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Raphaël J. Manlay

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ENVIRONMENT

DOCTORAL THESIS



ORGANIC MATTER DYNAMICS IN MIXED-FARMING SYSTEMS OF THE **W**EST **A**FRICAN SAVANNA

A VILLAGE CASE STUDY FROM SOUTH **S**ENEGAL

RAPHAËL MANLAY





THÈSE

présentée par

Raphaël Manlay

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Sujet :

**Dynamique de la matière organique
à l'échelle d'un terroir agro-pastoral
de savane ouest-africaine (Sud-Sénégal)**

*

*Organic matter dynamics in mixed-farming systems
of the West African savanna: a village case study from south Senegal*

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RESUME

La matière organique (MO) remplit de multiples fonctions dans les systèmes agro-pastoraux de savane d'Afrique de l'Ouest. Elle fournit de l'énergie, des éléments minéraux et des matériaux de construction aux paysans et aux animaux. Grâce à la jachère et à la fumure animale, elle assure l'entretien du système par des mécanismes biologiques. Dans la région, la disponibilité en MO peut être utilisée comme un indicateur de durabilité des systèmes de production traditionnels, car malgré une population croissante, les rendements progressent peu en raison d'un faible accès aux intrants chimiques. Les bilans du carbone (C), de l'azote (N) et du phosphore (P ; total dans la plante, assimilable dans le sol et noté P_{OD}) ont donc été établis pour un terroir agro-pastoral dans le sud du Sénégal afin d'en estimer la viabilité à différentes échelles, de la parcelle au village.

Le terroir choisi était organisé en auréoles, avec une intensification croissante des pratiques de la périphérie vers le village. Trois grandes unités de gestion des terres ont pu être mises en évidence : (1) l'auréole des champs de brousse, soumise à l'agriculture itinérante, (2) l'auréole des champs de case, en culture continue grâce à la fumure organique, (3) un bas fond rizicole périodiquement inondé. Les sols étaient sableux ferrugineux (Lixisols), sauf en bas fond (Gleysols). La densité de population humaine était de 33 habitants km^{-2} , celle de bovins de 51 unités de bétail tropical km^{-2} .

Une approche parcellaire a montré que les stocks dans le système sol-plante (jusqu'à 40 cm de profondeur) étaient de 27,8 tC, 2,03 tN et 17,3 kgP ha^{-1} dans les champs de brousse en arachide et s'élevaient à 54,7 tC, 2,63 tN et 43,5 kgP ha^{-1} dans les jachères âgées de plus de 10 ans, la majorité de l'augmentation ayant lieu dans la biomasse végétale. Dans le sol, la croissance rapide des stocks durant la première année de jachère (20 %) fut suivie par une stagnation (C, N) voire une régression (P). Dans six parcelles de céréales de case, les stocks mesurés étaient supérieurs à ceux des parcelles de cultures de brousse et s'élevaient à 29,9 tC, 2,30 tN et 83 kgP ha^{-1} . L'augmentation des stocks de P_{OD} fut significative à toutes les profondeurs et dans toutes les parcelles. Ce ne fut pas le cas pour le carbone et l'azote, dont la teneur ne s'améliora significativement que dans l'horizon 0-10 cm, et principalement dans les parcelles jouxtant les concessions et recevant les apports de MO minéralement les plus riches. Les stocks de C, N et P les plus élevés furent mesurés dans les rizières, aux sols à texture fine.

Le modèle conceptuel suivant a été proposé pour interpréter la faible réponse des stocks de carbone des sols sableux à la jachère et à la fumure, en réévaluant le rôle biologique et thermodynamique joué par le carbone grâce à son recyclage. Dans les sols tropicaux sableux de la zone, la biosphère contrôle fortement les propriétés physiques du sol et la disponibilité en éléments minéraux de la plante. Les systèmes racinaires pérennes, ou les apports de fumure organique exogène, sont nécessaires pour maintenir l'intégrité fonctionnelle de l'écosystème sol, car ils fournissent au biote l'énergie et les éléments minéraux nécessaires à son entretien.

Par intégration d'échelle, les stocks moyens contrôlables par la gestion des terres par l'homme furent estimés à 29,7 tC, 1,52 tN et 28,6 kgP ha⁻¹ (horizon 0-20 cm considéré pour le stock du sol) en 1997. Le carbone était stocké principalement dans le sol (50 %), la biomasse aérienne ligneuse (22 %) et les souches (8 %). Les récoltes, l'élevage et la collecte de bois ont représenté respectivement 27, 59 et 14 % des prélèvements de carbone dans l'espace approprié par le village. Les animaux ont assuré 79 à 85 % des retours de C, N et P aux parcelles. Par ce système de flux, des quantités importantes de carbone ont été apportées aux champs de case (3,8 tC ha⁻¹ an⁻¹), et les pertes d'azote et de phosphore du système furent estimées à seulement 4 kgN et 1 kgP ha⁻¹ an⁻¹, ce qui indique que le terroir est proche de l'équilibre minéral.

Dans les conditions actuelles de croissance démographique, la perte de carbone pourrait cependant atteindre 0.38 tC ha⁻¹ an⁻¹ durant les trois prochaines décennies, tandis que les flux de carbone liés à l'élevage et aux récoltes doubleraient dans le même temps. La viabilité du système pourrait donc être remise en question durant les prochaines années, si aucune intensification des pratiques n'a lieu.

MOTS CLES

Azote, Biomasse, Carbone, Elevage, Fertilité, Flux, Fumier, Jachère, Matière organique, Phosphore, Plante, Sénégal, Sol, Stock, Terroir agro-pastoral

ABSTRACT

Organic matter (OM) is a multi-purpose tool in smallholder mixed-farming systems of West African savannas (WAS). It provides people and animals with energy, nutrients and construction materials. Its cycling also ensures the biological maintenance of the system, mainly through fallowing and manuring. In the WAS, population grows faster than yields of food crops. Since access to industrial inputs will remain low in the coming years, OM availability can be used as an indicator of sustainability of local farming systems. Carbon (C), nitrogen (N) and phosphorus (P; total in plant, available in soil and noted P_{OD}) budgets were thus quantified in a tropical mixed-farming system of southern Senegal to assess its viability from the plot to the village levels.

The village territory of the study showed a ring-like, compound-centred organisation. Growing intensification of fertilization and cropping practices, from the periphery to the compounds, led to the distinction of (1) a plateau bush ring under semi-permanent cultivation (2) a compound ring under continuous cultivation receiving manure from night corralling and household wastes (3) lowland, seasonally flooded, rice fields. Soils were sandy Lixisols, except in the lowland (Gleysols). Human and livestock densities were respectively 33 inhabitants and 51 tropical livestock units km^{-2} .

According to the plot study set at the beginning of the rainy season, stocks in plant and soil (down to 40 cm deep) increased from 27.8 tC, 2.03 tN and 17.3 kgP ha^{-1} in groundnut crops of the bush ring to 54.7 tC, 2.63 tN and 43.5 kgP ha^{-1} in fallows aged more than 10 years. Plant biomass accounted for nearly all of the rise. In soil, fast increase within the very first year (+20 %) was followed by stagnation (C, N) or even decrease (P_{OD}) of stocks. In six more or less manured cereal fields of the compound ring, stocks were 29.9 tC, 2.30 tN and 83 kgP ha^{-1} . Large increase of soil P_{OD} stocks in comparison to cropped bush fields was recorded at all depths and in all plots. Although significant, increases of soil C and N stocks were restricted to the 0-10 cm layer, and occurred mainly in fields adjoining farmyards, which received organic inputs with highest chemical inputs. Highest C, N and P amounts were found in lowland rice fields as a result of soil fine texture. To account for the weak response of local sandy soils to management, a plant-soil conceptual model, reassessing the thermodynamical signification of soil organic carbon cycling was proposed. In these tropical sandy soils, biota strongly controls soil physical properties and nutrient availability to plant. Perennial rooting systems, or manure exogenous inputs, are thus needed to sustain the ecosystem structural and functional integrity, since they fuel the soil biota with C-mediated energy and nutrients.

Integrative estimates for manageable stocks of the whole village territory were 29.7 tC, 1.52 tN and 28.6 kgP ha^{-1} (soil stocks: 0-20 cm layer considered only) in 1997. Main C pools were soil (52 %), woody above-ground biomass (22 %) and stumps (8 %). Crop harvest, livestock, and wood and straw collecting were responsible for respectively 27, 59 and 14 % of the C outflows from the area exploited by the village. Livestock accounted for 79-85 % of the C, N and P returns to the soil. As result of these transfers large C

inputs were brought to the compound ring ($3.8 \text{ tC ha}^{-1} \text{ y}^{-1}$). N and P depletion of the system amounted to 4 kgN and $1 \text{ kgP ha}^{-1} \text{ y}^{-1}$, suggesting that the system was close to nutrient balance.

Under current demographic growth rate, simulated C depletion of the village farming system may reach $0.38 \text{ tC ha}^{-1} \text{ y}^{-1}$ during the next three decades; meanwhile C flows related to livestock activity and crop and wood harvest should double. The viability of the system might thus be called into question within the next few years, if practices of cropping and animal husbandry are not intensified.

KEY WORDS

Biomass, Carbon, Fallow, Fertility, Flux, Livestock, Manure, Mixed-farming system, Nitrogen, Organic matter, Phosphorus, Plant, Senegal, Soil, Stock

To my parents

To the people of Sare Yorobana

FOREWORD

This work was initiated in the framework of the European Union Projects “*Reduction of the Fallow Length, Biodiversity and Sustainable Development in Central and West Africa*” (TS3-CT93-0220, DG12 HSMU) and “*Improvement and management of the fallow lands in West Africa*” (Project n° 7 ACP RPR 269, DG8). These projects have been conducted since 1994 in Burkina Faso, Cameroon, Ivory Coast, Mali, Niger and Senegal. In Senegal, these programs have acted as a research and development network; they have focused mainly on the understanding of the functioning of fallow ecosystems and alternative farming systems (research activities) and on the briefing of techniques that can be passed on due to contracts with rural organisations (development actions). In this country, the network implied both local partners such as the Senegalese Institute for Agricultural Research (ISRA) and foreign institutions like the French Institute for Research and Development (IRD, ex-ORSTOM, initiator of the project), and the French International Centre for Agricultural Research in Hot Regions (CIRAD).

