b. chemical properties

Layer	Bush fields	Compound fields	F		
(cm)	Mean (±SE) (n=6)	Mean (±SE) (n=6)	Cult. Intens.	Texture	Overall
Carbon (g kg^{-1})					
0-10	4.49 ±0.19	7.54 ±1.00	31.0 ***	0.9	15.6 **
10-20	3.66 ±0.16	4.17 ±0.50	0.7	0.8	0.5
20-30	3.32 ±0.17	2.75 ±0.19	2.3	1.4	2.8
30-40	3.40 ±0.24	2.62 ±0.15	8.3 *	134.1 ***	103.2 ***
0-40	3.72 ±0.11	4.27 ±0.40	2.5	0.8	1.3
Nitrogen (g kg^{-1})					
0-10	0.36 ±0.02	0.65 ±0.11	33.6 ***	6.2 *	18.9 ***
10-20	0.31 ±0.02	0.34 ±0.04	0.2	1.0	0.5
20-30	0.30 ±0.02	0.24 ±0.02	1.1	9.5 *	7.2 *
30-40	0.32 ±0.03	0.24 ±0.03	7.3 *	56.2 ***	48.7 ***
0-40	0.32 ±0.02	0.37 ±0.04	2.9	2.0	1.7
Phosphorus $_{OD}$ (10^{-3}g kg^{-1})					
0-10	2.52 ±0.21	16.32 ±6.43	22.9 **	0.2	11.4 **
10-20	1.80 ±0.20	11.08 ±4.20	20.4 **	3.4	19.2 ***
20-30	1.73 ±0.21	8.62 ±2.64	19.2 **	0.5	12.2 **
30-40	1.52 ±0.15	8.30 ±2.47	19.4 **	1.5	15.3 **
0-40	1.89 ±0.14	11.08 ±3.82	21.6 **	2.6	18.8 ***
pH (H2O)					
0-10	5.92 ±0.08	6.52 ±0.06	55.5 ***	10.2 *	34.8 ***
10-20	5.44 ±0.13	6.45 ±0.09	26.4 ***	6.7 *	27.5 ***
20-30	5.23 ±0.17	6.25 ±0.16	58.2 ***	21.5 **	58.5 ***
30-40	5.20 ±0.17	6.07 ±0.20	7.5 *	4.3	9.5 **
0-40	5.45 ±0.13	6.32 ±0.12	49.6 ***	24.2 ***	64.0 ***
pH (KCl)					
0-10	5.15 ±0.12	5.93 ±0.12	18.0 **	4.0	11.7 **
10-20	4.63 ±0.17	5.69 ±0.14	25.2 ***	5.7 *	25.4 ***
20-30	4.44 ±0.17	5.42 ±0.20	10.6 *	10.0 *	15.5 **
30-40	4.34 ±0.17	5.21 ±0.24	5.1	2.7	6.3 *
0-40	4.64 ±0.15	5.56 ±0.17	8.3 *	12.3 **	18.1 ***
Ca (meq 100g^{-1}soil)					
0-10	1.32 ±0.13	2.75 ±0.39	13.2 **	0.0	6.7 *
10-20	1.06 ±0.17	1.84 ±0.27	4.6	1.3	5.0 *
20-30	0.99 ±0.13	1.35 ±0.16	3.2	0.7	2.8
30-40	1.03 ±0.14	1.20 ±0.15	0.2	0.3	0.2
0-40	1.10 ±0.13	1.79 ±0.22	4.7	1.1	4.8 *
Mg (meq 100g^{-1}soil)					
0-10	0.36 ±0.03	1.03 ±0.13	28.1 ***	0.1	14.1 **
10-20	0.32 ±0.04	0.69 ±0.09	26.8 ***	0.5	14.9 **
20-30	0.35 ±0.04	0.63 ±0.06	47.0 ***	4.7	23.5 ***
30-40	0.40 ±0.05	0.66 ±0.05	80.0 ***	12.8 **	40.0 ***
0-40	0.36 ±0.03	0.75 ±0.06	45.7 ***	4.6	23.2 ***
Na (meq 100g^{-1}soil)					
0-10	0.01 ±0.01	0.00 ±0.00	2.1	0.6	1.5
10-20	0.00 ±0.00	0.00 ±0.00	2.2	11.6 **	5.8 *
20-30	0.01 ±0.00	0.00 ±0.00	6.5 *	2.3	3.5
30-40	0.01 ±0.01	0.01 ±0.00	0.0	0.2	0.1
0-40	0.01 ±0.00	0.00 ±0.00	4.1	1.9	2.2
K (meq 100g^{-1}soil)					
0-10	0.04 ±0.00	0.25 ±0.05	28.5 ***	0.1	14.2 **
10-20	0.04 ±0.00	0.21 ±0.03	21.6 **	0.1	14.0 **
20-30	0.03 ±0.00	0.22 ±0.04	25.5 ***	0.1	14.0 **
30-40	0.03 ±0.00	0.24 ±0.04	28.2 ***	0.6	15.1 **
0-40	0.04 ±0.00	0.23 ±0.03	25.5 ***	0.3	14.5 **
CEC (meq 100g^{-1}soil)					
0-10	2.31 ±0.10	3.69 ±0.48	17.2 **	2.1	9.3 **
10-20	2.49 ±0.08	2.78 ±0.29	1.0	1.4	0.9
20-30	2.70 ±0.12	2.48 ±0.14	0.0	9.3 *	5.2 *
30-40	2.95 ±0.36	2.65 ±0.26	5.3 *	107.7 ***	55.6 ***
0-40	2.61 ±0.13	2.90 ±0.22	5.4 *	7.8 *	4.7 *
Saturation rate (%)					
0-10	74.5 ±5.2	109.5 ±3.8	33.6 ***	2.4	18.8 ***
10-20	57.3 ±7.4	98.2 ±5.0	9.5 *	3.1	10.6 **
20-30	51.5 ±4.9	89.3 ±6.8	28.8 ***	4.3	22.9 ***
30-40	54.8 ±9.9	81.3 ±5.7	3.7	3.3	5.6 *
0-40	59.5 ±6.3	94.6 ±4.1	16.5 **	7.1 *	20.3 ***

3.3.4.2. SOM quality

Carbon recovery after fractionation averaged 97 % but ranged from 70 to 117 % (Table 3.4a,b). These variations may be due to the different preparations of fractionated and non-fractionated (NF) samples, losses of water-soluble C and analytical method.

