Chapter 2.

Carbon, nitrogen and phosphorus allocation in agro-ecosystems of a West African savanna.

II. The soil component under semi-permanent cultivation

Root and soil sampling in a six-year old fallow

Chapter 2. CARBON, NITROGEN & PHOSPHORUS ALLOCATION IN AGRO-ECOSYSTEMS OF A WEST AFRICAN SAVANNA - II. THE SOIL COMPONENT UNDER SEMI-PERMANENT CULTIVATION

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ABSTRACT

The evolution of soil properties under semi-permanent cultivation was followed through a groundnut crop-fallow chronosequence located in the West African savanna belt. Special emphasis was put on contents and amounts of carbon (C), nitrogen (N) and available phosphorus as measured by Olson modified by Dabin (1967) (noted P_{OD}).

Soil physical properties (texture, pF, density) remained steady among all plots. Significant increases of C, N, and magnesium as a consequence of crop abandonment were statistically evidenced down to 20 cm deep only (texture being the main factor driving soil properties below). The amounts of C in the 0-20 cm soil layer were 12.2±0.6 (standard error) t ha^{-1} in groundnut cropped plots (n=6), 15.8±0.8 t ha^{-1} in young fallows (1-9 years old; n=6) and 14.9±0.8 t ha^{-1} in old fallows (n=5). Amounts of N were respectively 1.00±0.05, 1.30±0.08 and 1.28±0.05 t ha^{-1}. P_{OD} stocks amounted to 6.47±0.56, 8.47±0.82 and 6.19±0.64 kg ha^{-1}.

The unexpected fast evolution of soil properties after crop abandonment was attributed to fast recovery of woody vegetation. Practices of improvement of, or substitution for fallowing that should save the resprouting capacity of trees are thus needed. However, the steadiness of soil chemical properties in oldest fallows as compared to young fallows was not expected too. It was attributed to the poor protection of soil organic matter from oxidation by biological activity. This was confirmed by mesh-bag experiments, which indicated that more than 40-60 % of decaying woody root biomass disappeared after 6 months of *in-situ* incubation. Biologically mediated fast cycling patterns of C, and thus of N and P organic inputs to the soil, could be better indicators than soil C and nutrient storage to assess the restoration of sandy soils fertility during the fallow period in West African savannas.

KEY WORDS

Carbon, Nitrogen, Phosphorus, Root, Savanna, Senegal, Semi-permanent cultivation, Soil

2.1. INTRODUCTION

Mixed farming systems with low inputs are widespread in West African savannas (Ker, 1995). Their sustainability relies mostly on low population density and on management of organic resources (manuring and fallowing). Under traditional semi-permanent agriculture a field would be cropped during a few years, then left to fallow for 15 to 20 years, depending on soil, climate and human context (Nye and Greenland, 1960). Fallow would be meant to replenish the fertility of the agro-ecosystem, and provide food, wood and forage (Floret *et al.*, 1993).

As a result of fast demographic growth, uncertainty about land tenure, and technological improvements, which increase the efficiency of human labour, West African savannas experience a growing need for land. Thus, traditional organic practices that were fitted to low population density undergo a shift towards more intensified practices, resulting in long to short fallow rotation and in extension of permanent cultivation. Because of the subsequent and progressive shortening of the fallow period encountered in tropical Africa (Floret *et al.*, 1993; Gleave, 1996), improvements or alternatives of the practice of fallowing are needed; but such proposals must take into account the multiple functions of fallowing. Assessment of carbon (C), nitrogen (N) and phosphorus (P) allocation among the different components of the ecosystem is a prerequisite to any proposal for the transformation of existing cropping systems. The sustainability of these systems -like that of local natural ecosystems- still mostly relies on proper cycling of endogenous energy and nutrients.

The present paper is involved with soil C, N and P budgets during the crop-fallow cycle. A study of the dynamic of plant biomass undertaken in southern Senegal indicated that young fallows (aged less than 10 years) experienced fast accumulation of C, N and P in vegetation, most of it happening during the first year of fallow (Chapter 1). Increase in old fallows was much slower, but maintaining long periods of fallowing was necessary to preserve the productivity recorded at early stages of the succession, since it relied mostly on the capacity of stump resprouting. While much of N and P is lost from the system at clearing due to burning and wood harvest, the evolution of soil properties must be assessed as an indicator of the ecosystem fertility. In the chemically poor soils of the Tropics such as those of West African savannas, these properties largely hang on organic inputs (Swift and Woomer, 1993; Brown *et al.*, 1994). C, N and P status have been considered as reliable indicators of the fertility of savanna soils for a long time (Nye and Greenland, 1960; Jones and Wild, 1975). In heavily leached sandy sub-Saharan soils indeed, chemical (pH, cation exchange capacity or CEC) and physical (porosity, stability) properties rely heavily on soil organic matter (SOM) content (de Ridder and van Keulen, 1990; Feller, 1995a; Asadu *et al.*, 1997), even though soil organic carbon storage capacity is highly limited by coarse texture (Pieri, 1989; Feller and Beare, 1997). Moreover, organic matter is the main source of energy for below-ground biota, thereby driving biological fertility (Herrick and Wander, 1998). Carbon pools with different functions and turnover can be isolated using simple size-fractionation of SOM (Feller *et al.*, 2000). Meanwhile, N and P are recognised to be the most limiting nutrient factors to plant productivity in African savannas (Jones and Wild, 1975; Bekunda *et al.*, 1997). Their cycle is closely linked to SOM dynamics: much of available N and P is stored in the vegetation and made available to plants after microbial oxidation of fresh organic inputs. Published studies of C, N and P dynamics in soil under semi-permanent or shifting cultivation in dry West Africa are still few and, except the work of Tiessen *et al.* (1998) and Harmand *et al.* (2000), rather concern humid climates (Nye and Greenland, 1960; Kotto-Same *et al.*, 1997). On the other hand, much has been done on the impact of clearing of primary vegetation over soil properties, but little is known about that impact on the dynamics of below-ground plant biomass. When fallow is manually converted to crop, only rooting systems are spared (Floret *et al.*, 1993). Woody stumps allowing for regular resprouting survive several years before they die (Bohringer *et al.*, 1996). Removing stumps is however becoming a common precondition for cropping in West African savannas due to expanding mechanised tillage. This practice calls into question the sustainability of semi-permanent cultivation, since it has proved to severely damage soil physical and chemical properties (Hulugalle, 1994). But the fast decay of woody rooting systems that may be suspected for such an evolution has hardly been quantified in slash-and-burn systems of the dry tropics.

This work is the second of a series of three chapters aimed at quantifying carbon (C), nitrogen (N) and phosphorus (P) allocation in agroecosystems under continuous and semi-permanent cultivation as practised in a village of southern Senegal. The previous chapter dealt with C, N and P storage in plant under semi-permanent cultivation. In the third chapter, C, N and P storage are assessed in the plant and soil components under continuous cultivation.

Here we (a) compare patterns of soil C, N and available P storage through a crop-fallow chronosequence in a West African savanna and relate them to other soil properties (b) define temporal thresholds of evolution for these elements during the fallow period (c) quantify post-fallow decay of rooting systems and related N and P inputs to the soil.

2.2. METHODS

2.2.1. Site characteristics

The study has been undertaken between 1995 and 1997 in the village of Sare Yorobana (12°49'N – 14°53'W), High Casamance, southern Senegal. A detailed description of climate, vegetation and agricultural practices was given in Chapter 1. The climate is Sudanian, tropical dry (mean annual rainfall during the last 20 years: 960 mm 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). Semi-permanent agriculture is practised at the top of the typical, smooth toposequence. Two land use units are concerned:

(1) a plateau covered with a mosaic of woodlands, savanna, fallows and bush fields, anthropogenic formations being encountered mostly at the fringe of the plateau (Akpo, 1998). Soils were described as sandy ferruginous by Baldensperger *et al.* (1967) and are classified as ferric Lixisols (FAO, 1998b) (see Appendix 4 for a detailed description of a typical soil profile). Analyses made in 17 plots of the crop-fallow succession (see Methods below), indicate that texture is sand-loamy in the 0-20 cm layer, sand-clay-loamy in the 30-40 cm layer. Carbon content averaged 5.5±0.3 g kg^{-1} (± standard error) of soil in the 0-10 cm layer, 4.1±0.1 g kg^{-1} in the whole profile (0-40 cm). Respective nitrogen contents were 0.44±0.02 and 0.36±0.01 g kg^{-1}. Available phosphorus content was 2.7±0.2 and 2.0±0.1 μg kg^{-1}. Other main properties were: slight acidity (pHH_2O:5.5±0.1); CEC: 2.5±0.1 and 3.0±0.2 meq 100g^{-1} of soil in the 0-10 and 30-40 cm layers respectively, with saturation rate decreasing from 85±5 to 60±6 % from the 0-10 to the 30-40 cm layer; pF 4.2: 3.1±0.2 % in the 0-10 cm to 7.7±0.6 % in the 30-40 cm layer; bulk density: 1.50±0.01 kg dm^{-3} in the whole profile,

(2) a glacis, with soils similar to those from the plateau (haplic Lixisols), but with slightly less clay accumulation below a 30-cm depth. This unit bears all permanent crops and the compounds.

Sedentary Fulani herdsmen have adopted a diversified agriculture (rainfed and flooded cereals, groundnut and cotton cash crops) closely associated with extensive livestock raising.

2.2.2. Sampling schemes

A time-saving, synchronic method was adopted: neighbouring crop and fallow plots of different ages can be considered as the representatives of the same plot during the succession, assuming they share similar soil properties and land-use history (Sanchez, 1987).

The sampling was done at the onset of the dry season, close to peak above-ground biomass in fallows, or just before harvest in the groundnut fields.