The fieldwork reported in this thesis was conducted in Sare Yorobana, the wettest of the two main study sites chosen by the IRD team for its field experiment in Senegal. Both diachronic and synchronic studies were -and still are- held in these sites. Synchronic measures were aimed at characterising the dynamics of natural fallow (chronosequences) and some of the work is reported here. Diachronic experiments were set to evaluate the impact of the introduction or elimination of ecologically functional key-groups (tree, soil macrofauna, perennial grasses, woody nitrogen fixing species) on indicators of soil chemical, physical and biological properties, biodiversity and plant productivity (1994-1998), as well as their effect on crop after the clearing of fallow (1998-2001).

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The French Institute of Forestry, Agricultural and Environmental Engineering (ENGREF) is “*an application school of the Ecole Polytechnique and the Institut National Agronomique Paris-Grignon in its initial vocation, responsible for the training of the Corps of [civil servants] engineers of rural engineering, water, and forests (GREF); the school has now broadened its training, alone or in partnership (master’s and doctoral level training). (...) ENGREF is authorised to grant doctorates in the fields of its competency and the school develops scientific collaboration with numerous outside partners*” (ENGREF, 2000). The Corps of the GREF gives the opportunity to a tenth of its students to undertake a PhD thesis. The student is put on secondment in a laboratory of ENGREF or of another research institute (here IRD), by the French Ministry for Agriculture and Fishery, which thus funded a part of the research work reported here.

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Chapter 0. INTRODUCTION

0.1. VERSATILITY OF CARBON IN THE ECOSYSTEM

0.1.1. The sixth element

Atomically, carbon (C) is the sixth element of the periodic table of the elements and the sixth most abundant element in the universe, but only the 19th in the earth's crust on a weight basis (The New Encyclopaedia Britannica, 1990). However, carbon is unique among other elements in its “*almost infinite capacity of atoms to bond to each other in long chains*” (catenation), as well as to other elements. The four bonds of the carbon atom form a tetrahedron that enables molecules with C-made backbone to exhibit infinite three-dimensional spatial configuration, resulting in stable organised structures able to store and easily exchange nutrients, energy and information.

0.1.2. Static role of organic carbon

Most of carbon in live biomass is stored in plant cell walls. Its role there is to physically sustain plant architecture and channel energy, nutrients and water (Mohr and Schopfer, 1995).

In the soil, organic carbon mostly consists, on a weight basis, of a vast non-living continuum of organic compounds from fresh plant residues, produced by above- and below-ground litter decay, root exudation and faunal and microbiological casts, to humified compounds bound to fine mineral elements, thus forming the organo-mineral complex (Bonneau and Souchier, 1994). This complex plays numerous static roles in the soil: storage and exchange of nutrients, build-up of some of the cation exchange capacity, and improvement of aggregation, porosity, and water regime (Tiessen *et al.*, 1994; Syers and Craswell, 1995; Kay, 1998).

0.1.3. Dynamic role of organic carbon

Due to the ability of carbon to bind to other elements at low energetic costs, organic matter is also essential in cycling nutrients throughout the plant-soil system (Begon *et al.*, 1998). A major dynamic, ecological role of carbon is also to convey energy inside, as well as between, living beings (Lamotte and Bourlière, 1978; Begon *et al.*, 1998). Establishment of steady energy –and thus carbon- flows through living beings (Mohr and Schopfer, 1995) and systems (Odum, 1969; Perry *et al.*, 1989) is a necessity for the maintenance of their structural and functional integrity, since living individuals and communities are

thermodynamically open systems kept far from the equilibrium (Toussaint and Schneider, 1998; Straskraba *et al.*, 1999). This also applies to the soil, in which litter-C inputs initiate complex food webs implying energy and nutrient redistribution at successive trophic levels (Anderson, 1995; Neher, 1999).

0.1.4. Role of carbon in the Earth ecosystem

Of the 45000 GtC (1 Giga = 10^9) involved in biogeochemical cycles on earth, 2000-2200 are stored in the terrestrial biosphere, of which 610-640 GtC would lie in vegetation, the rest being as soil organic matter and detritus (Eswaran *et al.*, 1993; Schimel, 1995; Cao and Woodward, 1998).

Though modest by the size (750 GtC), the atmospheric reservoir is focussing growing attention, since it increased annually by 3.2 GtC during the 1980s, as a result from anthropic emissions of fossil carbon (5.6 GtC y^{-1}) and land conversion in the tropics (1.6 GtC y^{-1}) (Houghton, 1995; Schimel, 1995). And gaseous forms of carbon (CO_2 , CH_4 mainly) contribute to more than half of the radiative climate forcing due to anthropogenic release of greenhouse gas (Lambert, 1992).

0.2. SPECIFICITY OF THE ROLE OF ORGANIC MATTER IN THE FUNCTIONING OF TRADITIONAL MIXED-FARMING SYSTEMS IN SUB- SAHARAN AFRICA

0.2.1. Plant biomass as a multi-purpose tool

Plant biomass produced on site supplies most of the farmers' needs in traditional farming systems in tropical Africa:

- (1) as long as staple production meets the metabolic needs of human populations, food home consumption is the rule in West African farming systems (Kowal and Kassam, 1978),
- (2) feeding of livestock relies only on endogenous forage production, except where feed supplementation supply (recycling of industrial plant residues such as cotton and groundnut seed cake) is organised by technical advisory structures (Ruthenberg, 1971; Powell and Williams, 1994),
- (3) ninety percent of Sub-Saharan Africa (SSA) rural domestic energy consumption is provided by fuel wood (Breman and Kessler, 1995).

0.2.2. Soil organic status and soil quality

Most soils of the West African savannas (WAS) are settled on old Precambrian granitic or metamorphic parent material, or consolidated clastic sediments (Menaut *et al.*, 1985; Bertrand, 1998). As a result, they have experienced prolonged erosion and leaching, which have depleted upper soil layers from nutrients and fine elements. Thus, most of them show poor chemical status and coarse texture in the surface layer today, except for downslope clayey soils.

Meanwhile, SSA harbours 10 % of the world population but still accounted for less than 1 % of the world consumption of chemical fertilisers during the last decade (FAO, 1998a; UNDP, 1999). It suggests that farmers will not soon be able to rely on massive exogenous inputs to overcome intrinsic local soil constraints (Naseem and Kelly, 1999), hence the need for cautious recycling of local nutrients.

In these conditions soil organic matter (SOM) is crucial for the properties of these tropical sandy soils (Jones and Wild, 1975; Coleman *et al.*, 1989; Pieri, 1989; van Wambeke, 1991; Swift and Wooster, 1993; Feller, 1995a; Asadu *et al.*, 1997) such as:

- cation exchange capacity (CEC). Due to low clay content and low activity of predominant clay (kaolinit), organic matter accounts for most of the exchange capacity of soils,
- availability of nutrients (N and P), which may be protected from leaching mostly in plant debris,
- energy supply to below-ground fauna and microflora, which assist SOM in most of its functions and directly drive other soil properties such as porosity, stability and nutrient availability.

0.2.3. Relevance of organic matter availability as an indicator of the viability of West African farming systems

0.2.3.1. Conceptual considerations

Mixed-farming systems of the WAS are -and should still be for many years- self-sufficient for their functioning, since their dynamics relies basically on “*biological maintenance*”, “*the product of ecosystem properties*” (Izac, 1997a). In these systems, “*substitutional maintenance*” (management activities) such as manuring, crop and animal care, plays a vital role, but it is heavily sustained by biological maintenance. The latter is performed by the “*resource biota*” as defined by Swift and Anderson (1994), that is the “*organisms which contribute positively to the productivity of the system but do not generate a product directly utilised by the farmer*”. These authors also distinguish the “*productive biota*”, which encompasses the “*crops, plants, and livestock producing food, fibre and other products for consumption, use or sale*”. In local, low-input mixed-farming systems, the distinction between productive and resource biota is not always easy; for instance, livestock clearly belongs to both biota, since it provides meat and dairy products, as well as manure.

0.2.3.2. Organic matter: a resource and an indicator

As a matter of fact, organic matter (OM) produced on site in agricultural systems of the WAS, is not just aimed at satisfying farmers' food and cash needs. In the region, management of fertility relies mostly on fallowing and manuring. These organic practices are both processes of vertical (fallowing) and horizontal (manuring) transfers of carbon and nutrients (Floret *et al.*, 1993; Powell and Williams, 1994). They ensure organic cycling of high-quality energy and nutrients needed for both resource and productive biotas (man, animal, plant and soil). Organic matter can thus be approached as a resource, "*a form of energy and matter that is indispensable to the functioning of living beings, populations and ecosystems*" (Ramade, 1981).

In ecosystems, carbon cycling patterns yield much information about the ecosystem "wealth" (productivity and stability) (Odum, 1969). For instance, in the framework of restoration ecology, Aronson *et al.* (1993) retain three vital ecosystem attributes related to carbon cycling: biomass productivity, biomass storage and SOM content. Since farming systems of the WAS rely on their own resources, and for all that precedes, organic matter availability and use can thus be considered as indicators of the wealth of local agro-ecosystems, and in a more dynamic perspective, of their viability, that is as the aptitude to provide products (food, forage, livestock, wood...) and means of production (livestock, manure, household wastes) in a given range of values, for a given initial state, within a period of several years.

0.3. INCREASING SCARCITY OF THE ORGANIC RESOURCE IN AGRICULTURAL SYSTEMS OF THE WEST AFRICAN SAVANNAS AS A RESULT OF CLIMATIC AND ANTHROPIC CHANGES

0.3.1. Demographic growth rates and land-use change

With less than 40 people per square kilometre, SSA remains a weakly populated continent (Ker, 1995). However, it experiences the highest growth rate in the world (2.8 % between 1970 and 1995, UNDP 1999). The responses of rural populations to this evolution have usually followed three steps, well described throughout history of agriculture in the world (Mazoyer and Roudard, 1997), and confirmed by case studies in SSA (Vierich and Stoop, 1990; Lericollais and Milleville, 1993; Meertens *et al.*, 1996; Fanchette, 1999b):

- extension of cropped land to the expense of fallows, savanna and forest,
- migration to city or to less populated areas,

- intensification of cropping patterns (fertilisers, increased crop-livestock integration, and agroforestry...).

Each phase corresponds more or less to a threshold of higher labour supply and declining land availability. Of course, this general linear pattern of land-use evolution shows local variations depending on local and regional land availability, but it has proved to be relevant for most of the WAS belt (Pieri, 1989).

0.3.2. Declining trends in the balance between organic supply and need

In Senegal as in other countries of the WAS with dry tropical climate, land use change has impaired the availability of organic matter in all its forms because of (1) regression of the length and expansion of fallowing (2) shrinkage of marginal lands (3) growing exportation of cash crop harvest off the village (e.g., groundnut pods and even haulm now) (4) diminution of the SOM content due to increase of cropping intensity as a result from lower organic returns to the soil, increased erosion and oxidation due to thermo-hydric soil patterns and tillage practices (Pieri, 1989; Floret *et al.*, 1993; Ker, 1995).