Table 3.4 SOM quality as assessed by SOM fractionation in the soil sublayers of millet, maize and rice fields.

a. 0-10 cm layer

	Fraction 0-50 μm				Fraction 50-2000 μm				Fractionation
	Mass	C content in g kg^{-1} of		C/N	Mass	C content in g kg-1 of		C/N	recovery rate
Plot	(g 100 g^{-1} soil)	fraction	soil (1)		(g 100 g^{-1} soil)	fraction	soil (2)		((1)+(2))/C_t
GN01	19.4	14.38	2.79	12.1	80.6	0.92	0.74	37.8	90
GN02	18.7	16.54	3.09	12.2	81.3	1.25	1.02	34.9	93
GN03	25.6	14.43	3.70	13.4	74.4	1.38	1.03	23.8	93
GN04	19.0	18.10	3.45	13.6	81.0	0.85	0.69	28.2	82
GN05	18.9	15.18	2.87	12.1	81.1	0.88	0.72	26.5	85
GN06	23.2	12.73	2.95	12.5	76.8	1.35	1.04	25.2	93
MI01	17.1	30.95	5.29	13.1	82.9	2.31	1.92	28.8	103
MI02	19.7	17.92	3.53	13.4	80.3	1.26	1.01	16.4	87
MI03	19.2	22.16	4.24	13.9	80.8	3.15	2.54	27.0	103
MI04	28.7	17.11	4.91	14.3	71.3	1.55	1.11	25.9	101
MA01	17.3	29.03	5.02	11.8	82.7	5.28	4.36	22.7	110
MA02	25.7	29.94	7.70	12.0	74.3	8.00	5.95	26.5	114
RI01	77.0	20.51	15.80	12.9	23.0	12.28	2.82	26.0	128
RI02	82.5	25.47	21.01	12.8	17.5	16.64	2.91	22.1	125

b. 10-20 cm layer

	Fraction 0-50 μm				Fraction 50-2000 μm				Fractionation
	Mass	C content in g kg-1 of		C/N	Mass	C content in g kg-1 of		C/N	recovery rate
Plot	(g 100 g^{-1} soil)	fraction	soil (1)		(g 100 g^{-1} soil)	fraction	soil (2)		((1)+(2))/C_t
GN01	25.2	9.23	2.32	10.8	74.8	<0.2	<0.15		
GN02	26.0	10.30	2.68	12.5	74.0	1.29	0.96	48.0	110
GN03	27.1	10.88	2.95	12.7	72.9	1.11	0.81	31.7	88
GN04	23.8	11.65	2.77	12.4	76.2	0.31	0.24	26.2	80
GN05	27.8	9.07	2.52	9.7	72.2	0.58	0.42	44.3	78
GN06	30.6	9.66	2.96	13.1	69.4	0.58	0.40	26.0	91
MI01	22.5	13.39	3.01	13.2	77.5	1.08	0.84	42.6	109
MI02	22.5	9.86	2.22	15.6	77.5	0.41	0.32	12.9	70
MI03	26.9	10.71	2.88	11.0	73.1	0.62	0.45	26.6	88
MI04	31.8	8.80	2.80	13.2	68.2	0.47	0.32	24.9	84
MA01	25.0	9.51	2.38	11.0	75.0	1.02	0.76	32.4	84
MA02	33.1	14.66	4.86	14.2	66.9	1.84	1.23	32.2	91
RI01	74.3	15.12	11.23	14.9	25.7	3.66	0.94	41.0	117
RI02	85.8	21.43	18.39	11.7	14.2	6.63	0.94	22.4	117

Fractionation recovery rate computed as the [(1) + (2)]: [carbon content of non-fractionated soil (see Table 3.2a)] ratio.

The mass of the fraction [0-50] µm ranged from 17 to 33 % in layers 0-10 and 10-20 cm of the plateau and glacis soils, while rising to 80 % in the lowland soils. In the 0-10 cm layer, C concentration in the fine size-fraction averaged 20.3 g kg^{-1}, C content was 6.2 g kg^{-1}. In the 10-20 cm layer, these values were respectively 11.7 and 4.6 g kg^{-1}. C concentration was much lower in the [50-2000] µm fraction, ranging from 4.1 (0-10 cm) to 1.5 (10-20 cm) g kg^{-1}, with wide differences between sandy and clayey soils. This resulted in a lower contribution to total soil C from the coarse fraction content (2 out of 7.6 g kg^{-1} and 0.7 out of 5.3 g kg^{-1} in the 0-10 and 10-20 cm layers respectively) as compared to that from the fine size-fraction.

For a given plot, C:N ratio of NF soil remained steady in the whole profile and averaged 12 (Table 3.2d). Extreme values (9.3-16.6) were found in rice land. C:N varied strongly between fractions, being 12.7 in the fine fraction while rising to 29 in the coarse one (Table 3.4ab).

Table 3.5 Effect of cultivation intensity and texture (clay+fine silt content) on SOM quality as assessed by C concentration and content, and C:N ratio in non-fractionated soil and in fine- and coarse-size fractions.

a.

Layer	Bush fields	Compound fields	F		
(cm)	Mean (±SE)	Mean (±SE)	Cultiv. intensity	Texture	Overall
C/N on non-fractionated soil					
0-10	12.7 ±0.5	12.0 ±0.5	2.0	10.9 **	6.1 *
10-20	11.9 ±0.9	12.4 ±0.4	0.1	0.1	0.2
20-30	11.3 ±0.3	11.6 ±1.1	0.6	4.5	2.2
30-40	10.8 ±0.4	11.2 ±0.6	0.0	1.9	1.1
0-40	11.7 ±0.4	11.7 ±0.4	0.7	5.0	2.5

b.