Due to vegetation patterns, two designs were adopted, depending on land use:

(1) Groundnut plots (coded as GN): six fields that had been cropped with groundnut (*Arachis hypogaea* L.) in a biennial rotation with fallow or sometimes pearl millet for four to 15 years and that had never been chemically fertilised, were chosen. Four (GN01, GN02, GN03 and GN05) of them were located on the plateau, two (GN04 and GN06) on the upper glacis. In each of them, four 16-m^2 square subplots were randomly defined. After the clearing of vegetation, soil samples were taken from small pits dug at each subplot corner for soil analyses and bulk density. Bulk density was measured using a 100-cm^3 cylinder,

(2) Fallow plots (coded as FA), uncropped for one to 26 years (see Chapter 1 for the distribution of sampled plots according to fallow length). Soil was sampled for soil analyses and bulk density in a pit every meter along a 20-m long transect, in 11 plots.

For each situation, soil and bulk density were taken in 10-cm increments to a 40-cm depth. Deeper samples would not have modified our interpretations, since soil properties are not influenced by land use below this depth (Detwiler, 1986; Feller, 1995a).

2.2.3. Soil analyses

Soil samples were cautiously sieved (at 2 mm) and oven-dried at 105 °C for 24 hours. Samples were pooled and one analysis was made per each plot and/or soil layer. Soil pH was measured using a 1:2.5 soil/water or KCl solution. Total C and N from size fractions were determined by wet combustion (Fisons elemental analyser Na2000 Carlo Erba); total C of non-fractionated (NF) soil was measured after dichromate oxidation. N was determined with the Kjeldahl method, soil available P with the Olsen method modified by Dabin (1967); soil total-P was not determined, and "P_{OD}" will stand for " soil available-P" (in the way we measured it) in what follows (phosphorus in plant biomass refers to total P and will be noted P_t). Exchangeable cations were extracted with CH_3COONH_4 at pH=7. CEC was measured by saturating soil with $CaCl_2$, $2H_2O$ then exchanging Ca with K. Volumetric water content was determined at a suction equivalent to pF2.5 (0.322 atm) and pF4.2 (14.5 atm). All methods are fully described in Page *et al.* (1989).

Amounts of C, N and P_{OD} in soil were obtained from soil bulk density measures and C, N and P contents (Table 2.1). Because no significant differences in bulk density values between treatments were found (see 2.3.1.), soil element budgets and statistics were calculated for soil equivalent depth only, and not for soil equivalent mass as recommended by Ellert and Bethany (1995). Size fractionation of SOM was performed on fractions [0-50] and [50-2000] µm of samples of the 0-10 and 10-20 cm layers, according to the simplified, wet-sieving method from Gavinelli *et al.* (1995). 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. C content of both fractions allowed to estimate the partitioning of C storage between coarse and fine fractions, assuming that losses of water-soluble carbon due to wet fractionation were negligible and that bulk density of both fractions was equal.

Table 2.1 Soil C, N, and P_{OD} content, C:N ratio and modified [0-2000] µm bulk density in groundnut (GN) and fallow (FA) plots.

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
FA01a	5.82	4.20	3.02	2.48	3.88
FA01b	7.42	4.90	3.90	4.12	5.09
FA01c	5.09	3.91	3.67	4.00	4.17
FA02a	4.40	4.34	3.25	3.01	3.75
FA04	6.96	4.27	4.36	3.77	4.84
FA07a	5.35	5.29	4.95	4.01	4.90
FA12	7.49	3.58	3.45	3.11	4.41
FA13a	4.82	4.24	4.16	4.00	4.31
FA17	7.27	4.02	3.44	3.74	4.62
FA18a	5.25	3.57	3.10	3.22	3.78
FA26	5.96	3.36	3.40	4.49	4.30

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
FA01a	0.58	0.37	0.31	0.23	0.37
FA01b	0.58	0.43	0.34	0.39	0.43
FA01c	0.40	0.32	0.32	0.39	0.36
FA02a	0.37	0.33	0.28	0.27	0.31
FA04	0.46	0.35	0.32	0.28	0.35
FA07a	0.54	0.40	0.42	0.39	0.44
FA12	0.54	0.38	0.35	0.37	0.41
FA13a	0.47	0.39	0.39	0.38	0.41
FA17	0.51	0.36	0.32	0.30	0.37
FA18a	0.51	0.32	0.29	0.32	0.36
FA26	0.46	0.30	0.33	0.38	0.37

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
FA01a	4.7	2.9	2.3	3.3	3.3
FA01b	3.7	2.6	2.1	2.2	2.7
FA01c	2.9	2.6	2.0	2.5	2.5
FA02a	2.3	1.4	0.9	0.8	1.4
FA04	2.8	2.2	1.5	2.0	2.1
FA07a	2.7	2.5	2.1	1.2	2.1
FA12	2.2	0.7	0.7	0.5	1.0
FA13a	2.0	2.5	2.1	1.3	2.0
FA17	2.3	1.0	0.8	0.9	1.3
FA18a	2.8	2.3	1.2	1.2	1.9
FA26	2.6	2.2	1.7	1.3	2.0

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
FA01a	10.0	11.5	9.8	10.8	10.5
FA01b	12.7	11.5	11.5	10.6	11.7
FA01c	12.7	12.2	11.7	10.4	11.7
FA02a	11.9	13.2	11.6	11.1	12.0
FA04	15.1	12.2	13.6	13.5	13.7
FA07a	9.9	13.2	11.8	10.3	11.2
FA12	13.9	9.4	9.9	8.4	10.8
FA13a	10.2	10.9	10.7	10.5	10.6
FA17	14.3	11.2	10.8	12.5	12.4
FA18a	10.3	11.1	10.7	10.1	10.5
FA26	13.0	11.2	10.3	11.8	11.7

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
FA01a	1.50	1.54	1.45	1.48	1.49
FA01b	1.54	1.54	1.47	1.46	1.50
FA01c	1.61	1.50	1.55	1.51	1.54
FA02a	1.51	1.56	1.52	1.56	1.54
FA04	1.46	1.55	1.49	1.52	1.51
FA07a	1.47	1.57	1.54	1.51	1.52
FA12	1.56	1.51	1.52	1.55	1.54
FA13a	1.53	1.48	1.41	1.64	1.51
FA17	1.45	1.55	1.44	1.36	1.45
FA18a	1.50	1.52	1.51	1.53	1.52
FA26	1.45	1.51	1.50	1.42	1.47

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.
The age of the fallow plots is mentioned in plot coding

2.2.4. *In situ* root decomposition

Post-fallow root dynamics after stump removal was assessed with a mesh-bag decomposition experiment. Roots of *Combretum glutinosum* Perr., the most widespread tree species in fallows of the region, were sampled at the end of the dry season, washed, oven-dried at 70 °C to a constant weight and sorted in three diameter-classes ([0-2] mm, [2-5] mm and [5-10] mm). They were put in stainless-steel 3-mm mesh bags filled up with local soil and buried 15 cm deep in a 15 years old fallow plot at the onset of the rainy season. Vegetation was cleared and soil left bare during the whole experience. Twenty bags of each diameter class have been removed every six months, for two years. Remaining roots were washed under water and oven dried before weighting. Initial and final ash contents were measured after calcination during three hours at 500 °C. The decomposition rates determined from this experiment were then applied to estimate tree root decomposition occurring after the clearing of a young and an old fallow, assuming that (1) stumps were killed or removed (2) the decomposition rate remained constant whatever the soil depth down to 40 cm and the woody species to which the roots belonged (which was confirmed in a running experiment with roots of the three other main woody species of the ecozone, unpublished data). The initial root biomass of these hypothetical fallows was set as the mean value found for young fallows (aged 1-9 years) and old fallows (aged 10 years and more) on the study site (see Chapter 1).

2.2.5. Data analyses

Statistical analyses were done using SAS software 6.14 (Hatcher and Stepanski, 1994) except principal component analyses (PCA) that were computed with ADE 4 software (Thioulouse *et al.*, 1997).

Multivariate analyses were performed in each soil layer by computing Spearman R_S correlation coefficients (proc CORR) for the following soil variables: C (total, and in fine and coarse fractions for layers 0-10 and 10-20 cm only), N, P_{OD}, pH in H_20 and KCl, Ca, Mg, Na, K, CEC, S, five-fraction granulometry + sand, clay, clay+fine silt, clay+silt, pF 2.5 and pF 4.2. PCA were computed on the correlation matrix of the table containing 18 lines as cropped and fallow plot replicates, and 24-26 columns as variables listed above.

Using the synchronic method theoretically requires that properties inherent to soil and likely to drive the values of tested parameters be the same among all plots of the chronosequence. This condition is seldom fulfilled in field experimentation. However, such a variable may be introduced as a covariate in the linear model used for the analysis of variance (Anova), assuming that the range of variation of the variable is not too wide, so that bio-physical processes remain roughly the same between plots and differ only in their intensity. The works of Jones and Wild (1975), Feller (1993) and Zech *et al.* (1997) indicate that particular attention must be paid to texture as a possible bias for statistical interpretations trying to link SOM status to land management. Following the findings of Feller (1993), we introduced the clay+fine silt content as a covariate in Anovas. Results from Chapter 1 demonstrated that a threshold for the biomass of most plant components was reached after 10 years of fallowing on the study site. We thus clustered plot replicates in three groups: groundnut crop (GN), young fallows (YF) aged less than 10 years, and old fallows (OF) under which slow plant biomass accumulation occurs. Proc GLM was used 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). Pair-wise t-tests were performed on least-square means in order to segregate treatments that had different effects on the level of the variable tested (α=0.05).