Consequences are not only a decrease of the availability of biomass, but also a threat put on the means to produce this biomass, since fallowing and manuring opportunities are seriously brought into question by land use change. This organic crisis is sharpened by the dead end to which SSA countries were brought when applying structural adjustment programs. Removal of fertiliser subsidies have led to a drastic drop of fertiliser consumption and to mining agriculture in West Africa (van der Pol, 1992; Mwangi, 1997). Therefore, agricultural research and development programs have increasingly focused on means to intensify staple and cash crop production with the help of endogenous fertilising resource, that is the recycling of organic matter produced on site from the plot at the village scale (Pieri, 1989; Bekunda and Woomer, 1996; Defoer *et al.*, 1998; Dugué, 1998a; Woomer *et al.*, 1998; Bosma *et al.*, 1999; Dugué, 2000).

0.3.3. West African smallholder farming, carbon sequestration and global change

Including considerations about the way land use in the WAS might impact on global change for the definition of relevant new cropping and animal husbandry practices may seem academic and questionable at first glance. The satisfaction of land hunger and the increase of the lowest standards of living encountered on earth indeed should be the actual priority aims of any local development policy. However, from what was reported above, and as shown by Woomer *et al.* (1998) from case studies for East and Central Africa, improvement of carbon storage should help sustain farming systems and increase the standard of living of African smallholders.

On the other hand, it is now well established that evolution trajectories of even subsistence farming systems are deeply influenced by contextual factors which remain out of farmers' control such as rural

investment policies, availability of suitable technology and inputs. It is almost taken for granted that tradable pollution permits will be a preferential tool to control greenhouse gas release (Frommel, 1999). Such tools may significantly influence farming practices in Africa, provided that financial incentives are actually brought to poor-resource farmers for the adoption of carbon sequestering practices (Izac and Swift, 1994).

0.4. AIMS OF THE STUDY

0.4.1. Basic working hypothesis: carbon as a vital attribute of the village ecosystem

The work presented here is a contribution to (1) the assessment of the reliance of the viability of low-input mixed-farming systems of the WAS on their ecological dynamics (2) the prediction of possible trends experienced by these systems under basic constraints such as demographic growth and control by these ecological dynamics.

For these purposes, we focused on the dynamics of organic matter resource in both plant and soil of a village of southern Senegal. Although some of the terms of organic budgets carried out at the plot, the holding, and the village scales presented here were originally assessed in amounts of dry matter (bulk fresh organic matter minus water content, noted DM) and organic matter (ash-free DM), we tried to express organic budgets in carbon mass thanks to almost comprehensive measure of carbon content of each component, and using literature when it was not available. Though less operational than if expressed in DM units (since most of crop, animal husbandry and forestry handbooks refer to DM quantity), such a conversion in C equivalent is unavoidable before any attempt to quantify exchanges between organic component. Indeed ash content vary widely between carbon reservoirs, depending on contamination by earth or dust (roots, cow dung), and on content of “biologically inert” elements (e.g. silica), which can account for a significant fraction of the organic product.

According to what precedes, multiple roles of organic matter are involved, mainly in preservation of the biological components of the farming system. Thus, OM quality had also to be taken into account in C budgets. Therefore budgets were also computed for nitrogen (N) and phosphorus (P), availability of both elements being the main chemical constraint to agricultural intensification in the WAS (Jones and Wild, 1975; Bekunda *et al.*, 1997).

By restricting to C, N and P dynamics, we had to overlook the role of other variables such as biodiversity and water constraint to evaluate the productivity and viability of farming systems; this will be discussed in further chapters and in the general conclusion of this work.

0.4.2. A spatially integrative approach

In a first step (Part I), we study the organic status of the main representative agro-ecosystems of the village as related to land use and fertility management. Main land use systems investigated were fallow (11 plots), cash crop fields under semi-permanent cultivation (six plots), rainfed staple crop fields under continuous cultivation (six plots), and flooded rice crop fields (two plots). This approach at the plot scale was initiated for two main purposes. One was immediate, focusing on the comprehension of how organic components relate to each other, cooperate for production of usable biomass, control soil quality, and are conversely driven by soil intrinsic properties.

The second aim was the establishment of accurate C, N and P budgets at the level of the village territory (Part II), by linking easily measurable variables (such as length of the fallow period, harvest yield, cropping intensity, fertility management or land location) to estimates for other organic reservoirs.

The shift to the village scale was also meant to refine assessment of the viability of farming systems, since (1) land use systems are functionally connected to each other with regard to nutrient balances (2) land tenure and land management decision-making are mostly under communal control in rural West African societies, especially at the lineage and village levels (Pieri, 1989; Landais and Lhoste, 1993; Izac and Swift, 1994). But it should be kept in mind that multi-scale integration implied some simplifications about descriptors and determinants of organic matter dynamics at the plot scale.

To conclude with the organisation of this study, we believed that computer modelling was worth a try to formalise the knowledge obtained from the fieldwork and to attempt predictions about possible trajectories of the farming system. A first try was made in the second part of this work, using empirically based relationships between population density, livestock availability, need for food and cash and thus land management; these in turn drive C stocks and flows that are likely to occur in the WAS during the coming years.

0.4.3. Choice of the study site

This work was held in the village of Sare Yorobana, which belongs to the district of Dioulacolon, Department of Kolda, Region of High Casamance, Republic of Senegal. It is located 12°49'N 14°53'W (see Figure 0.1).

This village was mainly chosen to be the study site of two zootechnical and agroecological research programs already settled there for several years (see Foreword). Large amounts of data from different disciplines were needed for this specific kind of work, some of them being provided by these programs. The region itself exhibits two other positive characteristics for the study of current and future trends of OM dynamics in African mixed-farming systems. First, peasants of High Casamance are Fulani (Peulh) herdsmen who have been fixed for decades and have devoted themselves to both agriculture and breeding

of cattle, thus strongly integrating crop and livestock. Then, wide areas of arable land and rangeland still exist; so the region may be considered as an initial state of some of the overcrowded, saturated rural regions of the West African savanna belt; it also constitutes a good starting point to study the evolution of traditional farming systems over several decades (in an exploratory modelling perspective).

0.4.4. Organisation of the thesis

The work presented here has been submitted (Part I), or is intended to be (Part II), for publication in scientific journals concerned with agro-ecology. Therefore, chapters were made as much autonomous as possible from each other, and there is some unavoidable redundancy between them, mainly with information contained in “Introduction” and “Methods”. For the same reason, some of the data had to be presented in a synthetic manner, hence the numerous cross-references to full data presented in appendixes.

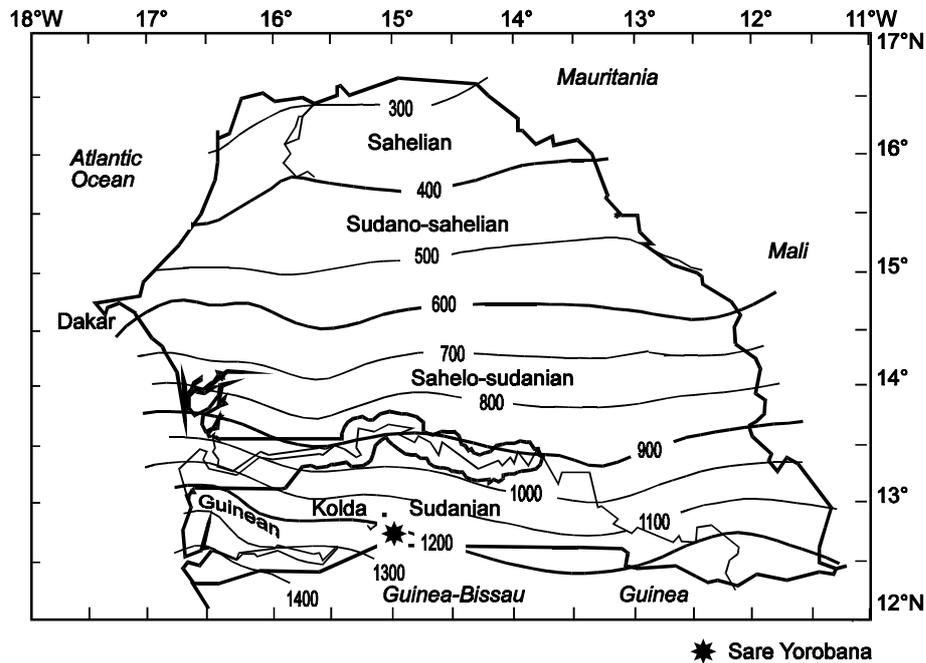
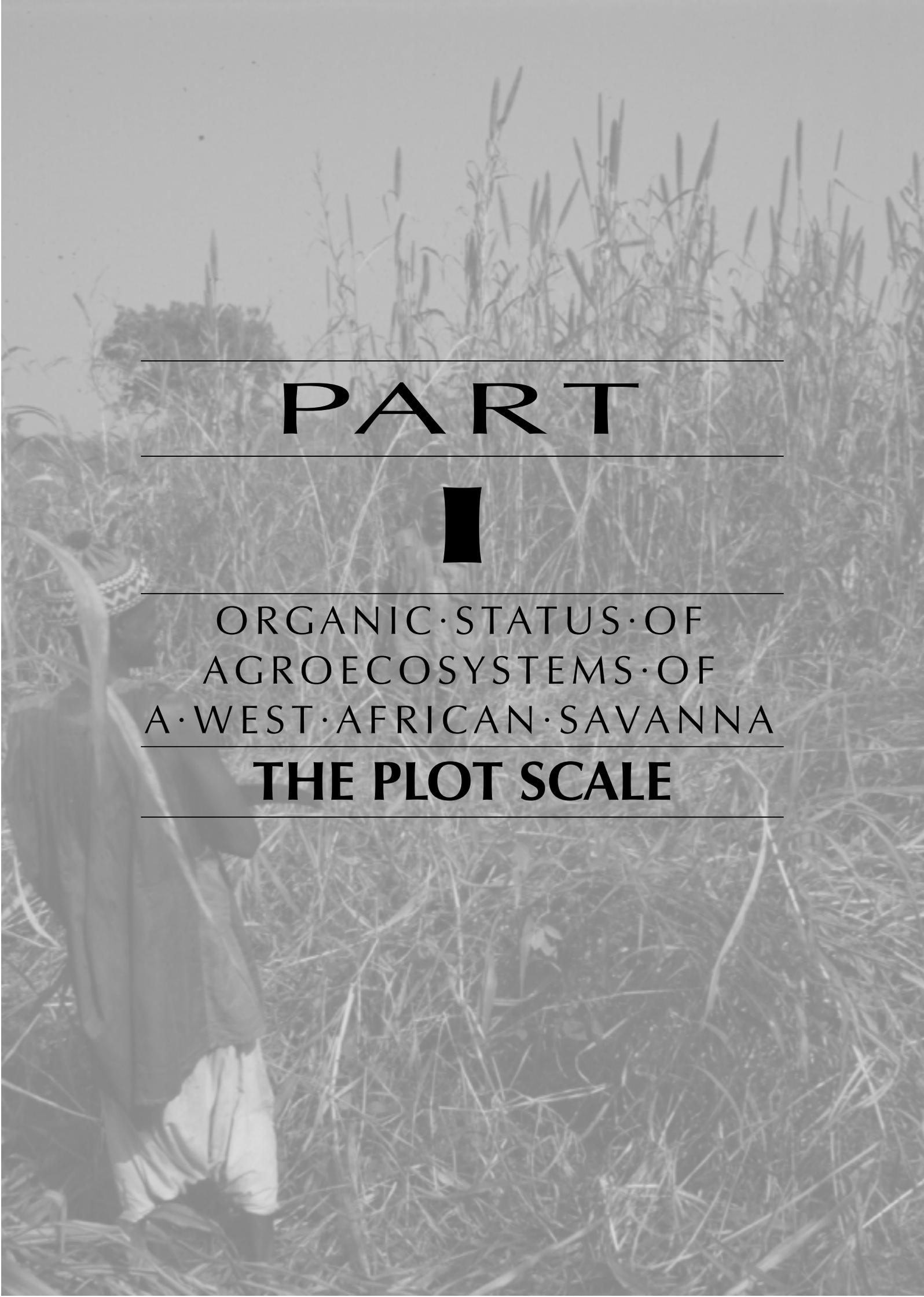