Layer	Fraction	Bush fields	Compound fields	F		
(cm)	(μm)	Mean (±SE)	Mean (±SE)	Cultiv. intensity	Texture	Overall
Carbon concentration (g kg^{-1} fraction)						
0-10	0-50	15.23 ±0.77	24.52 ±2.55	13.6 **	0.3	7.1 *
	50-2000	1.11 ±0.10	3.59 ±1.06	20.7 **	4.2	11.8 **
10-20	0-50	10.13 ±0.41	11.16 ±0.96	0.1	0.1	0.2
	50-2000	0.66 ±0.19	0.91 ±0.22	0.7	0.5	0.4
Carbon content (g kg^{-1} soil)						
0-10	0-50	3.14 ±0.15	5.12 ±0.58	23.3 ***	1.9	12.2 **
	50-2000	0.87 ±0.07	2.82 ±0.80	13.1 **	2.9	7.6 *
10-20	0-50	2.70 ±0.10	3.02 ±0.39	0.2	0.0	0.1
	50-2000	0.48 ±0.14	0.65 ±0.15	0.9	0.7	0.6
C/N on fractions						
0-10	0-50	12.7 ±0.3	13.1 ±0.4	0.2	0.0	0.1
	50-2000	29.4 ±2.3	24.5 ±1.8	0.8	0.1	0.5
10-20	0-50	11.9 ±0.5	13.0 ±0.7	1.5	0.1	1.1
	50-2000	35.2 ±4.6	28.6 ±4.0	0.1	0.7	0.7

$p\{Ho: F_{obs}>F_{th}=0\}$: $^{*}<0.05$; $^{**}<0.01$; $^{***}<0.001$.
See data in Table 3.2 and Table 3.4.

Total SOC content was higher in compound fields, as compared to bush fields, fine and coarse fractions contributing to the same extent to this gain (Table 3.3b; Table 3.5b). However, values of relative C increase differed between fractions. C concentration improved by 40 % between bush and compound fields in the [0-50] μm fraction, by 150 % in the coarse fraction. This differential evolution was particularly striking in the two maize fields, in which relative increases were found to be 70 and 300 % in each of the fine and coarse fractions; in these plots, the contribution of the coarse fraction to the total soil C pool increase (as compared to the other fields -millet and groundnut-) was thus more important than that of the fine fraction. Statistical tests on C status of each fraction exhibited very similar results to the ones obtain on NF soil, that is significant increases of C concentration (Table 3.5b). C:Ns of fractions and NF soil were rather independent from cultivation intensity.

3.3.4.3. Soil C, N and P storage

Mean differences of C amounts (expressed in soil equivalent depth) between compound (millet and maize) and bush fields were 60 % for the 0-10 cm layer (11.1±1.4 *vs.* 6.8±0.3 t ha^{-1}) but only 16 % for the 0-40 cm layer (25.8±2.4 *vs.* 22.3±0.7t ha^{-1}) (Table 3.6). Similar differences were found for N: these were 950±150 in compound fields *vs.* 540±30 kg ha^{-1} in bush fields for the 0-10 cm layer, and 2210±220 *vs.*

1920±110 kg ha^{-1} for the 0-40 cm layer. Considering values expressed in soil equivalent masses, significant increases on cumulated values of amounts of C and N in the compound ring could be seen only down to 20 cm deep (Table 3.6a). The increase in C was well balanced between the two fractions in the 0-10 and 0-20 cm layers (the coarse fraction was responsible for 54 and 52 % of the increase in these respective layers) (Table 3.6b). Soil P_{OD} storage exhibited more drastic increases. Amounts of P_{OD} of the compound fields were more than six times higher than those of the bush fields for the 0-10 cm layer (in equivalent depth: 23.7±9.2 *vs.* 3.8±0.3 kg ha^{-1}). The ratio was slightly lower when considering the 0-40 cm layer (67.0±23.0 *vs.* 11.3±0.8 kg ha^{-1}).

Maize plots -that had received the highest rates of manure or household waste- accounted for much of the differences between the pools of bush and compound fields: their total amounts of C, N and P_{OD} were found to be respectively 1.3, 1.4 and 3.3 higher than those of millet crops.

Table 3.6 Effect of cultivation intensity and texture (clay+fine silt content) on soil C, N and P_{OD} storage (computed in equivalent soil masses).

a. non-fractionated soil

Layer	Bush fields	Compound fields	F		
(cm)	Mean (±SE) (n=6)	Mean (±SE) (n=6)	Cultiv. intensity	Texture	Overall
Carbon storage (t ha-1)					
0-10	6.9 ±0.3	11.5 ±1.5	31.0 ***	0.9	15.6 **
0-20	12.5 ±0.5	17.7 ±2.2	18.7 **	0.3	9.7 **
0-30	17.5 ±0.6	21.8 ±2.4	5.7 *	0.1	3.0
0-40	22.6 ±0.7	25.7 ±2.3	3.1	0.9	1.6
Nitrogen storage (kg ha^{-1})					
0-10	546 ±26	983 ±164	30.0 ***	4.8	16.6 **
0-20	1026 ±52	1486 ±216	13.3 **	3.4	6.9 *
0-30	1471 ±78	1847 ±225	5.8 *	1.8	3.0
0-40	1955 ±117	2209 ±221	2.8	2.8	1.9
Phosphorus$_{OD}$ storage (kg ha^{-1})					
0-10	3.9 ±0.3	24.9 ±9.8	22.9 **	0.2	11.4 **
0-20	6.6 ±0.5	41.5 ±16.0	19.1 **	0.2	11.5 **
0-30	9.2 ±0.7	54.3 ±19.8	23.7 ***	3.0	19.5 ***
0-40	11.5 ±0.9	66.8 ±22.9	21.2 **	2.4	18.4 ***

b. soil size fractions

Layer	Fraction	Bush fields	Compound fields	F		
(cm)	(µm)	Mean (±SE)	Mean (±SE)	Cultiv. intensity	Texture	Overall
Carbon storage in fractions (t ha^{-1})						
0-10	0-50	5.40 ±0.28	7.51 ±0.63	13.8 **	0.2	6.9 *
	50-2000	1.48 ±0.10	3.97 ±1.01	10.0 *	0.0	5.0 *
0-20	0-50	10.19 ±0.44	12.73 ±1.15	7.0 *	1.8	3.7
	50-2000	2.29 ±0.28	5.00 ±1.19	5.8 *	0.1	3.0

Reference plot for equivalent soil mass calculation was set as GN03.
$p\{Ho: F_{obs}>F_{th}=0\}$: *<0.05; **<0.01; ***<0.001.
See data in Appendix 23 and Appendix 24.