2.3. RESULTS

2.3.1. Soil properties & fallow succession

Correlation analysis indicated the following statistically significant links between variables for each of the following soil layers:

- 0-10 cm: C (total, and in fine and coarse fractions) and N were highly positively correlated (R_S=+0.69** to +0.92***) (Appendix 9a). Other chemical variables such as pHKCl, Ca, Mg, CEC and saturation rate (S) were also well positively related to total C and N (R_S=+0.49* to +0.79***). Clay + Fine silt was positively correlated with total C (R_S=+0.50*) and to N (R_S=+0.63**). pF4.2 was positively related to clay for every layer, especially the deepest ones. PCA showed that the first principal component (PC) (relative inertia or RI: 35 %) was characterised by C, N, Mg and CEC on the negative side, and sand on the positive side; old fallows (associated with good SOM status) were separated from groundnut crops (Figure 2.1a,b). P_{OD} was the main contributor to the second axis (RI: 16 %) and isolated young fallows from other plots. The third axis (RI: 15 %) was determined by texture but did not allow to distinguish differences between the three stages of succession (GN, YF, OF) (Appendix 10a),
- 10-20 cm: neither C nor N were correlated to any variable, except CEC (Appendix 9b). But correlations were found for Clay+fine silt with CEC (R_S=+0.52*), and S (R_S=-0.53*), and pH (R_S=-0.67**to -0.71**). Clay, Clay+fine silt and Coarse sand were the main contributors to the first PC lying on the negative semi-axis, as opposed to pH and Ca (Figure 2.1c). PCA performed in this layer and in deeper ones did not allow for any possible distinction between GN, YF and OF plots (Figure 2.1d; Appendix 10a),
- 20-30 cm and 30-40 cm: C, N, pH, CEC and S were strongly (R_S=-0.55* to +0.93***) related to fine elements (Appendix 9c,d).

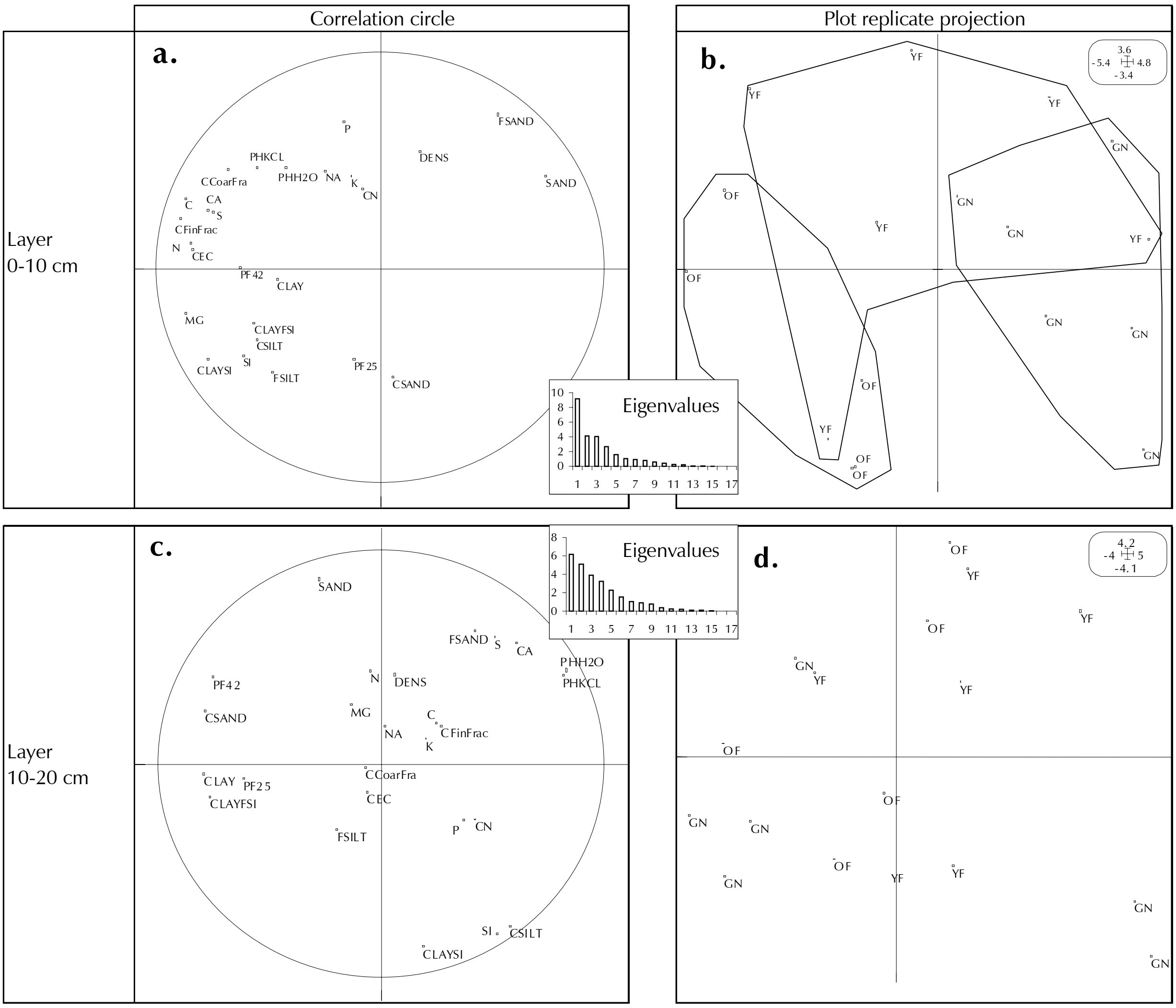

Figure 2.1 Principal components (PC) analysis of the soil properties of a chronosequence made of six cropped plots and 11 fallow plots. Correlation circles of the variables and projection of the plot replicates on plane PC 1x PC2: a.-b. layer 0-10 cm c.-d. layer 10-20 cm. Coding of variables: C: carbon. 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. YF: young fallow (0-9 years). OF: fallow older than 9 years.
See Appendix 11 for data used in the PCA and Appendix 10b for eigen values.

Statistical analyses (Table 2.2a) indicate no significant influence of fallowing on soil physical properties (fine texture, pF, and bulk density). On the other hand pF was greatly affected by texture below a 20-cm depth. Fallowing increased C and N only above a 20-cm depth, but C contents were lower in old fallows than in young ones (Table 2.2b). Highest P_{OD} contents were found in young fallows at any depth, but variability did not allow for statistically significant differences. Texture had no influence on chemical properties in the 0-10 cm layer, except on Mg and CEC. Below 20 cm, Clay+fine silt content strongly influenced C, N, pH, CEC and S.

Table 2.2 Effect of land management (fallowing) and texture (clay+fine silt content) on soil properties.
a. physical properties.

Layer	Groundnut field	Young fallow	Old fallow	F		
(cm)	Mean (±SE) (n=6)	Mean (±SE) (n=6)	Mean (±SE) (n=5)	Management	Texture	Overall
Clay + fine silt content (%)						
0-10	11.3 ±1.2	12.4 ±0.8	14.1 ±0.5	3.2		
10-20	17.1 ±1.3	16.5 ±1.1	17.6 ±1.1	0.1		
20-30	22.5 ±2.5	21.7 ±1.7	24.9 ±2.3	0.5		
30-40	29.4 ±4.3	28.3 ±3.5	33.2 ±3.7	0.4		
0-40	20.1 ±2.0	19.7 ±1.5	22.5 ±1.7	0.4		
pF2.5 (gH$_2$0 100 g^{-1}soil)						
0-10	6.95 ±1.02 ^{a}	4.95 ±0.48 ^{b}	8.28 ±1.74 ^{a}	4.7 *	0.9	3.4
10-20	8.02 ±1.13 ^{a}	5.53 ±0.19 ^{b}	8.52 ±1.75 ^{a}	4.4 *	2.6	4.1 *
20-30	8.80 ±1.42	6.82 ±0.28	10.78 ±1.97	2.3	16.9 **	9.3 **
30-40	11.35 ±2.03	9.18 ±1.00	13.36 ±1.83	2.0	18.3 ***	9.1 **
0-40	8.78 ±1.20 ^{ab}	6.62 ±0.42 ^{b}	10.24 ±1.66 ^{a}	4.9 *	19.4 ***	12.6 ***
pF4.2 (gH$_2$0 100 g^{-1}soil)						
0-10	2.70 ±0.34	3.08 ±0.35	3.74 ±0.33	0.6	5.2 *	4.1 *
10-20	4.03 ±0.46	4.00 ±0.12	4.28 ±0.21	0.6	3.4	1.6
20-30	5.35 ±0.75	5.18 ±0.30	6.26 ±0.41	0.8	31.8 ***	13.2 ***
30-40	7.30 ±1.22	7.25 ±0.79	8.84 ±0.83	0.1	158.4 ***	56.6 ***
0-40	4.85 ±0.64	4.88 ±0.34	5.78 ±0.32	0.7	38.1 ***	15.1 ***
Bulk density (kg dm^{-3})						
0-10	1.52 ±0.01	1.52 ±0.02	1.50 ±0.02	0.4	0.2	0.2
10-20	1.47 ±0.03 ^{b}	1.54 ±0.01 ^{a}	1.52 ±0.01 ^{ab}	4.2 *	1.1	3.0
20-30	1.54 ±0.03	1.51 ±0.02	1.48 ±0.02	1.1	0.5	0.8
30-40	1.45 ±0.03	1.51 ±0.01	1.50 ±0.05	0.6	0.0	0.5
0-40	1.50 ±0.01	1.52 ±0.01	1.50 ±0.02	1.3	0.1	0.8

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

Two mean values with different letters differ significantly in their LS means (α=0.05; pair-wise T-test).
See data in Appendix 11.