Figure 0.1 Location of the study site of Sare Yorobana (12°49'N 14°53'W) in Senegal, West Africa, and isohyets for the 1951-1980 period (Laboratoire d'Hydrologie, IRD-Dakar).



PART

I

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

THE PLOT SCALE

CHAPTER 1.

CARBON, NITROGEN AND PHOSPHORUS

ALLOCATION IN AGRO-ECOSYSTEMS

OF A WEST AFRICAN SAVANNA.

II. THE PLANT COMPONENT

UNDER SEMI-PERMANENT CULTIVATION



15- year old fallow in Sare Yorobana

Chapter 1. CARBON, NITROGEN & PHOSPHORUS ALLOCATION IN AGRO-ECOSYSTEMS OF A WEST AFRICAN SAVANNA - I. THE PLANT COMPONENT UNDER SEMI-PERMANENT CULTIVATION

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ABSTRACT

Dry matter (DM), carbon (C), nitrogen (N) and phosphorus (P) allocation occurring in plant biomass under semi-permanent cultivation in savannas of southern Senegal was measured through a chronosequence including 25 groundnut crops and plots left to fallow for one to 26 years. The amounts in cropped plots amounted to 14.7 tDM, 5.5 tC, 106 kgN and 5.9 kgP per hectare. They increased to 48 tDM, 17.7 tC, 231 kgN and 19.6 kgP in fallow plots aged 1-9 years. A threshold was reached after 10 years of fallow. Beyond it biomasses remained steady. Older fallow plots stored 79.2 tDM, 29 tC, 333 kg N and 33.8 kgP. Highest increases in woody components were found during the very first year following crop abandonment, and were achieved at the expense of the herbaceous layer. Carbon and nutrient allocation to woody below-ground biomass occurred only later, as testified by adjustments to the logistic model, and by the evolution of the shoot:root ratio. Simulations indicated that massive nutrient losses occurred at clearing due to both burning and wood exportation.

Because storage in woody and herbaceous biomass remained steady in fallows aged more than 10 years, young fallows were found to have the most interesting productivity for wood and forage. However, because this productivity relies on the high resprouting capacity of local tree species, and because this capacity can be maintained only thanks to long breaks of fallow, improving the management of fallows, or substituting agroforestry techniques for them, should aim at preserving perennial rooting systems in the semi-permanent cultivation systems of West African savannas.

KEY WORDS

Plant biomass, Carbon, Nitrogen, Phosphorus, Root, Savanna, Senegal, Semi-permanent cultivation

1.1. INTRODUCTION

Favourable temperature and insolation allow high potential values of net primary productivity in the Tropics. However, corollary drawbacks such as weed encroachment, and pest and disease vitality, seriously impede the efficiency of tropical farming (Ruthenberg, 1971). In the West African savanna belt, other specific biophysical restrictions to crop and animal production are: erratic and seasonal rainfall, soil sensitiveness to erosion and poor nutrient status (Jones and Wild, 1975; Kowal and Kassam, 1978). Low availability of working power due to weak mechanisation, limited access to chemical inputs and common land tenure are the main human features, that all together with natural constraints, explain the local choices for diversified, labour-saving, and extensive schemes of crop and animal production (Ker, 1995). Apart from restricted areas of flooded agriculture, practices that sustained soil fertility in traditional farming systems were mainly organic. In most of the subregion, this was, and yet is, the aim of manuring, fallowing, mulching and composting to a lesser extent (Ruthenberg, 1971). These techniques have proved to be adapted to sparsely populated areas and have led to the widespread practice of ring management in African villages (Pélissier, 1966; Ruthenberg, 1971; Prudencio, 1993).

Three main rings are roughly distinguished (Figure 1.1):

- (1) the savanna or forest ring, that has never -at least not for several decades- been cultivated. Because this is the farthest ring from the village, integration to the farming system remains low, although it can provide wood and essential pasture during the wet season. Unlike the other rings, this area is usually not appropriated by the village,

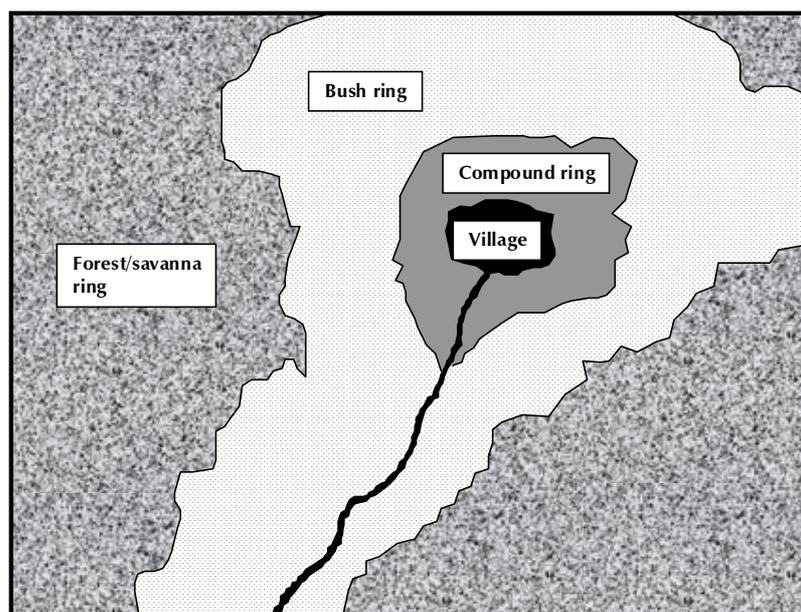


Figure 1.1 Simplified ring organisation of a village of the mixed-farming system of the West African savanna belt.

- (2) the bush ring, which consists of a mosaic of bush fields -mainly cash crops- and young to old fallows. Fertility is mainly sustained by fallowing. Fallow can also occur due to a shortage of working power or of crop seeds,
- (3) the compound ring, devoted to food crops. Intensified continuous cultivation is enabled by manuring (mostly during night corralling) and household waste inputs throughout the dry season.

Because of local and global reasons, there is a growing need to assess carbon, nitrogen and phosphorus storage in savanna agroecosystems of West Africa as related to soil characteristics and land management.

At a local scale, and for a few decades, rural population dynamics, land tenure politics and technical innovations have encouraged a shift in traditional practices. While the savanna ring has been almost vanishing, the bush ring area has dramatically shrunk because of growing needs for land, and for the benefit of continuous cultivation. Although this trend is not to be reversed soon, it is generally admitted that multi-purpose, improved fallows will keep playing a role in farming systems of savannas, while intensification in the compound ring will be maintained by better crop-livestock integration and agroforestry practices.

Most African agricultural policies implemented during the last 30 years have led to unsustainable and slow production increase due to incomplete knowledge about the ecological bases of tropical ecosystem fertility, especially in the savanna belt (Brown and Thomas, 1990). A better understanding of agro-ecological patterns of fertility conservation occurring in existing semi-permanent and continuous cropping systems in savanna is a prerequisite to the safe adoption of any technical innovation.

The hypothesis underlying our work is that this understanding mainly relies on the study of the organic matter-mediated cycles of carbon, nitrogen, and phosphorus. Special emphasis will be put on organic matter and carbon dynamics. In largely self-sufficient farming systems, indeed, organic matter supplies peasants with food and wood, and livestock with forage (Floret *et al.*, 1993). It is its proper management that ensures the sustainability of the agroecosystem too. In heavily leached sandy sub-Saharan soils, chemical, physical and biological soil properties hang on soil organic matter status (de Ridder and van Keulen, 1990). Nitrogen and phosphorus were also largely included in the present study, because these elements are the most limiting chemical factors to plant productivity in African savannas (Jones and Wild, 1975). Another reason for such consideration is that the nitrogen cycle is closely related to the organic matter cycle, and that it characterises the quality of carbon involved in the plant-soil system. Because the present work is an integral part of an attempt to assess current and future carbon stocks and fluxes at the scale of a village agroecosystem (Chapters 4 and 5), it also provides parameterised models of carbon dynamics in the main organic components of the agroecosystems of this savanna ecozone. The plant biomass produced under semi-permanent cultivation systems in West-African savannas does not only provide a valuable source of fibre and energy for farmers and their livestock. Because of the chemical poverty of local soils, soil fertility is closely related to the dynamics of the vegetation, which ensures the

safe accumulation of nutrients, drives soil nutrient availability to plants, and initiates patterns of energy redistribution to the soil biota (Perry *et al.*, 1989; Hendrix *et al.*, 1990).