3.3.5. Influence of the management of organic inputs on soil organic status

The second set of more accurate Anovas testing the influence of five organic practices at the subplot scale yielded some significant differences in soil physical properties between treatments, especially for soil bulk density (Table 3.7). In the 0-10 cm layer, treatments could be classified as follows, with regard to the carbon content and T-tests on least-square means: ComCorWa (10.26±1.05 g kg^{-1}) > Com = ComCor (6.27±0.63 g kg^{-1}) > BuFa = BuCor (4.26±0.41 g kg^{-1}). In the 10-20 cm layer, ComCorWa had the highest organic content while other treatments exhibited similar values. Trends in mean carbon content became less obvious below this depth, due to different content of fine elements between treatments. As a matter of fact, the contribution of management to SOC variability was significant for layers 0-10, 10-30 and 0-40 cm only. Carbon storage and C content exhibited similar trends. In the soil layer 0-10 cm, the most efficient practices to store organic carbon were: ComCorWa (15.4±1.6 tC ha^{-1}) > Com = ComCor (6.27±0.63 tC ha^{-1}) > BuFa = BuCor (4.26±0.41tC ha^{-1}). Due to differential clay accumulation at the bottom of the soil profile, the classification of the five treatments, with regard to cumulate amounts of carbon down to lower depth, was difficult. For instance, ComCorWa exhibited highest C amounts down to a 40-cm depth; but in the whole profile Com and BuFa treatments ranked second and third for storing highest, significant amounts of carbon.

Table 3.7 Effect of management of organic inputs on soil physical properties and organic status.

Depth (cm)	BuFa Mean(±SE) (n=10)		BuCor Mean(±SE) (n=8)		Com Mean(±SE) (n=6)		ComCor Mean(±SE) (n=8)		ComCorWa Mean(±SE) (n=8)		F Management	F Texture	F Overall
Fraction [0-50]μm (g $100g^{-1}$ soil)													
0-10	21.6 ±1.1		21.0 ±1.5		18.0 ±0.7		23.9 ±2.4		21.5 ±2.2		1.6		
10-20	25.5 ±0.5	a	29.2 ±1.0	a	22.5 ±0.6	b	29.3 ±1.8	a	29.1 ±3.4	a	5.1 **		
20-30	28.9 ±1.2		31.9 ±1.5		26.2 ±1.6		31.2 ±2.4		27.7 ±3.2		2.0		
30-40	33.6 ±2.6		38.3 ±2.0		33.0 ±2.2		37.7 ±3.0		28.3 ±2.5		2.6 *		
0-40	27.4 ±1.1	ab	30.1 ±0.8	a	24.9 ±0.8	b	30.6 ±1.9	ab	26.7 ±2.6	ab	2.7 *		
Bulk density (kg dm^{-3} soil)													
0-10	1.53 ±0.01	a	1.52 ±0.01	ab	1.54 ±0.01	b	1.44 ±0.01	c	1.45 ±0.03	a	4.3 **	1.0	3.7 **
10-20	1.44 ±0.03	c	1.51 ±0.01	ab	1.51 ±0.02	ab	1.56 ±0.01	a	1.54 ±0.02	bc	4.5 **	1.5	3.8 **
20-30	1.59 ±0.03	a	1.50 ±0.01	ab	1.52 ±0.01	a	1.56 ±0.01	a	1.55 ±0.02	b	4.2 **	0.8	3.5 *
30-40	1.42 ±0.04	b	1.49 ±0.01	a	1.54 ±0.00	a	1.57 ±0.01	a	1.57 ±0.02	b	8.9 ***	0.7	7.4 ***
0-40	1.49 ±0.01	b	1.51 ±0.00	a	1.53 ±0.01	a	1.53 ±0.01	a	1.53 ±0.02	b	3.6 *	1.2	2.9 *
Carbon content (g kg^{-1} soil)													
0-10	4.92 ±0.15	c	4.26 ±0.41	c	6.39 ±0.62	b	6.27 ±0.63	b	10.26 ±1.05	a	17.0 ***	2.1	13.6 ***
10-20	3.87 ±0.18	a	3.73 ±0.19	a	3.55 ±0.33	a	3.74 ±0.33	a	5.20 ±0.73	a	1.1	0.8	1.2
20-30	3.39 ±0.12	a	3.29 ±0.33	ab	2.73 ±0.09	bc	2.53 ±0.35	c	2.97 ±0.34	ab	5.5 **	20.3 ***	8.5 ***
30-40	3.33 ±0.27	a	3.08 ±0.22	ab	2.74 ±0.25	ab	2.88 ±0.26	ab	2.36 ±0.13	b	2.1	13.0 **	5.5 ***
0-40	3.87 ±0.09	b	3.59 ±0.20	b	3.85 ±0.17	ab	3.86 ±0.33	b	5.20 ±0.51	a	4.8 **	4.9 *	4.0 **
Carbon storage in equivalent soil mass (t ha^{-1})													
0-10	7.5 ±0.2	c	6.5 ±0.6	c	9.7 ±0.9	b	9.4 ±0.9	b	15.4 ±1.6	a	17.0 ***	2.4	13.7 ***
0-20	13.4 ±0.5	bc	12.1 ±0.8	c	15.2 ±1	ab	15.0 ±1.3	bc	23.1 ±2.5	a	9.1 ***	3.2	7.7 ***
0-30	18.3 ±0.4	bc	16.9 ±1.1	c	19.1 ±0.9	ab	18.6 ±1.6	bc	27.2 ±2.8	a	5.7 **	4.3 *	4.7 **
0-40	23.0 ±0.5	ab	21.3 ±1.2	c	23.0 ±1	ab	22.7 ±1.9	bc	30.6 ±2.9	a	4.2 **	5.1 *	3.5 *

See description of the treatments in Figure 3.1. Two mean values with different letters differ significantly in their LS means (α=0.05; pair-wise T-test). p{Ho: $F_{obs}>F_{th}=0$}: $^{*}<0.05$; $^{**}<0.01$; $^{***}<0.001$.
Texture stands for the soil relative mass of the [0-50] μm fraction mass determined without SOM destruction. The reference subplot for equivalent soil mass calculation was set as one of the GN03 field subplot. See data in Appendix 25.