Table 2.2 (continued) b. chemical properties

Layer	Groundnut field		Young fallow		Old fallow		F		
(cm)	Mean (±SE) (n=6)		Mean (±SE) (n=6)		Mean (±SE) (n=5)		Management	Texture	Overall
Carbon (g kg^{-1})									
0-10	4.49 ±0.19	b	5.84 ±0.47	a	6.16 ±0.53	a	3.8 *	0.7	4.9 *
10-20	3.66 ±0.16	b	4.49 ±0.21	a	3.75 ±0.16	b	7.8 **	3.7	6.0 **
20-30	3.32 ±0.17		3.86 ±0.29		3.51 ±0.18		2.6	14.6 **	5.9 **
30-40	3.40 ±0.24		3.57 ±0.27		3.71 ±0.25		1.3	35.5 ***	12.5 ***
0-40	3.72 ±0.11	b	4.44 ±0.23	a	4.28 ±0.14	a	6.6 *	3.9	5.5 *
Nitrogen (g kg^{-1})									
0-10	0.36 ±0.02	b	0.49 ±0.04	a	0.50 ±0.01	a	4.6 *	3.3	7.9 **
10-20	0.31 ±0.02	b	0.37 ±0.02	a	0.35 ±0.02	ab	2.9	1.8	2.4
20-30	0.30 ±0.02		0.33 ±0.02		0.34 ±0.02		1.0	13.0 **	5.3 *
30-40	0.32 ±0.03		0.32 ±0.03		0.35 ±0.02		1.5	64.5 ***	22.0 ***
0-40	0.32 ±0.02	b	0.38 ±0.02	a	0.38 ±0.01	a	5.1 *	7.6 *	6.2 **
Phosphorus$_{OD}$ (10^{-3}g kg^{-1})									
0-10	2.52 ±0.21		3.18 ±0.36		2.38 ±0.14		2.3	1.1	2.1
10-20	1.80 ±0.20		2.37 ±0.21		1.74 ±0.37		2.6	1.3	2.3
20-30	1.73 ±0.21		1.82 ±0.21		1.30 ±0.27		1.4	0.4	0.9
30-40	1.52 ±0.15		2.00 ±0.37		1.04 ±0.15		1.9	0.0	1.4
0-40	1.89 ±0.14	ab	2.34 ±0.27	a	1.62 ±0.20	a	2.8	0.0	2.0
pH (H2O)									
0-10	5.92 ±0.08		5.94 ±0.07		5.98 ±0.09		1.0	4.1	1.4
10-20	5.44 ±0.13		5.69 ±0.12		5.66 ±0.13		1.7	16.2 **	6.9 **
20-30	5.23 ±0.17		5.41 ±0.11		5.17 ±0.17		0.6	30.9 ***	11.3 ***
30-40	5.20 ±0.17		5.15 ±0.13		4.90 ±0.14		0.6	9.9 **	4.3 *
0-40	5.45 ±0.13		5.54 ±0.10		5.43 ±0.13		0.7	19.5 ***	7.3 **
pH (KCl)									
0-10	5.15 ±0.12		5.24 ±0.09		5.33 ±0.11		2.4	2.7	1.7
10-20	4.63 ±0.17		4.95 ±0.14		4.88 ±0.18		1.5	12.2 **	5.4 *
20-30	4.44 ±0.17		4.63 ±0.12		4.40 ±0.15		0.7	23.9 ***	9.1 **
30-40	4.34 ±0.17		4.40 ±0.15		4.17 ±0.12		0.3	18.2 ***	6.7 **
0-40	4.64 ±0.15		4.80 ±0.12		4.69 ±0.14		0.6	16.5 **	6.2 **
Ca (meq 100g^{-1}soil)									
0-10	1.32 ±0.13		1.60 ±0.19		1.94 ±0.39		0.6	0.1	0.7
10-20	1.06 ±0.17		1.29 ±0.20		1.42 ±0.43		0.3	3.6	1.5
20-30	0.99 ±0.13		1.12 ±0.15		1.55 ±0.61		0.1	5.0 *	1.7
30-40	1.03 ±0.14		1.12 ±0.15		1.23 ±0.32		0.5	3.1	1.2
0-40	1.10 ±0.13		1.28 ±0.17		1.54 ±0.41		0.4	2.8	1.1
Mg (meq 100g^{-1}soil)									
0-10	0.36 ±0.03	c	0.48 ±0.03	b	0.64 ±0.01	a	14.9 ***	4.7 *	23.1 ***
10-20	0.32 ±0.04	c	0.45 ±0.05	b	0.60 ±0.05	a	12.3 **	5.9 *	10.0 **
20-30	0.35 ±0.04		0.48 ±0.07		0.58 ±0.08		3.3	0.9	2.7
30-40	0.40 ±0.05		0.50 ±0.07		0.52 ±0.08		1.6	1.4	1.7
0-40	0.36 ±0.03	b	0.48 ±0.05	ab	0.59 ±0.05	a	4.7 *	1.3	3.8 *
Na (meq 100g^{-1}soil)									
0-10	0.01 ±0.005		0.02 ±0.008		0.01 ±0.005		0.5	0.8	0.4
10-20	0.00 ±0.002		0.01 ±0.003		0.01 ±0.008		2.2	0.9	1.9
20-30	0.01 ±0.003		0.02 ±0.003		0.01 ±0.005		2.3	0.8	1.8
30-40	0.01 ±0.005		0.02 ±0.008		0.02 ±0.007		0.5	0.2	0.3
0-40	0.01 ±0.002		0.02 ±0.003		0.01 ±0.003		2.4	0.1	1.6
K (meq 100g^{-1}soil)									
0-10	0.04 ±0.004		0.06 ±0.008		0.04 ±0.008		3.1	0.1	2.1
10-20	0.04 ±0.004		0.06 ±0.006		0.04 ±0.009		2.0	0.0	1.3
20-30	0.03 ±0.004	b	0.05 ±0.006	a	0.03 ±0.007	b	5.1 *	1.7	3.5 *
30-40	0.03 ±0.003	b	0.05 ±0.005	a	0.03 ±0.005	b	3.7	1.5	2.6
0-40	0.04 ±0.003	ab	0.05 ±0.005	a	0.04 ±0.007	b	3.1	0.3	2.1
CEC (meq 100g^{-1}soil)									
0-10	2.31 ±0.10		2.54 ±0.10		2.65 ±0.08		0.5	8.7 *	6.0 **
10-20	2.49 ±0.08	ab	2.44 ±0.07	a	2.15 ±0.14	b	3.0	7.2 *	4.2 *
20-30	2.70 ±0.12		2.57 ±0.17		2.48 ±0.18		2.1	16.7 **	6.2 **
30-40	2.95 ±0.36	a	2.94 ±0.22	ab	2.99 ±0.29	b	3.8 *	144.1 ***	48.5 ***
0-40	2.61 ±0.13	ab	2.62 ±0.11	a	2.57 ±0.12	b	4.2 *	74.8 ***	25.3 ***
Saturation rate (%)									
0-10	74.5 ±5.2		84.8 ±7.4		98.4 ±11.9		1.4	0.2	1.0
10-20	57.3 ±7.4	b	74.0 ±7.4	ab	96.0 ±20.3	a	2.9	6.7 *	4.4 *
20-30	51.5 ±4.9		67.7 ±8.8		95.4 ±33.5		1.2	6.9 *	3.0
30-40	54.8 ±9.9	b	59.5 ±6.8	ab	67.4 ±18.5	a	2.6	22.9 ***	8.3 **
0-40	59.5 ±6.3		71.5 ±7.4		89.3 ±20.1		1.5	6.2 *	2.9

2.3.2. SOM quality

SOM quality was investigated using several criteria: the C:N ratio of organic matter of the non-fractionated soil, and the C concentration and content, and the C:N ratio of the [0-50] µm and [50-2000] µm size-fractions.

C:N ratio of the NF soil did not vary significantly during the fallow period and averaged 11.6±0.3 (Table 2.1 and Table 2.4a). It slightly decreased with depth from 12.7 (0-10 cm) to 10.7 (30-40 cm layer).

The mass of the [0-50] µm fraction averaged 22.1±0.7 and 25.4±1.0 g 100g^{-1} of soil in the 0-10 and 10-20 cm layers (Table 2.3a,b). C concentration of the [0-50] µm fraction averaged 17.4±0.7 g kg^{-1}, the C content being 3.8±0.2g kg^{-1} in the 0-10 cm soil layer. In the 10-20 cm layer these values reached only 10.7±0.3 gC kg^{-1} of fraction and 2.7±0.1 gC kg^{-1} of soil. The [50-2000] µm fraction had poorer C concentration and content: 1.7±0.1 gC kg^{-1} fraction (that is 1.3±0.1 gC kg^{-1} soil) in the 0-10 cm layer, 1.1±0.2 gC kg^{-1} fraction (0.8±0.1 gC kg^{-1} soil) in the 10-20 cm layer. The comparison of the different

Table 2.3 SOM fractionation in groundnut (GN) and fallow (FA) plots.