On a more global perspective, land use changes in the tropics would have been responsible for nearly a fifth of the total release of anthropogenic carbon in the 1980s (Schimel, 1995). In Senegal, more than 40 % of carbon dioxide emissions stems from agriculture, land use changes and forests (Sokona, 1995). Reviews of Desanker *et al.* (1995) and Tiessen *et al.* (1998) emphasise the scarcity of carbon budget assessment in dry tropical ecosystems as compared to wetter zones, and the particular paucity of studies in Africa with regard to the work already achieved in other dry tropical regions of the world. Considering West African demographic and economic contexts, the control of greenhouse gas emissions may not become a priority as such for political leaders. But carbon sequestration in African smallholder agriculture is a key to sustainable intensification and recovery of farmers' wealth (Woomer *et al.*, 1998). Evaluating carbon sequestration potential of agro-ecosystems of the sub-region was thus another goal of our work.

This chapter is the first of a series of three, aimed at assessing carbon (C), nitrogen (N) and phosphorus (P) allocation in the bush and compound rings of a mixed-farming system of southern Senegal. The present part deals with C, N and P allocation in plant biomass during the crop-fallow cycle usually happening in the bush ring, while soil allocation is studied in Chapter 2. Storage of C, N and P in plant biomass and soil under continuous cultivation is reported in Chapter 3.

In this study we (a) describe recovery patterns of dry matter (DM), C, N and P biotic allocation and study hierarchical relations between organic components during fallow (b) define temporal thresholds of evolution for DM, C, N and P in the components of plant biomass (c) evaluate the fate of above-ground plant biomass and related nutrients after conversion to crop.

1.2. METHODS

1.2.1. Site characteristics

The study has been led between 1993 and 1997 in High Casamance, southern Senegal. Crop and fallow plots were investigated in the village of Sare Yorobana (12°49'N – 14°53'W). The climate is Sudanian, tropical dry. Annual rainfall ranged between 570 and 1320 mm (mean: 960 mm) during the last 20 years and occurred from May to October (Figure 1.2); 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).

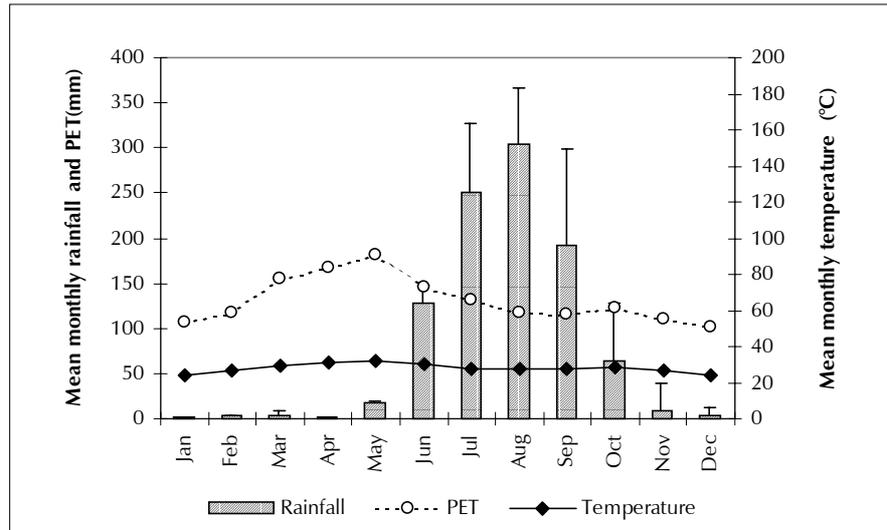


Figure 1.2 Monthly patterns of rainfall, potential evapotranspiration and temperature at the station of Kolda, 1978-1997. Vertical bars stand for standard error. PET: potential evapotranspiration. See data in Appendix 3.

Ring-like, compound-centred management of the village individualises three main land use systems or units along the typical, smooth toposequence:

- (1) The up-slope plateau. It is still covered with vast areas of “woodlands with a well developed tree stratum and shrubby undergrowth” (de Wolf, 1998), savanna and old fallows. Resprouting Combretaceae are the major component of woody vegetation. In the study site four woody species dominate, amounting to 70 % of woody above-ground biomass (AGB): *Combretum geitonophyllum* Diels, *Combretum glutinosum* Perr., *Piliostigma thonningii* (Sch.) Miln.-Redh and *Terminalia macroptera* G. et Perr.. 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, usually in rotation with millet if manured, but mostly with short fallow rotation. Cotton (*Gossypium hirsutum* L.), the main other cash crop, is also to be found in this unit. The soil is sandy, ferruginous (Baldensperger *et al.*, 1967), and is classified as a ferric Lixisol (FAO, 1998b). A more detailed description can be found in Chapter 2 and in Appendix 4. This unit encompasses the forest/savanna and most of the bush rings. All sampled plots, except three, belong to the plateau (see Methods).
- (2) the mid-slope glacis, sharing soils similar to the plateau (haplic Lixisols). It bears the compound ring, and thus continuous cultivation crops with cereals (pearl millet -*Pennisetum glaucum* L.; maize -*Zea mays* L.; sorghum -*Sorghum bicolor* L. Moench).
- (3) the lowland, devoted to rice and palm plantation, with soils being Gleysol (FAO, 1998b) (see Chapter 3 for more details).

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

groundnut, fallow and sometimes millet is quite unpredictable. The traditional pattern of cropping in this ring is as follows. In practice, plant biomass produced during fallowing is either exported for wood and forage use, or burnt during uncontrolled fires. Massive disappearance of plant biomass happens at clearing, due to on-site burning and wood removal; only rooting systems are saved (Floret *et al.*, 1993). Traditional hand clearing can be labour-intensive, but woody stumps allowing regular resprouting are maintained several years before they die (Bohringer *et al.*, 1996). Clearing of old fallows or savanna is usually followed by two to four years of continuous cropping implying the biennial rotation of groundnut with cereals (millet, sorghum). After the rapid loss of the initial fertility (four to five years), continuous cultivation can be maintained a few more years if proper manuring is carried out prior to cereal cropping. However, food needs are usually met with crops from the compound ring, and livestock availability is often insufficient, so that the biennial rotation of groundnut with fallow occurs rapidly, if not straight away, after clearing. The rotation is maintained as long as soil fertility and low weed competition allow good yields. The field is then returned to fallow for several years, the length of fallow depending on soil properties, labour availability or land tenure factors.

1.2.2. Sampling schemes

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

The sampling was done at the onset of the dry season, very close to peak plant above-ground biomass (AGB).

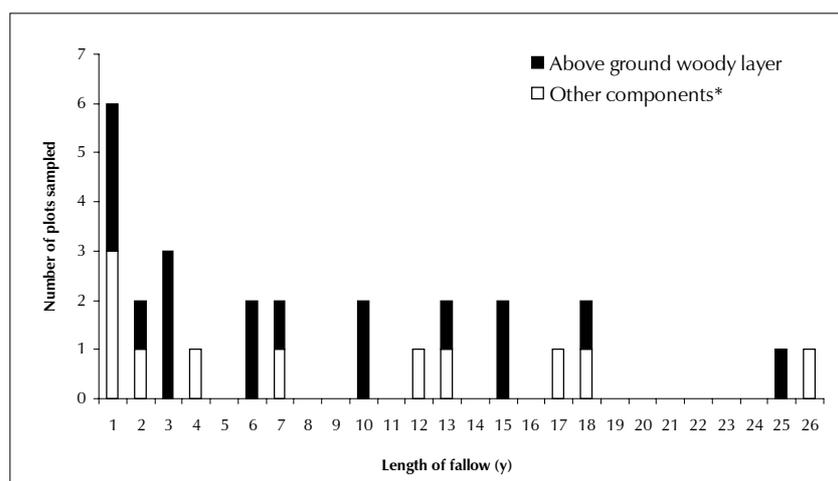


Figure 1.3 Distribution of the length of fallow among the 28 sampled plots of fallow.
* including soil (see Chapter 2).

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

- (1) Fallow plots (FA), aged 1-26 years (Figure 1.3): woody AGB was estimated on 17 plots (three 900 m² square-like subplots for each). Woody AGB (trunk –any branch with a diameter above 4 cm-, twig and leaf) and stump biomass (in fallows aged more than 4 years) were estimated using a regression relationship based on the tree diameter at breast height, that is 1.3 m (Table 1.1) (Kairé, 1999). Other variables were sampled every meter in a 0.5-m² parallelepiped, along a 20-m long and 0.5-m wide transect, in 11 plots different from the previous ones but all located on the plateau (except plot FA01a, settled on the upper glaxis) (Appendix 1). Herbaceous layer was harvested, comprising live and dead (but standing) plant biomass. Litter was picked as the figured A0 organic layer ($\varnothing > 2\text{mm}$). Fine roots were sampled with a core auger (\varnothing : 5.6 cm) in 10-cm increments. On-field manual separation from soil excavated down to a 40-cm depth was used for coarse roots recovery, because core sampling is not accurate for roots coarser than 2 mm. In fallows aged four years or less, stumps were pulled out together with coarse roots.

Table 1.1 Regression coefficients used for woody biomass estimate for the four main species found in Sare Yorobana.

Species	Component	a	b	R ²
Combretum geitonophyllum	above ground biomass	0.283	2.17	0.97
	- trunk	0.103	2.44	0.97
	- twig	0.0947	2.15	0.96
	- leaf	0.0682	1.74	0.94
	stump	0.205	1.63	0.89
Combretum glutinosum	above ground biomass	0.149	2.33	0.98
	- trunk	0.0965	2.43	0.96
	- twig	0.0782	2.16	0.91
	- leaf	0.0676	1.99	0.94
	stump	0.175	1.78	0.80
Piliostigma thonningii	above ground biomass	0.157	2.27	0.97
	- trunk	0.0898	2.29	0.94
	- twig	0.0785	1.99	0.96
	- leaf	0.0554	1.79	0.89
	stump	0.149	1.66	0.89
Terminalia macroptera	above ground biomass	0.0979	2.40	0.96
	- trunk	0.0966	2.52	0.97
	- twig	0.0626	2.38	0.97
	- leaf	0.035	2.02	0.92
	stump	0.155	1.69	0.92
Others	above ground biomass	0.172	2.29	
	- trunk	0.0965	2.42	
	- twig	0.0785	2.17	
	- leaf	0.0566	1.89	
	stump	0.1710	1.69	

Model: biomass (in kgDM) = $a \cdot D^b$ with D the diameter -in cm- at breast height

Number of replicates: above-ground biomass: $n=40$; trunk, twig, leaf and stump: $n=15$.

Other species: parameters estimated as the mean of the parameters of the four main species.

Derived from Kairé (1999).