C, N and P fluxes linked to organic inputs were computed for the Com, ComCor and ComCorWa fields (Figure 3.3). C input was estimated to reach 2.0 t ha^{-1} for the Com treatment in 1997. It amounted to 5.3 t ha^{-1} in the corralled plots (ComCor treatment), with high returns from ungrazed crop residue to the soil. This figure was close to that found for the ComCorWa treatment (6.3 t ha^{-1}), which benefited from household wastes and manure. Greater differences were found among the three treatments when considering N and P inputs. These inputs were 24.2 kgN ha^{-1} for the Com treatment, which was less than a fifth of those for the ComCor treatment. N input for the ComCorWa treatment was nearly twice that for the ComCor one. The same trends were recorded for P_t.

As a result, mean C:N ratios of organic inputs were respectively 84, 45 and 30 in the Com, ComCor and ComCorWa plots; C:P_t ratios were respectively 474, 257 and 169.

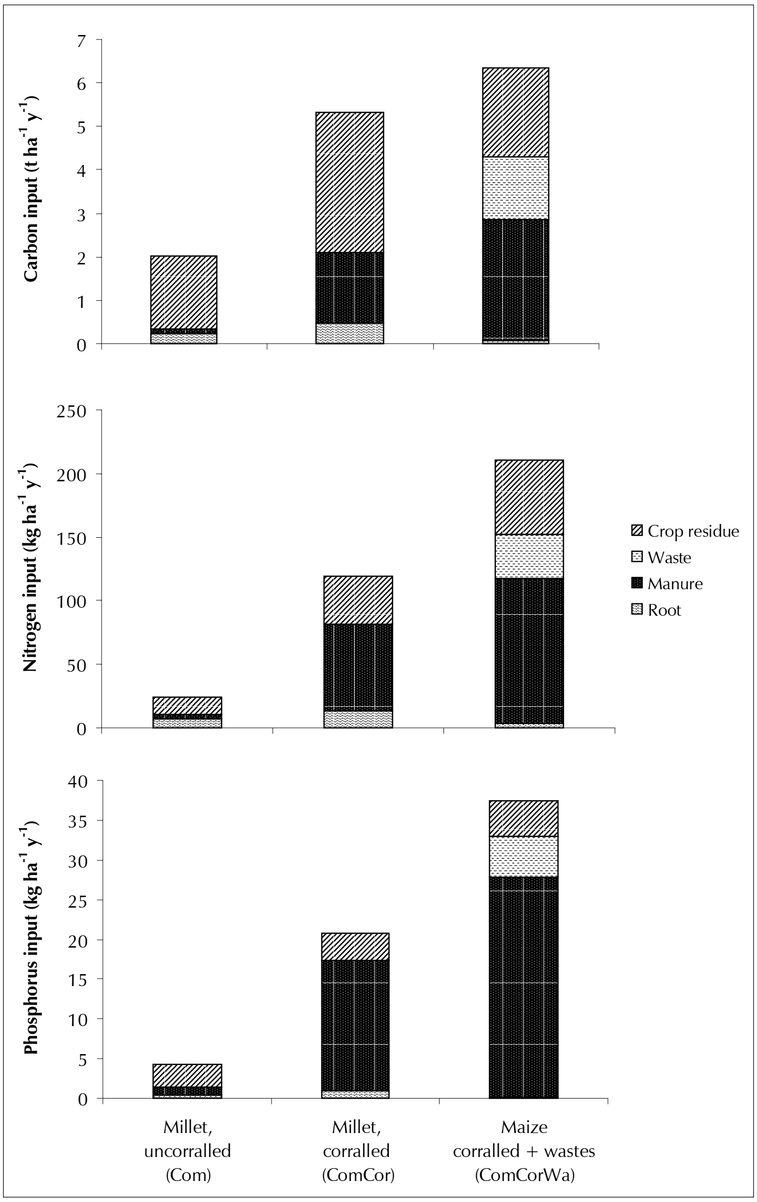


Figure 3.3 Carbon, nitrogen and phosphorus organic inputs in compound fields under three different patterns of organic management of fertility.
Assumption: (1) chemical composition of fresh dungs (g 100g^{-1} dry OM): C: 35 (de Ridder and van Keulen, 1990); N: 1.44; P_t: 0.35 (Hamon, in Coulomb et al.*, 1980). (2) 80 % of crop residues are returned to the soil as a result of trampling by livestock.*
Note: root exudation of C and biological fixation of N are not included.
See data in Appendix 26.

3.4. DISCUSSION

3.4.1. Biomass of cropped fields as a multi-purpose tool for farming

In the area, grains produced in cropped fields are either used for food needs (cereals) or commercialised (groundnuts). Because of the availability of wood and the shortage of labour power, crop residues are left on site. This is not the case for groundnut, which haulms are stored at the farmyard and given as feed supplementation to calves, oxen and small ruminants. Fields are left to common grazing after harvest. Stover feed value differs among cropped species. For instance, in our study millet yielded four times more biomass than groundnut, but groundnut, as a legume, stored more nitrogen. Weed feed value is more difficult to estimate, since it depends on advent species composition, and only a few studies have been devoted to it. However, higher N and P_t content in weeds than in stover (except in the groundnut fields), local observations on livestock foraging behaviour within the first days of common grazing (Chapter 5), and the findings of Lamers *et al.* (1996) all indicate a much higher feed value for weeds than for associated millet. Means for a better use of weeds as feed supplementation for animals should thus be worked out, if associated with less valuable forage such as cereal residues.

Common grazing leads to incomplete uptake of crop residues, due to trampling of weed and stover, and to tainting by urine. As a result, only 20 to 50 % of the biomass left on site would be browsed by livestock (Quilfen and Milleville, 1983; this work, Chapter 5). Common grazing saves labour, not forage, but it should be kept in mind that unbrowsed biomass is not lost for the ecosystem (see below).