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
FA01a	20.0	19.87	3.97	13.6	80.0	2.23	1.79	40.4	99
FA01b	21.4	21.40	4.59	13.9	78.6	2.18	1.71	34.0	85
FA01c	18.8	18.23	3.44	14.0	81.2	2.10	1.70	36.9	101
FA02a	22.7	15.81	3.58	12.2	77.3	1.64	1.27	35.4	110
FA04	23.8	16.61	3.96	14.0	76.2	1.77	1.35	36.4	76
FA07a	26.0	18.02	4.69	12.8	74.0	1.99	1.47	41.0	115
FA12	22.2	22.50	5.00	13.7	77.8	2.28	1.77	44.3	90
FA13a	27.7	14.31	3.96	13.4	72.3	1.71	1.24	57.6	108
FA17	22.5	20.67	4.65	15.3	77.5	1.84	1.43	42.3	84
FA18a	23.4	18.13	4.24	15.0	76.6	1.70	1.30	50.7	106
FA26	22.7	18.87	4.29	15.7	77.3	2.09	1.61	48.7	99

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
FA01a	20.8	12.41	2.58	13.1	79.2	2.18	1.73	32.7	103
FA01b	21.8	12.90	2.81	13.0	78.2	<0.2	<0.15		
FA01c	22.7	10.45	2.37	12.6	77.3	1.09	0.84	62.6	82
FA02a	28.0	9.26	2.59	12.4	72.0	1.11	0.80	45.8	78
FA04	26.6	11.39	3.03	13.2	73.4	2.23	1.63	44.3	109
FA07a	29.9	10.98	3.28	12.6	70.1	1.73	1.21	70.1	85
FA12	23.0	12.30	2.83	13.5	77.0	1.28	0.99	57.1	107
FA13a	31.3	9.06	2.84	11.9	68.7	1.34	0.92	79.9	89
FA17	24.7	12.23	3.02	13.8	75.3	<0.2	<0.16		
FA18a	25.7	10.28	2.64	14.2	74.3	1.34	0.99	123.3	102
FA26	25.1	10.11	2.54	14.9	74.9	2.06	1.54	68.8	122

Fractionation recovery rate computed as the sum of (1) and (2) out of carbon content of non-fractionated soil (from Table 2.1). The age of the fallow plots is mentioned in plot coding.

situations indicated that, whatever the soil layer, the C concentration of both particle-size fractions ([50-2000] µm, [0-50] µm) increased significantly from the GN plots, to the YF and OF situations (Table 2.4b). The gain of C was particularly evident for the coarse fraction [50-2000] µm isolated from the 10-20 cm layer. As a matter a fact, this fraction was responsible for about 50 % of the total C increase recorded between GN and YF plots.

C:N ratio of fine and coarse fractions raised steadily and significantly along the whole succession at both depths; progression was stronger in the coarse fraction than in the fine one (Table 2.3a,b and Table 2.4b).

Table 2.4 Effect of land management (fallowing) and texture (clay+fine silt content) on SOM quality as assessed by: a. C:N ratio of NF soil b. C concentration and content, and C:N ratio in fine and coarse soil fractions.

a.

Layer	Groundnut field		Young fallow		Old fallow		F		
(cm)	Mean (±SE) (n=6)		Mean (±SE) (n=6)		Mean (±SE) (n=5)		Management	Texture	Overall
C/N on non-fractionated soil									
0-10	12.7 ±0.5		12.1 ±0.8		12.3 ±0.9		0.3	0.6	0.3
10-20	11.9 ±0.9	ab	12.3 ±0.3	a	10.8 ±0.3	b	3.7	0.0	2.5
20-30	11.3 ±0.3		11.6 ±0.5		10.5 ±0.2		2.0	0.0	1.4
30-40	10.8 ±0.4		11.1 ±0.5		10.7 ±0.7		0.1	1.4	0.6
0-40	11.7 ±0.4		11.8 ±0.4		11.2 ±0.4		0.1	4.3	1.7

b.

Layer	Fraction	Groundnut field		Young fallow		Old fallow		F		
(cm)	(µm)	Mean (±SE) (n=6)		Mean (±SE) (n=6)		Mean (±SE) (n=5)		Management	Texture	Overall
Carbon concentration (g kg^{-1} fraction)										
0-10	0-50	15.23 ±0.77	b	18.32 ±0.84	a	18.90 ±1.37	a	3.7	0.4	2.8
	50-2000	1.11 ±0.10	b	1.98 ±0.1	a	1.92 ±0.11	a	10.8 **	0.1	9.8 **
10-20	0-50	10.13 ±0.41		11.23 ±0.54		10.80 ±0.64		1.3	3.9	2.4
	50-2000	0.66 ±0.19		1.41 ±0.33		1.22 ±0.32		1.9	0.6	1.4
Carbon content (g kg^{-1} soil)										
0-10	0-50	3.14 ±0.15	b	4.04 ±0.21	a	4.43 ±0.18	a	5.8 *	3.3	10.4 ***
	50-2000	0.87 ±0.07	b	1.55 ±0.09	a	1.47 ±0.10	a	12.8 ***	0.1	10.3 **
10-20	0-50	2.70 ±0.10		2.78 ±0.14		2.77 ±0.08		0.2	0.4	0.3
	50-2000	0.48 ±0.14		1.05 ±0.25		0.90 ±0.24		2.0	0.2	1.4
C/N on fractions										
0-10	0-50	12.7 ±0.3	b	13.4 ±0.3	ab	14.6 ±0.5	a	4.9 *	0.0	4.7 *
	50-2000	29.4 ±2.3	c	37.3 ±1.1	b	48.7 ±2.7	a	18.4 ***	0.9	15.2 ***
10-20	0-50	11.9 ±0.5	b	12.8 ±0.1	b	13.7 ±0.5	a	5.3 *	6.3 *	5.7 *
	50-2000	35.2 ±4.6	c	51.1 ±6.7	b	82.3 ±14.4	a	12.4 **	5.4 *	10.2 **

p{Ho: $F_{obs}>F_{th}=0$}: $^{*}<0.05$; $^{**}<0.01$; $^{***}<0.001$.
Two mean values with different letters differ significantly in their LS means ($\alpha=0.05$; pair-wise T-test).
See data in Table 2.1 and Table 2.3.

2.3.3. Patterns of soil C, N & P_{OD} storage along the succession

Temporal patterns of C, N and P_{OD} storage during the crop-fallow cycle are shown in Figure 2.2 (detailed soil data; see Table 2.1 for calculation) and Figure 2.3 (aggregate data for the ecosystem). Soil C, N and P increased within the very first year of fallow (+4.4 tC, +430 kgN, and +5.7 kgP_{OD} ha^{-1} in the whole profile, that is a gain of 20, 22 and 50 % relatively to amounts in soil of cropped fields). Vertical distribution of C, N and P_{OD} remained quite constant between the treatments. The concentration of C, N and P_{OD} in the upper soil layer (0-10 cm) was barely pronounced (33 % of the whole amount in the 0-40 cm profile). C storage in the whole profile was 22.3±0.7 t ha^{-1} in the groundnut fields but reached 25.6±0.8 t ha^{-1} in oldest fallows. N averaged 1920±110 and 2300±810 kg ha^{-1} in plots of cropped fields and old fallows, respectively. P_{OD} storage in these clusters reached 11.3±0.9 kg ha^{-1} and 9.7±1.2 kg ha^{-1} respectively. Highest C and P_{OD} amounts were found in young fallows.

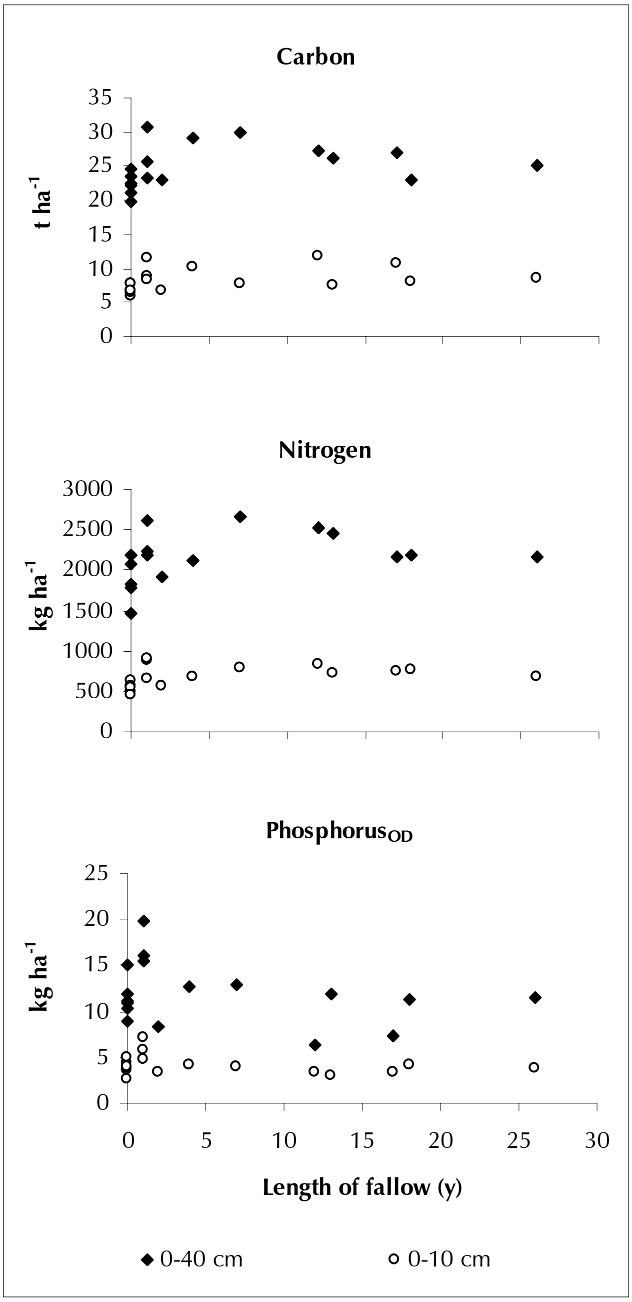

Figure 2.2 Evolution of soil C, N and P_{OD} storage in the 0-10 and 0-40 cm layers along the crop-fallow succession.
See data in Appendix 13.

Fallowing influenced significantly the value of C and N stocks in the 0-10, 10-20 and 0-40 cm layers (Table 2.5a). C storage equally increased in fine and coarse fractions in the 0-10 and 10-20 cm layers (Table 2.5b). But significant differences were found in the [50-2000] μm fraction only, because initial C contained in the coarse fraction was only a fourth of that in the fine fraction. In the 0-10 cm layer, highest amounts of total C were reached in old fallows; this happened in the young fallows when considering layers 10-20 and 0-40 cm. However, C and N did not increase significantly in the old fallows as compared to the young ones. Fine elements were a better predictor for C and N storage than stage of succession in the 20-30 and 30-40 cm layers. No statistically significant evolution of P_{OD} storage along the succession could be evidenced, although P_{OD} storage was 30 % higher in young fallows than in other plots.