- (2) Cropped groundnut plots (coded as GN): six fields that had borne groundnut in a biennial rotation with fallow -or sometimes millet- for four to 15 years, and that had never been chemically fertilised, were chosen up-slope. Four lay on the plateau, two on the upper glaxis (GN04 and GN06). In each of them, four 16-m² square subplots were randomly defined. In each square, vegetation was cut for plant biomass assessment, with a distinction made between woody (stump regrowth) and herbaceous (weed and groundnut) layers. Litter biomass was nearly negligible, and it was not sampled. Fine roots were cored at each subplot's corner. Coarse root biomass was estimated with a regression relationship, established in fallows. This relation proved to be satisfactory to link coarse root biomass as measured by full excavation (a) to that measured by the coring technique (b): $a=1.73 \cdot b + 2.95$ (in tDM ha⁻¹); $R^2=0.6$; $p\{F_{obs} > F_{th}\} < 0.05$; $n=9$ (Appendix 5). Three out of the six groundnut fields (GN02, GN03 and GN04) investigated in 1996 were re-sampled in 1997 as one-year old fallows; in these plots stump

biomass was assumed (and thus probably slightly over-evaluated) to be that measured in the same (uncropped) plots in 1996.

In all plots, below-ground plant biomass (BGB) was sampled down to a 40-cm depth. This limit was chosen according to local unpublished observations and to other published works (Chopart, 1980; Tomlinson *et al.*, 1998). They indicate a very weak root activity below a 40-cm depth in soils of dry tropical West Africa.

1.2.3. Plant analyses

Stumps and coarse roots were hand washed and sorted according to their diameter ([2-5], [5-10], >10 mm). Fine roots were recovered from soil after hydro-pneumatic elutriation above a 1-mm sieve (Webb, 1995). All plant samples were oven-dried at 70 °C to constant weight for dry matter (DM) content determination. Samples were pooled and one analysis of each component was made for each plot. C content was determined after dichromate oxidation, N with the Kjeldahl method; P was measured on ashes. All methods are fully described in Page *et al.* (1989). C, N and P storage values were obtained by directly combining DM stock values and chemical content of plant biomass (Table 1.1 and Table 1.2a,b; see Kairé, 1999 for the detailed calculation of C, N and P amounts in woody biomass).

1.2.4. Study of the fate of post-fallow above-ground biomass

The fate of woody AGB (burnt on site or brought back to the compound) at clearing hangs upon branch diameter. Enquiries among farmers indicated that 4 cm was the threshold beyond which tree biomass was exported for wood need, while smaller twigs and leaves (available biomass for burning or ABB) were burnt on site. Combustion efficiency was not measured, and hangs upon local practices. Taking into account the works of Stromgaard (1985) and Fearnside and Barbosa (1998), two scenarios were considered, depending on the burning efficiency (90 and 50 %) of remaining plant biomass. They were applied to two hypothetical fallow plots: a young (aged less than 10 years) and an old fallow plots (aged 10 years or more); woody AGB of these plots was derived from the means computed in Table 1.6.

1.2.5. Data analyses

In sub-humid savannas, plants compete more for nutrients than for water, and fire yearly destroys most of the grass layer; this is why the dynamic of woody plant is not driven much by competition with the grass layer (Walker, 1985). We therefore hypothesised that temporal dynamics of plant dry matter and related nutrient storage could be adjusted to the logistic model. This model accounts well for population dynamics with limited nutrient availability (Pavé, 1994). Mathematical expression is:

$$S(t) = \frac{K}{1 + \frac{(K - S_0)}{S_0} \cdot e^{-r \cdot t}}$$

where S_0 is the value of the stock at $t=0$ and $K = \lim S$ when $t \rightarrow +\infty$.

A slightly modified generalised form of the model had to be adopted for two reasons:

- (1) Tree dynamics at crop abandonment is all the more autonomous with regard to other living functional groups, because it relies on stump re-growth and not just seedling. Thus, maximum increase of plant biomass can occur during the first years of fallow.
- (2) We also wanted to test the two following hypotheses (a) in local savannas, grass biomass is controlled by competition for light with trees (Akpo, 1998) and could thus be modelled as a simple linear function of tree biomass (b) tree and grass layers contributed equally to fine root biomass with respect to their biomass, and thus fine root biomass could be described as the sum of two linear functions of woody and herbaceous AGB.

The model finally tested was:

$$S(t) = \frac{a \cdot K}{1 + \frac{(K - S_0)}{S_0} \cdot e^{-r \cdot t}} + b$$

Including values measured in crop plots for model parameterisation depended on the biological continuity of each component between crops and fallows (see Table 1.4 and Figure 1.4a,b).

All statistical analyses were done using SAS software 6.14 (Hatcher and Stepanski, 1994). NLIN and REG procedures were used for the estimation of non-linear regression parameters. Model adequacy was estimated testing R^2 , slope and intercept of the regression of modelled *vs.* observed data (Pavé, 1994). Analyses of variance (Anova) were performed with proc GLM on ranks of data due to the small size of the population measured, and uncertainty about normality of distributions of data and residues (Potvin and Roff, 1993). SNK multiple-comparison test was used to segregate treatments according to the mean of rank values ($\alpha=0.05$).

1.3. RESULTS

1.3.1. General trends

C contents were very stable among tree species and other plant biomass components (Table 1.2a,b). N and P contents were highest in tree leaves, herbaceous layer and fine roots of crop vegetation.

Table 1.2 Carbon, nitrogen and phosphorus content of: a. Plant components of the four main woody species. Contents for other species were estimated as the mean of these values. b. Other above- and below-ground plant components of cropped and fallow fields.

a.

Species	C (g 100g ⁻¹ DM)			N (g 100g ⁻¹ DM)			P (g 100g ⁻¹ DM)		
	Trunk / stump	Twig	Leaf	Trunk / stump	Twig	Leaf	Trunk / stump	Twig	Leaf
<i>Combretum geitonophyllum</i>	38.8	35.8	35.8	0.45	0.29	1.48	0.04	0.04	0.09
<i>Combretum glutinosum</i>	37.6	38.5	39.7	0.16	0.32	1.18	0.03	0.02	0.05
<i>Piliostigma thoningii</i>	37.3	37.0	37.5	0.23	0.37	1.55	0.02	0.03	0.08
<i>Terminalia macroptera</i>	36.5	37.6	36.1	0.16	0.18	1.15	0.02	0.02	0.07

Derived from Kairé (1999)

b.

	Herb. layer	Litter	Fine root	Coarse root	Stump
C (g 100g ⁻¹ DM)					
Groundnut	37.5 ±0.4		34.1 ±0.5	38.0 ⁺	38.0 ⁺
Fallow	34.4 ±0.9	33.1 ±0.5	34.3 ±0.4	36.6 ±0.4	37.0 ±0.8 [‡]
N (g 100g ⁻¹ DM)					
Groundnut	1.93 ±0.02		1.66 ±0.03	0.35 ⁺	0.35 ⁺
Fallow	0.72 ±0.05	0.51 ±0.03	0.78 ±0.05	0.40 ±0.03	0.41 ±0.06 [‡]
P (g 100g ⁻¹ DM)					
Groundnut	0.11 ±0.00		0.07 ±0.01	0.02 ⁺	0.02 ⁺
Fallow	0.07 ±0.01	0.03 ±0.00	0.04 ±0.00	0.03 ±0.00	0.02 ±0.01 [‡]

±: standard error. Groundnut plots: n=6. Fallow plots: n=11.

+ : estimated as the mean of coarse root's values from FA1a, FA1b and FA1c.

‡: estimated as the content of coarse root measured in fallows aged one to four years; used for the calculation of C, N and P stock values in fallows aged one to four years only.

See data in Appendix 6.

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

The plant biomass of the whole ecosystem averaged 49 tDM ha⁻¹ among the cropped and fallow plots investigated. This corresponded to 18 tC, 250 kgN and 21 kgP per hectare, of which more than 40 % and 50 % of N and P respectively were stored in woody AGB (Table 1.3, Figure 1.4a). Stumps were the second contributors to the storage of DM, C, N and P in the ecosystem. There was a more than three fold increase of DM storage in woody AGB between one-year old fallow plots (14 t ha⁻¹) and those older than 18 years (43 t ha⁻¹), half of it being stored in trunks in oldest fallows. C (from 5.1 to 15.9 t ha⁻¹), N (75 to 161 kg ha⁻¹) and P (7 to 21 kg ha⁻¹) amounts showed temporal patterns similar to DM during the fallow succession, though N storage occurred mainly in leaves. Stump biomass doubled meanwhile, reaching 15 t ha⁻¹ and storing 26 % of N and 17 % of P contained in the woody vegetation. Herbaceous biomass averaged 3.0 t ha⁻¹ (1.1 tC ha⁻¹) in crops and it increased to 6.0 t ha⁻¹ in youngest fallows but dropped to 1.6 t ha⁻¹ in the two oldest fallows. Organic and nutrient amounts in fine and coarse roots increased four (N) and six (P) folds between crops and oldest fallows, finally reaching 20 tDM, 7.2 tC, 88 kgN and 8.1 kgP per hectare. Fine roots represented 14 % of root biomass but more than a third of N and P storage in roots (not including stumps). Fine roots distribution between soil layers did not differ through the chronosequence; half of it was stored in the upper 10 cm. Shoot:root ratio averaged 0.22 in crops. It was higher in fallows aged less than 10 years than in older plots of the succession (0.62 vs. 0.56).

Table 1.3 Dry matter storage ($t\ ha^{-1}$) in plant components under a crop-fallow succession.