Although often considered as the keystone of sustainable agriculture in savannas (Pieri, 1989; Brown *et al.*, 1994), published assessments of crop below-ground biomass in the subregion remain scarce. For sandy soils of the Sahelian zone, Chopart (1980) estimated root biomass of groundnut and millet at harvest to be 0.27 and 0.28 t ha^{-1}; this is only 7 % and 24 % of our findings, but these include root biomass of woody and herbaceous advents. Charreau and Nicou (1971) report higher root biomass for millet and maize (1.5 and 2.0 t ha^{-1}) than our estimate, and similar figures for groundnut. Millet and groundnut shoot:root ratios computed in the present study were also consistent with their results. However, relevance of such comparisons is limited, because carbon allocation by the plant to below-ground biomass is affected by many factors such as soil, climate, pest incidence, interactions with advent perennial rooting systems and sampling technique (Mordelet, 1993). Root biomass in successional ecosystems of the village rises up to 18.3 and 34.8 t ha^{-1} in young (< 10 years old), and old fallows (Chapter 1), being respectively 4.9 (young fallows) and 9.3 (old fallows) times higher than that of crops.

3.4.2. Land management & soil properties

Our general results are more or less consistent with those of Prudencio (1993) in Burkina Faso, who found that only the fields very close to the compounds exhibit improved soil organic status as compared to the bush fields. In a national survey conducted throughout Gambia, Peters and Schulte (1994) relate soil organic content improvement only in maize fields, that is those adjoining the compound. By contrast, C and N contents were not significantly different between millet and groundnut fields, which received none to little manure; in our study, C content was significantly higher in the millet compound fields than in the bush groundnut fields for the 0-10 cm layer only.

At a given time, the soil carbon content is the balance between organic inputs (residue, dung, waste) and outputs (harvest, grazing, fire, mineralization), thus leading to the concept of a minimum threshold value of carbon input for the maintenance of SOM content (de Ridder and van Keulen, 1990). This value depends on local soil and climate conditions that drive erosion and leaching effects (Brouwer and Powell, 1998), and SOM turnover rates (Feller, 1993).

3.4.2.1. Influence of soil intrinsic properties

In our study, the control of silt+clay size particles over carbon content, well demonstrated in tropical soils, has been evidenced in soil layers below 20 cm only. Land management was clearly the main source of variation of chemical properties in the 0-20 cm layer. Vertical zoning of the influence of texture and management was also demonstrated to happen under semi-permanent cultivation (see Chapter 2). On a methodological point of view, further studies on the influence of land management on soil organic status conducted under similar soils in West Africa could be restricted to the 0-20 cm layer.

3.4.2.2. Soil chemical status of cropped fields in compound & bush rings

Improved chemical soil properties in the compound ring, as compared to the bush ring, stem mainly from different levels of organic inputs. These inputs improve soil chemical properties in three different ways: (1) they are a net source of carbon and nutrients (2) they contribute to a larger extent to the gain in CEC (3) they stimulate biological mechanisms (Feller, 1995a; Asadu *et al.*, 1997). For instance, the increased availability of an element such as phosphorus can result as well from an increased amount of P_t -which is probably the case here, at least in heavily manured fields, but further measures of P_t are needed- or from the release of unavailable P previously adsorbed on clay and released by substitution with organic compounds or modification of soil pH (Jones and Wild, 1975; Feller, 1995a).

The way SOM improves soil properties depends on its location in soil size fractions (Feller *et al.*, 2000). In tropical soils with 1:1-type clay, stable SOM complexed with clay and silt in the [0-50] µm fraction drives the capacity of storage and exchange of nutrients. Our findings are consistent with these features, since pHKCl, Ca, Mg, K, CEC and S were more strongly correlated to the C content of the [0-50] µm fraction than to that of the [50-2000] µm fraction. The low C:N ratio of the fine fraction also testifies that organic matter from this fraction consisted of organo(humic compounds)-mineral complexes. Carbon stored in the fraction [50-2000] µm is usually reported to have a higher turnover rate and to carry biological functions (supply of energy and nutrients to soil microflora and macrofauna). Our results agree with the general findings, since the organic compounds isolated in the [50-2000] µm fraction had a high C:N ratio (29), indicative of newly incorporated vegetal debris, likely to be oxidised by microbiological catabolism.

For the compound fields, the contribution of these fractions to the increase of SOC was equivalent (except in maize fields). However, in sandy tropical soils, variations of C content due to land management are generally reported to occur mainly in the coarse fraction (Feller and Beare, 1997). The date of sampling might be put forward to explain such a discrepancy between our results and some other studies. Sampling was performed at the end of the rainy season, when massive seasonal SOM mineralization is likely to occur, mostly in fractions having high turnover.

3.4.2.3. Quality of organic inputs

The SOC content depends not only on the local climate and soil conditions but also the amount and chemical quality of the organic matter added to the soil. The effect of manuring alone on soil carbon status is generally reported to be null or little (Schleich, 1986; Diouf, 1990), or moderate, and limited to the subsoil (Powell, 1986; Bacyé, 1993; Feller, 1995a). But imprecise information on manuring intensity render comparisons between other works and ours difficult.

In our study, two treatments (Com and ComCor) receiving different amounts of carbon stored similar quantities of SOC, while two treatments (ComCor and ComCorWa) receiving the same quantities of carbon exhibit different SOC storage (Figure 3.1, Figure 3.3 and Table 3.7). Differences in C:N and C:P ratios of these amendments might explain these results, since these ratios play a key role in the decomposition of organic residues.

Under drier conditions Feller *et al.* (1981; 1987) have already shown that adding mineral N to straw and compost amendments significantly stabilised SOC content. Higher N content of organic inputs prevents microflora from mineralising SOM, which has usually a higher N content than fresh plant biomass (Pieri, 1989). Biochemical properties of structural carbon ("neutral detergent fibre:cellular content" ratio as recommended by Feller, 1979) or enzyme content (Mathur, 1982) might also account for the various effects of stover, roots, household wastes and manure on SOC content.