Table 2.5 Effect of land management (fallowing) and texture (clay+fine silt content) on soil C (total and in fractions), N and P_{OD} storage.

a. non-fractionated soil

Layer	Groundnut field	Young fallow	Old fallow	F		
(cm)	Mean (±SE) (n=6)	Mean (±SE) (n=6)	Mean (±SE) (n=5)	Management	Texture	Overall
Carbon storage (t ha^{-1})						
0-10	6.8 ±0.3 ^{b}	8.8 ±0.7 ^{a}	9.2 ±0.8 ^{a}	4.1 *	0.3	4.5 *
10-20	5.4 ±0.3 ^{b}	6.9 ±0.3 ^{a}	5.7 ±0.2 ^{b}	10.4 **	3.5	7.6 **
20-30	5.1 ±0.3	5.8 ±0.5	5.2 ±0.2	2.6	13.5 **	5.2 *
30-40	4.9 ±0.4	5.4 ±0.4	5.6 ±0.4	1.2	35.7 ***	12.8 ***
0-40	22.3 ±0.7 ^{b}	26.9 ±1.4 ^{a}	25.6 ±0.8 ^{a}	7.7 **	3.6	6.1 **
Nitrogen storage (kg ha^{-1})						
0-10	538 ±28 ^{a}	740 ±56 ^{a}	747 ±28 ^{b}	5.1 *	2.1	7.3 **
10-20	458 ±24 ^{b}	563 ±27 ^{a}	530 ±25 ^{a}	6.9 **	3.4	5.4 *
20-30	458 ±33	498 ±31	496 ±21	0.6	12.2 **	4.5 *
30-40	466 ±46	487 ±43	527 ±37	1.5	31.1 ***	11.6 ***
0-40	1920 ±114 ^{b}	2289 ±119 ^{a}	2300 ±81 ^{a}	5.6 *	5.7 *	5.5 *
$Phosphorus_{OD}$ storage (kg ha^{-1})						
0-10	3.8 ±0.3	4.8 ±0.5	3.6 ±0.2	2.4	1.2	2.2
10-20	2.7 ±0.3 ^{b}	3.6 ±0.3 ^{a}	2.6 ±0.6 ^{ab}	3.2	0.7	2.5
20-30	2.7 ±0.3	2.7 ±0.3	1.9 ±0.4	2.7	0.2	1.8
30-40	2.2 ±0.2	3.0 ±0.5	1.6 ±0.2	1.8	0.0	1.3
0-40	11.3 ±0.9 ^{b}	14.2 ±1.6 ^{a}	9.7 ±1.2 ^{a}	3.0	0.0	2.1

b. soil size fractions

Layer	Fraction	Groundnut field	Young fallow	Old fallow	F		
(cm)	(μm)	Mean (±SE) (n=6)	Mean (±SE) (n=6)	Mean (±SE) (n=5)	Management	Texture	Overall
Carbon storage in fractions (t ha^{-1})							
0-10	0-50	5.34 ±0.30	6.38 ±0.54	6.93 ±0.59	0.9	0.9	1.9
	50-2000	1.47 ±0.10 ^{b}	2.45 ±0.22 ^{a}	2.30 ±0.23 ^{a}	12.0 **	0.0	10.2 **
10-20	0-50	4.61 ±0.28	5.18 ±0.54	4.39 ±0.49	0.6	0.9	0.7
	50-2000	0.77 ±0.19 ^{b}	1.75 ±0.35 ^{a}	1.30 ±0.30 ^{ab}	4.7 *	0.9	3.3

$p\{Ho: F_{obs}>F_{th}=0\}$: *<0.05; **<0.01; ***<0.001.

Two mean values with different letters differ significantly in their LS means (α=0.05; pair-wise T-test).

See data in Appendix 13 and Appendix 14.

When considering the whole ecosystem (Figure 2.3), the contribution of soil to C storage decreased from 80 % in the cropped fields to 47 % in old fallows. The same trends were recorded for N, although allocation to soil remained high in all treatments (95-87 % of the whole amount in the plant-soil system). A sharper evolution was evidenced for soil P_{OD} that represented 66 % of the amount of biologically active P (plant P_t+Soil P_{OD}) in the fields and only 22 % in old fallows.

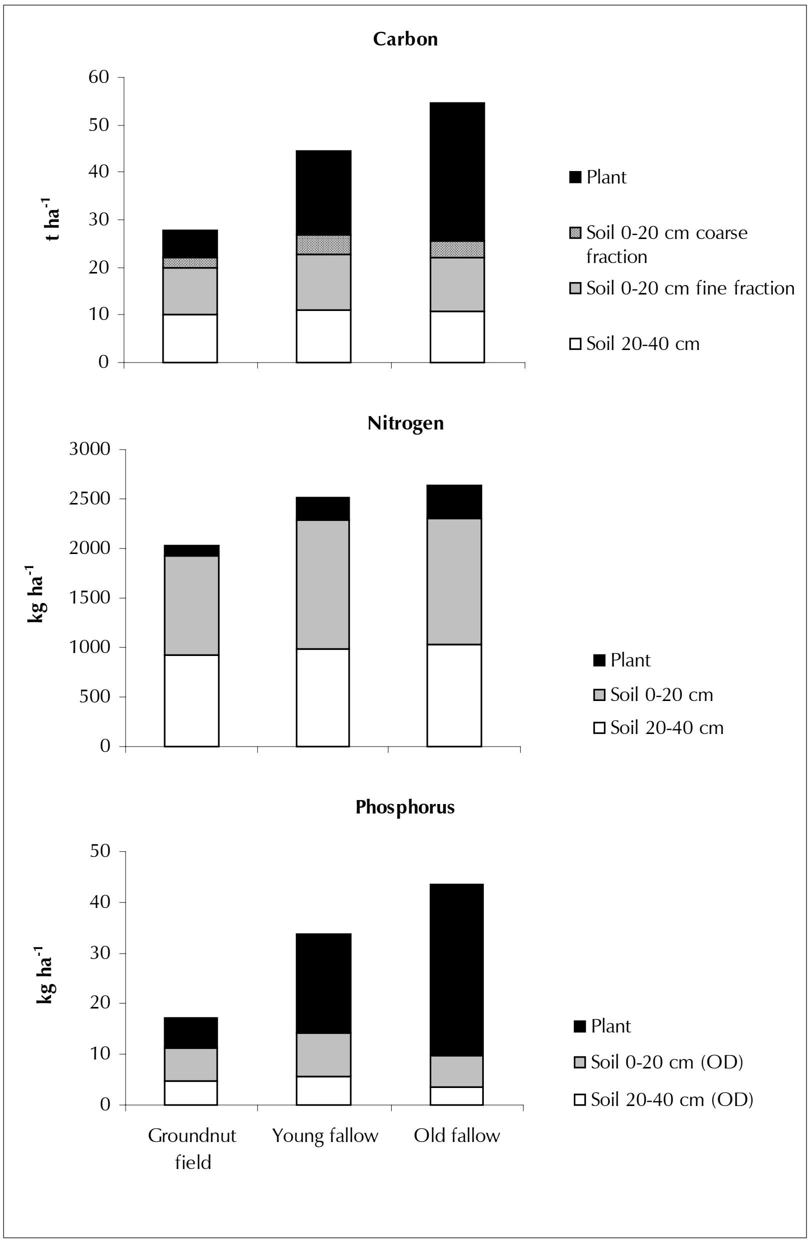

Figure 2.3 C, N and P storage in the plant-soil system at three main stages of the crop-fallow succession. Figures for plant biomass derived from Chapter 1.
Young fallow: aged 0-9 years. Old fallow: older than 9 years.
OD: available phosphorus (soil) as measured by Olsen's method modified by Dabin (1967).
See data in Appendix 12.

2.3.4. Post-fallow dynamics of root biomass

Dead tree root biomass disappeared quickly after being dug in the soil of the fallow cleared (Figure 2.4). After the six first months of *in situ* incubation, highest initial decomposition rates were recorded for the finest roots: 61 % *vs.* 50 % and 41 % of mass loss for the [2-5] and [5-10]mm diameter classes. As incubation went on, the rates decreased and remained constant beyond the second year.