Plot	AGB ⁽¹⁾				Litter	Root				Stump	ABB ⁽²⁾		
	Woody		Herb.			Fine (per sampling depth in cm)							
	Trunk	Twig	Leaf	Total		0-10	10-20	20-30	30-40			Coarse	
GN01				0.13	2.37			0.19	0.15	0.11	0.07	5.2	
GN02				0.02	3.41			0.20	0.17	0.10	0.07	3.0	13.8
GN03				0.29	2.34			0.25	0.16	0.12	0.08	3.1	5.0
GN04				1.20	3.45			0.33	0.18	0.11	0.07	3.0	3.5
GN05				0.24	2.76			0.21	0.09	0.08	0.05	2.9	
GN06				0.03	3.42			0.29	0.18	0.10	0.07	3.0	
FA1a					6.51	1.84		0.78	0.28	0.20	0.14	5.4	3.5
FA1b					5.51	2.10		1.17	0.28	0.25	0.26	8.6	13.8
FA1c					4.99	1.53		0.81	0.16	0.22	0.19	3.4	5.0
FA1d													4.3
FA1e	2.2	1.3	0.8	4.3									16.9
FA1f	8.0	5.3	3.6	16.9									19.8
FA2a					6.01	0.57		0.72	0.27	0.30	0.20	5.9	11.7
FA2b	11.5	7.5	5.1	24.1									20.8
FA3a	5.9	3.2	1.4	10.5									8.0
FA3b	14.7	9.1	5.8	29.6									23.0
FA3c	12.4	8.2	4.5	25.1									19.8
FA4					9.45	2.77		0.90	0.28	0.21	0.16	4.7	4.7
FA6a	15.4	9.0	6.2	30.6									11.5
FA6b	15.8	9.0	4.4	29.2									15.6
FA7a					3.32	2.97		1.11	0.57	0.44	0.34	13.8	
FA7b	16.2	8.5	3.3	28.0									11.1
FA10a	19.8	11.4	6.7	37.8									11.8
FA10b	21.6	11.4	6.0	39.0									17.7
FA12					1.93	3.86		1.19					14.3
FA13a					0.96	1.19		1.82	1.19	0.74	0.68	19.6	
FA13b	21.5	10.5	3.9	35.9									12.5
FA15a	24.0	13.3	7.7	45.0									12.0
FA15b	22.3	11.8	6.2	40.4									18.6
FA17					2.15	2.65		1.32					15.8
FA18a					1.81	1.75		1.22	0.74	0.62	0.53	14.1	
FA18b	27.0	11.5	5.8	44.3									15.4
FA25	22.5	12.1	6.4	41.0									13.8
FA26					1.43	1.73		1.21	0.80	0.69	0.82	19.9	17.6

GN: groundnut crop. FA: fallow; the associated number stands for the age of fallow (in years).

⁽¹⁾ AGB: live above-ground biomass. Derived from Kairé (1999).

⁽²⁾ ABB: available biomass for burning. Derived from Kairé (1999).

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

1.3.2. Adjustment of temporal dynamics of C, N & P in plant biomass to the logistic model during fallow

Best fits to the model were found for data of DM and C in woody and herbaceous AGB (Table 1.4, Figure 1.4a). A threshold was observed as from 10 years of fallow, whatever the variable and the component, except for stumps for which initial biomass was already substantial. However, different patterns were noticed before the threshold was reached, depending on variable and component. Models adjusted to data of AGB components showed no point of inflection, indicating maximum growth during the first years of fallow; this was not the case with coarse root DM and C, and fine root N and P storage (Figure 1.4b). Estimating herbaceous and fine root biomass as linear functions of respectively woody AGB, and woody and herbaceous AGB, led to little loss of explanatory power of the model, although it modified the aspect of the curves for N and P storage in fine roots.

Table 1.4 Estimates for parameters of a regression of $S = \{\text{amount of dry matter, carbon, nitrogen or phosphorus}\}$ on $t = \text{length of fallow}$, according to a logistic-like model: $S(t) = \frac{a.K}{1 + \frac{(K - S_0)}{S_0} \cdot e^{-r \cdot t}} + b$.

Unit	Component	Constraint(s)	a	K	So	r	b	R ²	F	p>F	n	p{Ho:intercept=0}	p{Ho:slope=1}
DM (t ha ⁻¹)	Woody layer	(1)	1	1150.3	1109.9	0.275	-1109.59	0.91	212.8	***	23	0.64	0.39
	- trunk	(1)(2)	1	580.7	557.0	0.211	-556.80	0.87	97.8	***	17	0.79	0.63
	- twig	(1)(2)	1	281.2	269.8	0.340	-269.69	0.71	37.2	***	17	0.24	0.18
	- leaf	(1)(2)	1	138.07	132.51	0.648	-132.44	0.27	5.6	*	17	***	***
	Herbac. layer	Low : (2)	1	1.60E-03	6.94	4.14E-05	0.00	0.90	75.3	***	10	0.41	0.35
		High : (3)	-0.14	1150.3	1109.9	0.275	159.33	0.89	67.2	***	10	0.43	0.36
	Fine root	Low : (1)	1	113.29	110.31	0.204	-109.74	0.89	121.1	***	17	0.63	0.39
		High : (4)	0.07	1150.3	1109.9	0.275	-75.20	0.88	110.3	***	17	0.25	0.17
	Coarse root	(1)	1	15.1	1.4	0.444	2.01	0.89	122.1	***	17	0.64	0.37
	Stump	(1)	1	15.54	7.77	0.211	-0.31	0.41	11.3	**	18	**	***
C (t ha ⁻¹)	Woody layer	(1)	1	416.3	401.2	0.278	-401.09	0.91	211.1	***	23	0.63	0.38
	- trunk	(1)(2)	1	255.8	246.9	0.212	-246.84	0.86	95.8	***	17	0.77	0.62
	- twig	(1)(2)	1	111.11	106.84	0.339	-106.80	0.72	38.1	***	17	0.24	0.18
	- leaf	(1)(2)	1	46.59	44.49	0.650	-44.46	0.28	5.9	*	17	***	***
	Herbac. layer	Low : (2)	1	0.00	2.69	4.31E-05	0.00	0.93	114.0	***	10	0.48	0.42
		High : (3)	-0.14	416.3	401.2	0.278	60.51	0.93	100.8	***	10	0.54	0.46
	Fine root	Low : (1)	1	24.73	23.70	0.198	-23.50	0.88	113.2	***	17	0.66	0.40
		High : (4)	0.06	416.3	401.2	0.278	-24.79	0.87	100.4	***	17	0.23	0.16
	Coarse root	(1)	1	5.10	0.25	0.548	1.04	0.88	107.3	***	17	0.69	0.38
	Stump	(1)	1	5.50	2.75	0.202	0.08	0.37	9.6	**	18	**	***
N (kg ha ⁻¹)	Woody layer	(1)	1	4086.1	3930.9	0.405	-3929.41	0.82	97.4	***	23	0.25	0.11
	- trunk	(1)(2)	1	1510.8	1457.4	0.229	-1457.06	0.72	38.5	***	17	0.31	0.21
	- twig	(1)(2)	1	777.5	745.9	0.383	-745.60	0.66	29.2	***	17	0.11	0.08
	- leaf	(1)(2)	1	1826.7	1755.5	0.708	-1754.61	0.22	4.3	0.05	17	***	***
	Herbac. layer	Low : (2)	1	1.12E-02	37.60	3.33E-05	0.00	0.86	47.7	***	10	0.31	0.27
		High : (3)	-0.19	4086	3931	0.405	798.91	0.78	27.9	***	10	0.20	0.17
	Fine root	Low : (2)(5)	1	17.2	0.1	1.036	9.63	0.87	59.2	***	11	0.46	0.38
		High : (4)	0.16	4086	3931	0.405	-637.50	0.78	32.7	***	11	0.18	0.15
	Coarse root	(1)	1	1254.5	1195.4	0.134	-1183.63	0.89	123.3	***	17	0.34	0.22
	Stump	(1)	1	66.1	33.0	0.272	-7.20	0.44	12.7	**	18	***	***
P (kg ha ⁻¹)	Woody layer	(1)	1	463.0	442.5	0.247	-442.33	0.91	212.3	***	23	0.72	0.60
	- trunk	(1)(2)	1	500.6	484.3	0.204	-484.19	0.86	91.1	***	17	0.84	0.67
	- twig	(1)(2)	1	83.02	80.14	0.365	-80.12	0.56	18.9	***	17	0.09	0.06
	- leaf	(1)(2)	1	33.70	32.20	0.978	-32.18	0.12	2.0	0.18	17	***	***
	Herbac. layer	Low : (2)	1	1.23	4.84	0.159	0.00	0.83	39.7	***	10	0.30	0.25
		High : (3)	-0.13	463.0	442.5	0.247	60.95	0.82	36.8	***	10	0.27	0.22
	Fine root	Low : (2)(5)	1	0.82	0.00	0.748	0.60	0.88	68.9	***	11	0.38	0.34
		High : (4)	0.05	463.0	442.5	0.247	-22.83	0.80	37.1	***	11	0.20	0.18
	Coarse root	(1)	1	359.77	350.53	0.052	-349.85	0.87	100.6	***	17	0.22	0.12
	Stump	(1)	1	5.89	2.94	0.229	-1.45	0.71	39.1	***	18	**	**

Constraints:

(1) sets $S(0)$ as the average value of S measured in crops.

(2) excludes crop data for model parameterisation.

(3) sets $S_{\text{herbaceous layer}}$ as a linear function of $S_{\text{woody layer}}$

(4) sets $S_{\text{fine root}}$ as a linear function of $S_{\text{herbaceous layer}}$ and $S_{\text{woody layer}}$

(5) sets $S(1)$ as the average value of S measured in one-year old fallows.

F test performed on R² and slope of linear regression of observed vs. predicted (t-test on the intercept).

p(:): * < 0.05; ** < 0.01; *** < 0.001.

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

See data in Appendix 7.