3.4.3. An insight at the village scale: agro-ecological complementarity of semi-permanent & continuous cultivation

On our study site, continuous cultivation and associated organic practices of agricultural intensification have a stronger effect than fallowing on improving soil chemical status (see Chapter 2). Differences are especially striking when considering P_{OD}, Ca, K, CEC, S and pH evolution. However, the improvement of these variables is restricted mainly to the 0-10 cm layer, except for P_{OD}. On the other hand, the maintenance of good soil properties in the compound ring relies mostly on the conservation of bush and savanna rings. Indeed these zones harbour cattle during the wet season, where they feed, avoiding therefore any damage on cropped fields. And during the dry season, they provide farmers with manure since about 60 % of the forage needs by cattle originate from the vegetation of this area (Chapter 5). The potential of livestock-mediated organic transfers to balance nutrient exportation at harvest has been well demonstrated for areas drier than the region of Kolda (de Leeuw *et al.*, 1994; Powell *et al.*, 1996; Buerkert and Hiernaux, 1998). Inputs of nutrients to the compound ring are not only mediated by manure but by crop harvest, as well as fuelwood collecting, which represents a great loss of phosphorus for local fallow ecosystems (Chapters 1 and 5).

One should keep in mind that even a few years of fallow increase soil C, N, P_{OD}, Mg and CEC, provided that the resprouting capacity of woody advent had been kept by the conservation of long breaks of fallow (Chapter 2). For instance, C content of the 0-20 cm soil layer reaches 5.2 g kg^{-1} in fallows aged 1-10 years, which compares fairly well with that of fields of the compound ring (5.9 g kg^{-1}).

3.4.4. Methodological considerations: relevance of SOM as an indicator of soil quality & agricultural sustainability

The study of carbon allocation and dynamics in the permanent cropping ring of the village and in peripheral semi-permanent cultivation (Chapter 2) calls into question the link between soil organic matter status as defined by the soil carbon content, and fertility of the savanna agro-ecosystems, and to a larger extent the sustainability of agricultural practices.

Under temperate climates, where frigid to thermic soil temperature regimes prevail, SOC content has proved to be well related to soil quality and ecosystem health (Gregorich *et al.*, 1996), and even to crop yields (Bockstaller *et al.*, 1997). In the tropics, its usage has been seriously criticised (Sanchez and Miller, 1986; Greenland *et al.*, 1992; Crétenet, 1996), an attitude supported by the difficulties in defining the optimal value of SOM as an indicator of sustainable soil quality (Pieri, 1989; Almasie, 1996). The agroecological interpretations of SOC content without methodological considerations are questionable and limited in the sandy soils of West-African savannas for two main reasons.

(1) Soil total carbon content provides only limited information about the agroecological role of carbon in tropical sandy savanna soils.

Except in mountain areas or for chemically well-endowed soils, the productivity of tropical ecosystems is not temperature-, but nutrient-limited during the growing period (Murphy and Lugo, 1986; Anderson and Spencer, 1991). This is particularly true in West African savannas (Jones and Wild, 1975; Pieri, 1989). Savanna ecosystems experience considerable dissipation of auxiliary energy, which leads to low nutrient availability and destabilisation of soil structure (leaching, crusting and erosion). Due to coarse texture and weak organic matter content, soil physical properties (stability and porosity) rely very much on soil biota (perennial rooting systems), and on organo-mineral complexes bound by biogenic glues with high turnover resulting from faunal (mostly termite and earthworm channels and casts) and microflora activities. Biota response to the climate and soil constraints has also been a conservative management of nutrients, protected either in root biomass or in stable organic compounds (Menaut *et al.*, 1985). Therefore biological mechanisms have a crucial position in processes leading to plant nutrition. They might be considered as a substitute for weak chemical mechanisms of nutrient cycling, because of low CEC of the sandy soils. Live biomass and biological activity thus exert a strong control over physical properties and over the dynamics of nutrients in savanna soils of West Africa (Chotte *et al.*, 1995).

This has three implications. First, characterising SOM quality is needed for a better agroecological diagnosis of soil quality as assessed from the study of soil organic status. This study clearly indicated that the coarse size fraction ([20-2000] or [50-2000] μm) is the most relevant fraction to be studied (Feller *et al.*, 2000). However, for an accurate assessment of soil biological "fertility" under tropical climate such as the one of our study site, organic status of this fraction should be characterised precisely at the beginning of the rainy season (see below). Secondly, in this region, the contribution to soil organic status of its biological components is of great importance (i.e. fauna inventory, microbial biomass and root biomass); the root component should also be included in SOC computation. Thirdly, a "fertile" savanna soil should be viewed as a living, dynamic system. Recent advances in thermodynamics applied to ecosystem theory suggest that living systems be approached as open, self-organised systems kept far from thermodynamic equilibrium (death). This implies the establishment of a continuous energy flow through the soil system (Toussaint and Schneider, 1998), necessary coupled with matter (carbon) dissipation (Straskraba *et al.*, 1999). In this way, withdrawal of carbon from the soil system through faunal and microbial catabolism and termite-induced spatial redistribution, and subsequent low carbon sequestration potential of soils, should be seen as the price to pay for the maintenance of soil organisation and proper functioning (Perry *et al.*, 1989). In this perspective, emphasis should be put on carbon flows (as assessed directly by carbon gaseous emissions, or indirectly by fine root and litter production measurement), and not only on stocks. A shift is yet to be made from a static/structural to a dynamic/energetic conception of the role of organic matter, as a support for nutrient-limited tropical agro-ecosystems.

(2) Influence on SOC of other factors unrelated to the management practices

Variability of soil physical inherent properties such as texture can lead to inaccurate agro-ecological diagnostic when considering soil carbon content alone. To overcome such a drawback, Feller (1995b) has proposed to linearly relate SOC to the clay+fine silt content as a potential indicator to assess the quality of tropical soils with low-activity clay. Applying the relation to the 23 field and fallow plots described in this study and in Chapter 2 would attribute good soil quality to two thirds of the plots (Figure 3.4). But while proving satisfactory for the compound fields, the criterion does not allow for segregation between bush fields and old fallow plots, which are more fertile according to farmers.