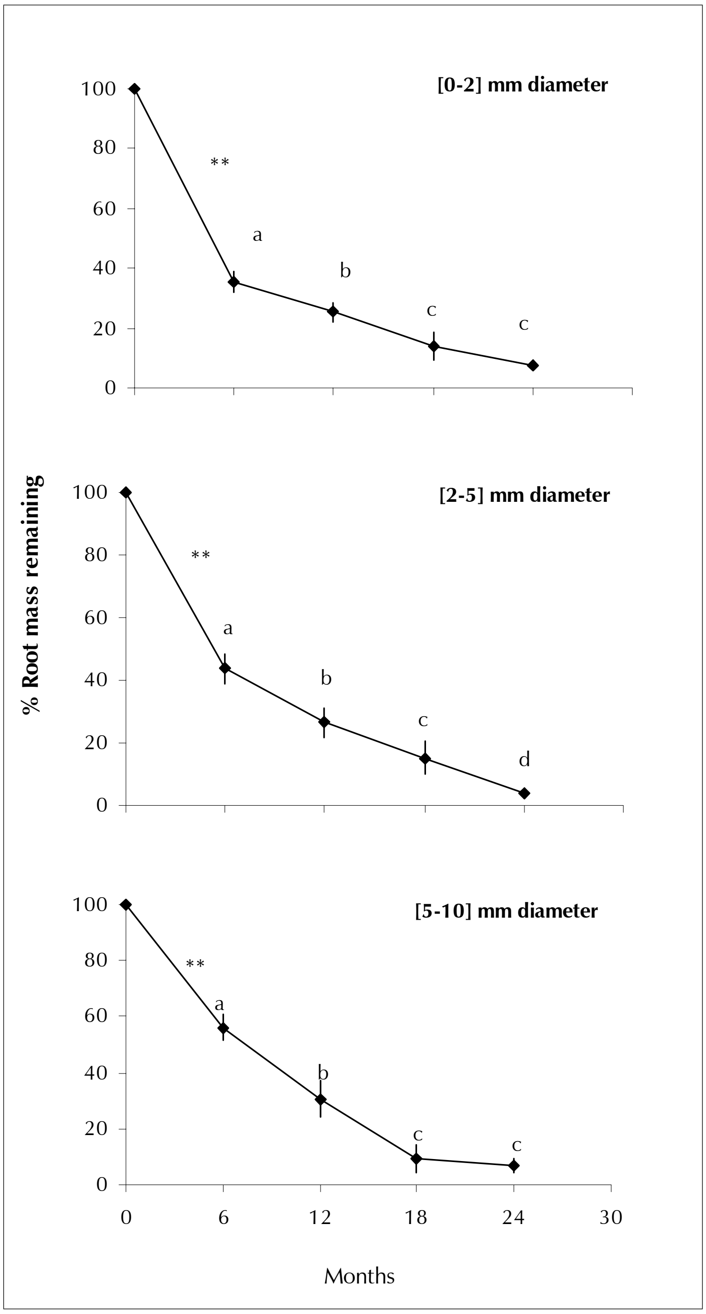

Figure 2.4 Root decomposition dynamics of Combretum glutinosum Perr. *after clearing of a 15 years old fallow as measured during a mesh-bag experiment.*
Vertical bars stand for SE. Results of Z- and SNK-tests (α=0.05; n=20).
See data in Appendix 15.

These results were applied to simulate the decay of root biomass occurring after the clearing of two hypothetical young and old fallows in which stumps would have been removed (Figure 2.5). Estimated disappearance (oxidation and spatial redistribution) of dry matter (DM), C, N and P_t related to decaying root biomass would be massive during six months following the clearing of fallow plots and amount to 4.0/9.3 tDM, 1.4/3.3 tC, 20/43 kgN and 1.1/3.4 kgP_t ha^{-1}, depending on the age of fallow (young/old). During the second cropping season these values would drop by nearly two thirds.

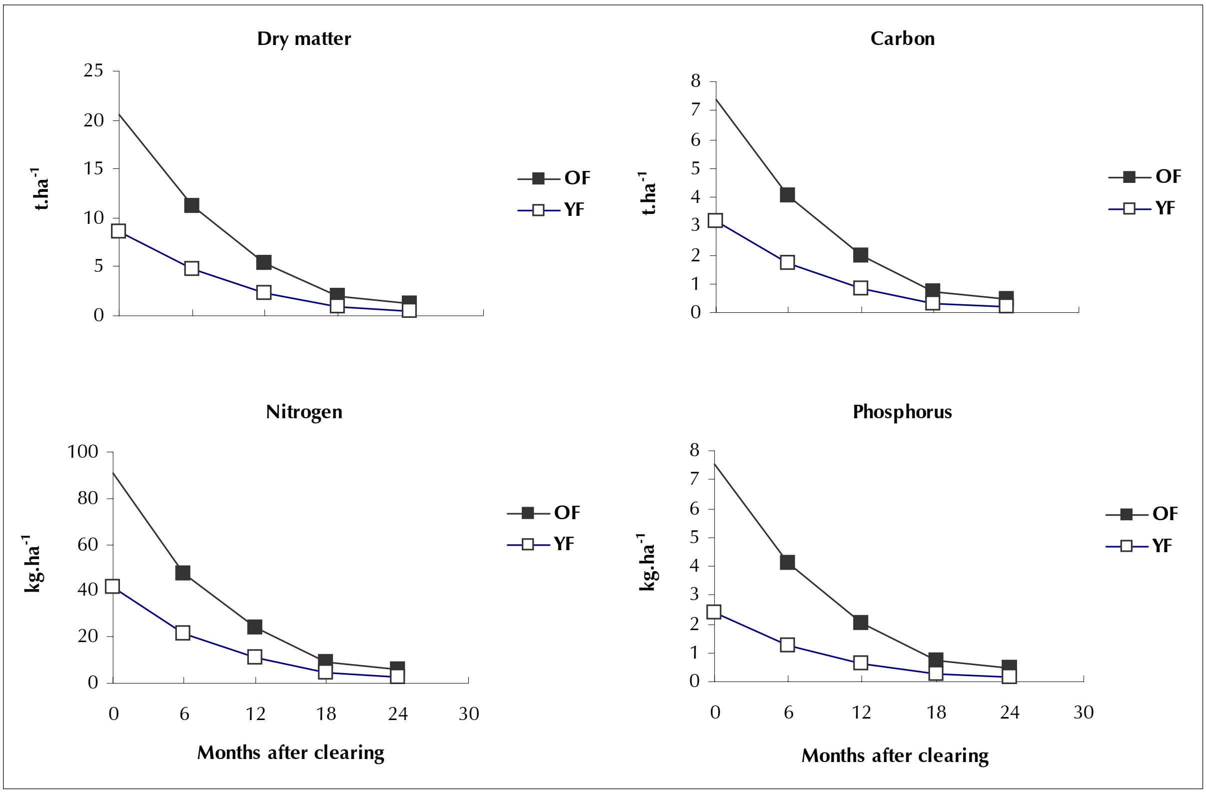

Figure 2.5 Estimated remaining amounts of dry matter, carbon, nitrogen and phosphorus from the decaying root component after clearing of a young (YF) and old (OF) fallow (stumps removed).
See data in Appendix 16.

2.4. DISCUSSION

2.4.1. General trends in soil C, N & P dynamics

General results of this study on soil organic carbon compare fairly well with the findings of Jones and Wild (1975), at least for the upper soil layer. These authors report the mean carbon content of 245 ferruginous soils to be 6.2 g kg^{-1} (5.5 g kg^{-1} in our study). Nye and Greenland (1960) found C values to average 7.6 g kg^{-1} in the upper soil layer (0-5 cm) of various uncropped ecosystems of the dry tropics. Figures from the Senegalese case study detailed by Tiessen *et al.* (1998) are close to ours, though lower than our findings, mostly due to the different environmental constraints of their study zone(drier climate and higher human pressure). Our results report N content to be 0.44 g kg^{-1} in the 0-10 cm layer, which compares well with the review of Nye and Greenland (1960) and is close to the value predicted by the multiple regression relation computed by Jones (1973) linking N content to clay content and annual rainfall. As suggested by this author, it must however be kept in mind that high spatial and temporal variability is a feature of C and N soil content in West African savannas.

Comparing available-P content (as defined by P_{OD}) with other studies is questionable, since results are highly reliant on the analytical method. The phosphorus status of the soils of our study may be particularly poorer than expected for the ecozone. Indeed, total P reported by Manlay (1994) for four fallow plots aged one to 15 years averaged 60 µg kg^{-1}, which is only half of that reported by Jones and Wild (1975) in 181 tropical sandy soils. Nye and Greenland (1960) also provide much higher available-P content (7.2 µg kg^{-1}, Truog method) under soil and climate conditions similar to those of south Senegal. Their review reports higher contents of Mg, K and Ca in soils under fallow than those found in our study except for humid savanna fallows.

2.4.2. Influence of intrinsic soil properties

The abundance of fine elements seemed to play a key role in explaining variations of chemical and physical properties –among which SOM content-, especially below 20 cm deep. For the 0-20 cm layer, our results indicate that the soil properties (including C, N and P_{OD} content) are driven mostly by the duration of the fallow in the crop-fallow rotation, probably due to the low variation of the soil fine elements content. Fallowing has only little impact, if any, on soil water retention capacity, nor does it improve density, although repeated tillage in cropped fields might also have decreased soil density and thus biased the tests. On a methodological point of view, our results suggest that studies aimed at connecting fallow management and soil properties could restrict sampling to the 0-20 cm layer only.

2.4.3. Nutrient balance of the crop-fallow system

Annual increase of N and P (plant P_t + soil P_{OD}) for the whole system was highest after one year of fallow and nearly nil beyond the 10-years threshold (Figure 2.3). Efficiency of young fallows and pastures for achieving fast recovery of substantial amounts of soil N and available P has already been underlined by Jones (1971), Friesen *et al.* (1997), Brand and Pfund (1998), and Harmand and Njiti (1998), although nutrient pumping by trees might not be significant in the region (Breman and Kessler, 1995). Under high soil chemical constraint, savannas have developed nutrient-conservative strategies (Myers *et al.*, 1994), and spontaneous vegetation exhibits particular efficiency in recycling nitrogen from litter and extracting assimilable phosphorus from soil (Abbadie *et al.*, 1992; Friesen *et al.*, 1997). The decrease of soil P_{OD} content in the oldest fallows is another illustration of this feature, as it might be linked with immobilisation in woody live biomass (Breman and Kessler, 1995). Data from Manlay (1994) report indeed stable P_t:P_{OD} ratio (28.3±2.9; n=4) in soil during the fallow succession in Sare Yorobana, indicating a limited reallocation of P from the available pool to more unavailable forms during fallowing. We thus suggest that P_{OD}, together with water availability, may be the main limiting factor responsible for the asymptotic property of the curve of tree biomass as a function of the length of fallow established in Chapter 1 (Murphy and Lugo, 1986; Akpo, 1998; Sirois *et al.*, 1998). In nearby Guinea, Sirois *et al.* (1998) found similar, decreasing trends for soil extractable-P and exchangeable K during the first eight years of fallow. However, these authors recorded decreases for Mg, CEC and pH, while our study did not reveal such patterns.