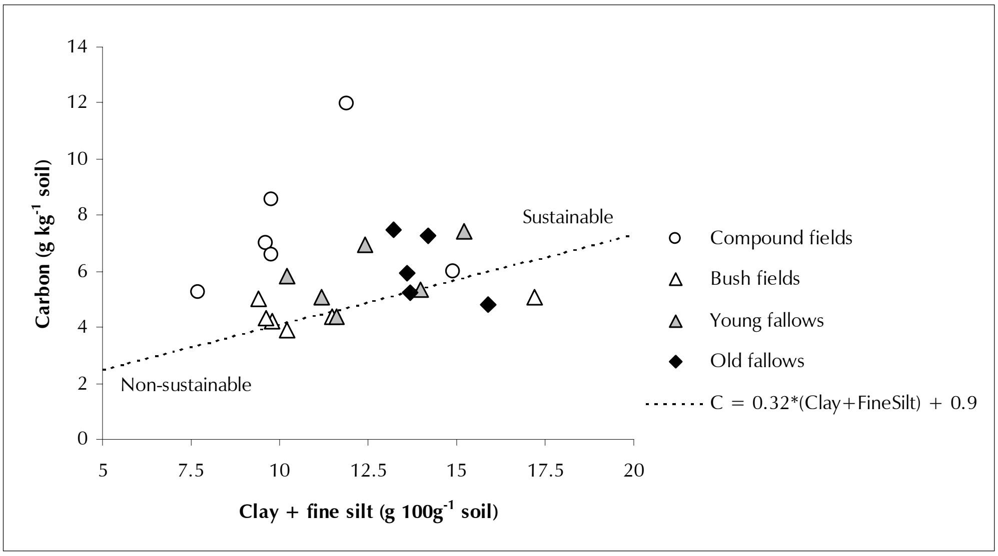


Figure 3.4 Assessment of soil quality of 23 crop and fallow plots (this study and Chapter 2) as predicted by Feller's criterion (1995b) based on carbon content and fine texture.
Young fallow: aged 0-9 years. Old fallow: older than 9 years.
See data in Appendix 27.

Another often-neglected factor influencing SOC is the date of sampling. Van't Hoff's law – which states that temperature and kinetic constants of chemical reactions increase together – leads indeed to higher SOM turnover rates under tropical climate than under temperate one (Jenkinson and Ayanaba, 1977; Greenland *et al.*, 1992), and thus to possible great seasonal variations of total SOC content. Apart from Fearnside and Barbosa (1998), only few authors warned of this feature of tropical soils. This misconsideration is well illustrated by the lack of indications about sampling dates in most SOC-related field studies. To our knowledge, no exhaustive methodological study has ever been undertaken about interseasonal variations of SOC. However, interannual variations have been found to reach 80 % from one year to another in shifting cultivation plots on seasonally flooded, Amazonian plains (Zarin *et al.*, 1998). In a humid fallow succession of India, Saxena and Ramakrishnan (1986) report seasonal variations of SOC up to 40 % in the 0-10 cm layer. The same authors recorded a 30 % loss of SOC six months after fallow conversion to crop. Feller (1981) indicated a decrease of 20 % of the carbon content within the four months after sowing millet in a pot experiment in Senegal. In fact, the date of sampling might be of particular importance in the determination of SOC content in sandy soils of West African savannas because:

- root biomass carbon significantly contributes to total below-ground organic carbon storage. This contribution would reach up to 30 % in fallows of the study site (Parts I and II).
- carbon amounts in, and annual flows through the soil are of the same order of magnitude. In our study, carbon inputs can represent significant amounts as compared to the amount of carbon in the 0-20 cm layer of compound fields (not including exsudation and pre-harvest mortality of roots). Schaefer (1974) demonstrated that annual C-CO_2 emissions from a ferruginous soil of an Ivorian subhumid savanna could amount up to 75 % of the organic carbon stored in soil.
- carbon inputs in fallow and savanna cropped ecosystems are highly pulsed in time (Menaut *et al.*, 1985).

We therefore suggest that the coarse texture of the soils of our study site alone may not fully account for the weak potential of carbon storage in the different agro-ecosystems reported in Chapter 2 and here (excepting organically well-endowed fields adjoining compounds) at the end of the wet season. We put forward the possible levelling of below-ground organic stocks at the onset of the rainy seasons due to soil moisture replenishment. This hypothesis is supported by our results on SOM fractionation (see 3.3.4.2. and Chapter 2).

3.4.5. Organic matter management in savanna cropping systems & the global carbon cycle

Limited perspectives for soil carbon sequestration enhancement in traditional cropping systems of the West African savanna belt are suggested by this study. Apart from intrinsic soil properties, reasons for this are (1) the limited stability of organic carbon gains in soils following intensive manure and residue management, (2) the high levels of carbon inputs required, that remain far from organic matter availability in the subregion (Williams *et al.*, 1995).

Because sustainable and manageable sequestration of carbon can occur mainly in live woody biomass, agroforestry practices such as hedgerow planting, parkland rehabilitation and improved fallows, associated with local mineral fertilizer such as rock phosphate could be recommended. Woomer *et al.* (1998) estimated that such low-cost improvements could double the amount of carbon stored in the whole agricultural system in East African Highlands.

However, the contribution of savanna ecosystems to global mitigation of carbon gaseous release should not necessarily imply local sequestration of carbon, especially if it does not lead to immediate cash income to farmers (Brown and Lugo, 1990). Setting people in savannas is a means to prevent further deforestation and subsequent carbon release in close, wetter ecozones. This can be achieved by sustainable intensification of cropping. Favouring carbon sequestration, through the adoption of crops and trees with stronger rooting systems, the development of perennial plantations and the use of fertilisers, is relevant of course (Woomer *et al.*, 1998). But maximising carbon fluxes through the system also prevents it from ecological crash. For this purpose, more efficient ways of managing organic resources aimed at limiting carbon losses during short biogeochemical cycles (fire, residue sale) should be adressed. Nevertheless, the success of such practices will rely very much on a better integration of livestock to crop strategies, and the adoption by the farmers of agricultural practices such as hay-making, cover crop, slash-and-mulch, compost or no-till practices. Organic management of soil biological "engineers" such as termites and earthworms is promising too (Lavelle *et al.*, 1998; Mando, 1998). The tighter savanna cropping systems will mimic natural ecosystems in the way they store and recycle carbon, nutrients and energy, the more sustainable they will be (Brown and Thomas, 1990).

At the same time, operational appraisal of carbon and nutrients availability and management options should be evaluated at the holding and village scale, given the collective organisation of land tenure and social structures in West Africa (Defoer *et al.*, 1998; Woomer *et al.*, 1998) (Chapters 4 and 5).