2.4.4. Soil organic status after crop abandonment

Mineral fertilization without organic amendments barely leads to sustainable productivity in West Africa, as it often results in SOM mineralization and subsequent soil structure disruption, pH decrease and aluminic toxicity increase (Pieri, 1989; Mokwunye and Hammond, 1992). The study of plant biomass dynamics indicates that fallowing raises below-ground C stored in plant biomass up to 12.6 t ha^{-1} and sets C input fluxes up to at least 3.6 t ha^{-1} y^{-1} in old fallows (see Chapter 1).

It is commonly accepted that clearing primary forests or woodlands and subsequent cropping leads to a dramatic decline of soil carbon content in dry and wet tropics (Brams, 1971; Siband, 1974; Feller and Milleville, 1977; Tiessen *et al.*, 1992; Juo *et al.*, 1995). Reasons put forward for this are the (1) drop of organic inputs to the soil due to lower below-ground productivity and plant biomass removal at harvest, (2) modification of soil water and temperature conditions, (3) erosion and leaching enhancement, (4) tillage (Brown *et al.*, 1994). However, the potential of fallowing to reverse SOM losses due to prolonged cultivation remains much more controversial. Many authors relate significant increases of soil carbon contents following crop abandonment (Greenland and Nye, 1959; Aina, 1979; Areola *et al.*, 1982; Tiessen *et al.*, 1992; Feller, 1993). But from their works no consensus arises about the shape of the curve of carbon accumulation as a function of the length of fallow, and the minimal period of fallow required for a significant improvement of SOM content. At least as many studies held under various tropical climates report no significant evolution of carbon storage after crop abandonment (Bebwa and Lejoly, 1993; Breman and Kessler, 1995; Jaiyeoba, 1995; Juo *et al.*, 1995; Kotto-Same *et al.*, 1997; Sirois *et al.*, 1998; Denich *et al.*, 2000 among others). Whatever their findings, these works seldom include texture as a covariate in their model of carbon dynamics as inferred from chronosequences. Nevertheless, as hypothesised by Nye and Greenland (1960), the capacity of fallowing to restore the organic content of a soil should be judged regarding how far the C content stands from the equilibrium level under native vegetation. This is barely documented in the previously cited studies. Recent findings of Harmand *et al.* (2000) suggest that carbon storing capacity of fallowing could also hang upon tree species composition of the secondary vegetation.

The present work reveals a low -though significant- capacity of carbon storage in the sandy soils of fallows of West African savanna. This aptitude is detectable within the very first year after crop abandonment, which is a feature of coarse textured soils (Feller and Beare, 1997). Yet, later apparent inertia of SOM storage does not agree with most of the previously cited studies; usually these show a steady increase of soil carbon even in old fallows. In addition, more than a half of the rise recorded in the 0-20 cm layer after crop abandonment occurs in the coarse fraction [50-2000] µm. Feller (1995b) showed that this fraction had a high turn-over rate (0.4 to 1.0 over 10 years), and was restricted to biological functions such as C, N and P supply to microflora and faunal communities. Thus, the effect of fallowing is rather transient and has only little impact on the improvement of soil chemical properties.

Several factors may explain the weak and fragile response of local soils to fallow management. Jones and Wild (1975) and Feller (1995b) have shown that clay mineralogy, and rainfall to a lesser extent, were the best predictors for carbon content in tropical soils. For plateau soils of High Casamance, large coarse-sand fraction and limited clay content do not allow for efficient SOM protection against microbial oxidation, leaching and erosion losses (Feller and Beare, 1997). Rainfalls, constraining the duration of the plant growth period, soil moisture and temperature patterns unfavourable to humification are the other abiotic reasons for limited SOM storage (Moureaux, 1967). Harvest of deadwood by people, as well as CO_2 mineralization induced by fire might also be put forward, although the effect of fire on SOM content of young fallows has recently been questioned (Masse *et al.*, 1997).

2.4.5. Fallowing as a tool for the recovery of biological control over ecosystem fertility

As a matter of fact, we put forward the growing control exerted by biological activity over SOM dynamics as the ultimate factor limiting carbon storage capacity of soils under fallow and suggest that this control confers a particular ecological role to SOM in savanna sandy soils.

Because the study site lies in a region of recent human settlement leaving wide areas of non-cleared savanna, soil living populations are quite similar to those found in weakly disturbed savanna or under more humid climate (Derouard *et al.*, 1998). Massive root decay following fallow clearing, observed by Harmand *et al.* (2000) in Northern Cameroon too, testifies intense biological activity even during the dry season. Such an activity would be constrained more by available C shortage than by temperature (Kaiser, 1983), and even than by soil humidity in the case of termites. Termites are the main conveyors of organic inputs to the soil in wooded African savannas throughout the year and may re-dispatch more than 90 % of net carbon production of the ecosystem (Jones, 1990). Earthworms improve physical and chemical availability of SOM to micro-organisms as well as soil porosity through annual remixing of the whole soil upper layer (Lavelle *et al.*, 1998). As a consequence of climate and of the "priming effect" by macrofauna, mineralization activity by soil microflora is much higher in tropical than in temperate soils (Jenny *et al.*, 1949; Jenkinson and Ayanaba, 1977), resulting in more mature humic compounds in SOM of tropical soils (Grisi *et al.*, 1998). For instance, yearly, *in situ* emissions of C-CO_2 from soil respiration have been reported to reach even up to 75 % of soil organic carbon stored in a sandy soil bearing a subhumid savanna (Schaefer, 1974).

But we suggest that massive "grazing" over soil carbon by the soil heterotrophic community is not out of benefit for the fallow ecosystem-as-a-whole. Recent findings of research studies held in West African fallows report increased biomass and diversity of soil microflora (Wick *et al.*, 1998) and termites (Black and Okwakol, 1997; Sarr *et al.*, 1998 and Fall, 1998 in Senegal) after crop abandonment. Fallowing modifies faunal biodiversity too (Derouard *et al.*, 1998), thus altering the structure and weakening the pathogenicity of nematode population (Pâte, 1997; Manlay *et al.*, 2000b). It might also stimulate mycorrhizal soil infectivity (Duponnois, pers. comm.). In fact, so-called below-ground heterotrophic "engineers" (Jones *et al.*, 1994; Lavelle *et al.*, 1997) together with rooting systems contribute to the aptitude of the fallow ecosystem to buffer the effects of the pronounced harshness of climate and of soil nutrient poverty and physical instability (Menaut *et al.*, 1985; Perry *et al.*, 1989; Brown *et al.*, 1994). This is achieved through efficient nutrient conservation strategies, structural integrity relying on live plant biomass, and functional stability through biodiversity enhancement (Odum, 1969; Giller *et al.*, 1997). The weak potential of fallow soils to stabilise organic inputs into humic compounds should thus be viewed as the energetic cost to pay for the self-organising process occurring in the fallow ecosystem, which is necessary for the replenishment of soil fertility in savanna agricultural systems with low inputs.

2.4.6. West African fallow management in a global change perspective

On a global change perspective, this study provides information for carbon sequestration potential in savanna as an attempt to mitigate anthropogenic greenhouse emissions, of which 20 % would stem from land use change in the tropics (Schimel, 1995).

When integrating results from Chapter 1 into the discussion, C dynamics exhibit various trends, depending on the plant or soil component considered (Figure 2.3). What has already been observed under more humid contexts (Toky and Ramakrishnan, 1983a; Toky and Ramakrishnan, 1983b; Kotto-Same *et al.*, 1997) is being confirmed in the present study: during the crop-fallow succession most reactive DM, C, N and P reservoirs are also the most biologically active ones, while amounts in soil remain quite stable. After crop abandonment, woody and root biomasses increase, while those of the herbaceous layer drop, and amounts of litter and SOM show no clear trend of evolution.

According to current slash-and-burn practices, clearing of a mature fallow in south Senegal would lead to the release of 27 tC ha^{-1} through immediate burning, later combustion of wood for energetic needs and on-site decomposition of roots, stumps and remaining unburnt twigs and leaves, and mineralization of a small part of SOM. Nearly half of this value (12.3 tC ha^{-1}) can be recovered during the first year of fallow. Then, annual rate of storage is only 2 tC ha^{-1} during the 10 following years of fallow. However, this aptitude requires that long breaks of fallow be maintained, or at least that rooting systems and stump be saved during cropping. The potential of fallowing for carbon sequestration is thus weak in West African savannas as compared to values given for tropical subhumid and wet forest (10 tC ha^{-1} y^{-1} according to Kotto-Same *et al.*, 1997 during the first 15 years of fallow; Denich *et al.*, 2000 during the first seven years of a secondary succession). What is more, the gain of stable carbon in the fine-size fraction of soil contained in the 0-20 cm layer is only 1.5 tC ha^{-1}. Thus sequestration is likely to happen mostly in pools with high turnover rates (soil coarse fraction, plant biomass), unless channelling wood felling for construction usage only.

Anyway, the main restriction to the potential of savannas to sequester carbon may well be the local need for land (Tiessen *et al.*, 1998) and the non-immediate financial profitability of carbon sequestration for the farmer (Izac and Swift, 1994). As suggested by Brown and Lugo (1990) for tropical secondary forests, the contribution of West African savanna fallows to the control of greenhouse gas emissions in a global change perspective is likely to be rather indirect. That is, by providing more incomes to local population from intensified agroecosystems, thus limiting the need for land on the northern fringe of ecosystems with high carbon storage capacity such as humid forests. Intensification itself relies on more efficient organic management of the ecosystem biological fertility. Technical solutions such as stump-saving clearing, slash-and-mulch (Vielhauer *et al.*, 1998), management of fire, conservation of below-ground communities, planted fallows (Peltier and Pity, 1993; Lopes da Silva *et al.*, 1998), cover crops and no-tillage options (Azontonde *et al.*, 1998) are promising. But most of them demand much labour and imply mechanisation and eventual motorization that are far beyond possible local access to credit, and, most of time economic viability of farming systems in the current socio-economic context.