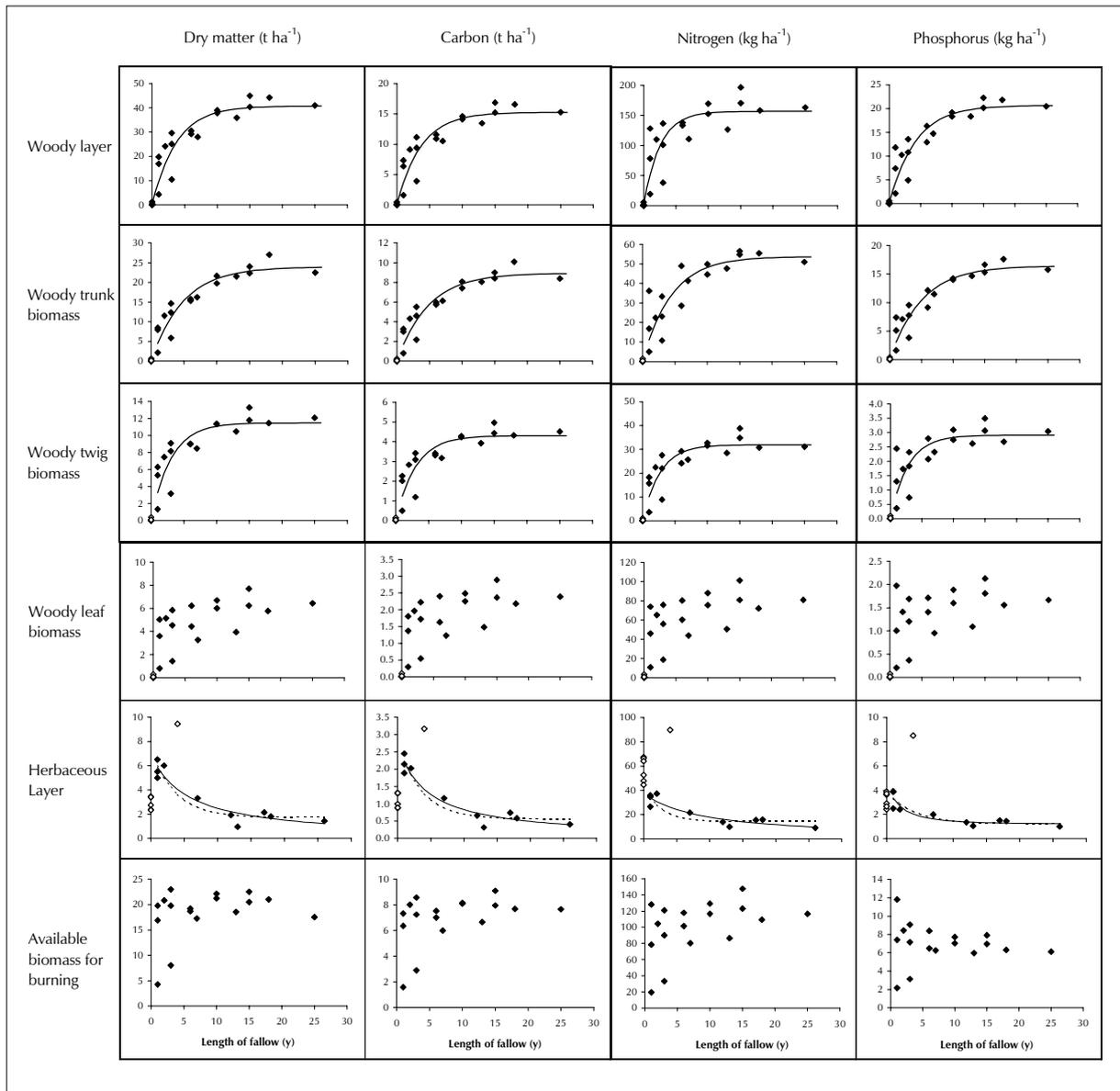


Figure 1.4 Dry matter, carbon, nitrogen and phosphorus storage in plant biomass during a crop-fallow succession, and fitting to a

modified, logistic-like model:
$$S(t) = \frac{a.K}{1 + \frac{(K - S_0)}{S_0} \cdot e^{-r \cdot t}} + b .$$

a. above-ground components.

Plain line: low-constraint model (see text and Table 1.4). Dotted line: high-constraint model. Plain dots: data used for model adjustment.

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

See data in Appendix 7.

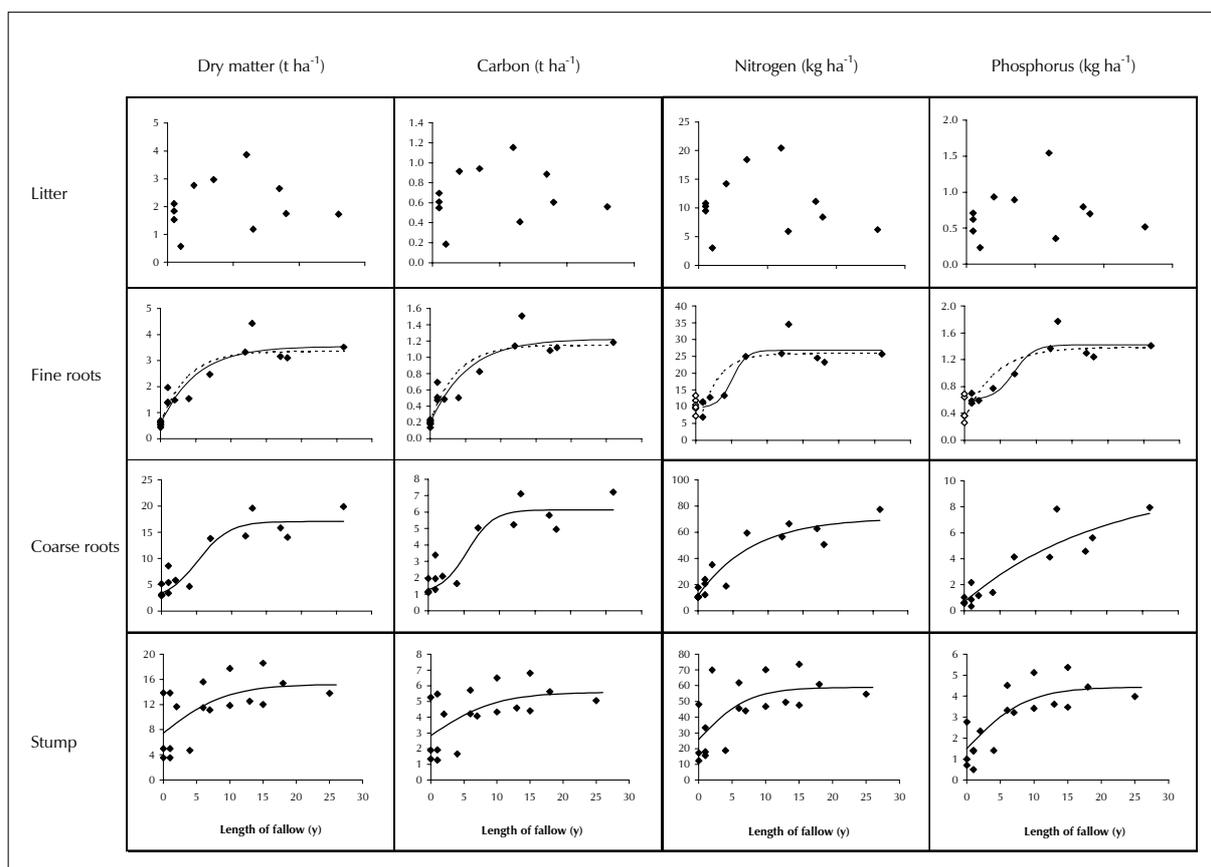


Figure 1.4 (continued) b. below-ground components

Plain line: low-constraint model (see text and Table 1.4). Dotted line: high-constraint model. Plain dots: data used for model adjustment.

All below-ground values calculated for the 0-40 cm layer.

See data in Appendix 7.

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

1.3.3. Statistical analyses

Considering the quite stable value of the length of fallow beyond which no clear evolution of plant biomass and nutrient storage could be observed (see 3.2), data were clustered in three groups: groundnut fields (GN); young fallows (YF) aged less than 10 years; old fallows (OF) aged 10 years or more.

Table 1.5 Simplified budget and annual increase of dry matter, carbon, nitrogen and phosphorus in above- and below-ground plant biomass during a crop-fallow succession.

	Total storage			Annual variation (acc. to years of fallow)		
	Groundnut field	Young fallow	Old fallow	0-1 y	1-10 y.	10-25y.
DM (t ha ⁻¹)						
AG biomass	3.3	29.7	44.4	17.9	2.1	0.0
BG biomass	11.4	18.3	34.8	3.4	1.6	0.2
C (t ha ⁻¹)						
AG biomass	1.2	11.0	16.4	6.6	0.8	0.0
BG biomass	4.3	6.7	12.6	1.3	0.6	0.0
N (kg ha ⁻¹)						
AG biomass	59	151	186	59.2	9.0	-0.7
BG biomass	47	80	147	4.0	6.9	0.5
P (kg ha ⁻¹)						
AG biomass	3.3	15.0	22.1	7.8	1.0	0.0
BG biomass	2.6	4.6	11.6	0.3	0.7	0.1

Annual increases were estimated by using mean values calculated from the adjusted logistic-like model when available (see 1.3.2.), from a simple linear regression otherwise.

Table 1.6 Anova performed on dry matter, carbon, nitrogen and phosphorus amounts in plant biomass of cropped and fallow plots (young fallow: aged less than 10 years; old fallows: 10 years and more).

		Groundnut field		Young fallow		Old fallow		F
		Mean(±SE)	n	Mean(±SE)	n	Mean(±SE)	n	
DM storage (t ha⁻¹)								
AGB ⁽¹⁾	Woody, includ.	0.3 ±0.2 ^c	6	21.8 ±2.8 ^b	10	40.5 ±1.2 ^a	7	69.1 ***
	- trunk	nd		11.0 ±1.5 ^b	10	22.7 ±0.9 ^a	7	40.4 ***
	- twig	nd		6.7 ±0.9 ^b	10	11.7 ±0.3 ^a	7	40.4 ***
	- leaf	nd		4.03 ±0.57 ^b	10	6.11 ±0.43 ^a	7	10.1 **
	Herbaceous	2.96 ±0.22 ^b	6	5.97 ±0.83 ^a	6	1.65 ±0.21 ^c	5	29.6 ***
Litter		nd		1.96 ±0.36 ^a	6	2.24 ±0.47 ^a	5	0.0
Root	Fine 0-10 cm	0.24 ±0.02 ^c	6	0.92 ±0.08 ^b	6	1.35 ±0.12 ^a	5	56.5 ***
	10-20 cm	0.15 ±0.01 ^c	6	0.31 ±0.06 ^b	6	0.91 ±0.14 ^a	3	18.0 ***
	20-30cm	0.10 ±0.01 ^c	6	0.27 ±0.04 ^b	6	0.68 ±0.03 ^a	3	39.4 ***
	30-40 cm	0.07 ±0.00 ^c	6	0.22 ±0.03 ^b	6	0.67 ±0.08 ^a	3	45.6 ***
	0-40 cm	0.57 ±0.04 ^c	6	1.70 ±0.18 ^b	6	3.51 ±0.24 ^a	5	56.5 ***
	Coarse	3.4 ±0.4 ^c	6	7.0 ±1.5 ^b	6	16.7 ±1.3 ^a	5	35.2 ***
	Stump	7.5 ±3.2 ^a	3	9.6 ±1.6 ^a	8	14.6 ±1.0 ^a	7	3.5
C storage (t ha⁻¹)								
AGB ⁽¹⁾	Woody, includ.	0.1 ±0.2 ^c	6	8.2 ±1.1 ^b	10	15.2 ±0.47 ^a	7	69.1 ***
	- trunk	nd		4.15 ±0.57 ^b	10	8.49 ±0.32 ^a	7	40.4 ***
	- twig	nd		2.52 ±0.32 ^b	10	4.38 ±0.12 ^a	7	40.4 ***
	- leaf	nd		1.52 ±0.22 ^b	10	2.29 ±0.16 ^a	7	7.8 *
	Herbaceous	1.11 ±0.09 ^b	6	2.14 ±0.27 ^a	6	0.54 ±0.08 ^c	5	29.6 ***
Litter		nd		0.65 ±0.11 ^a	6	0.72 ±0.13 ^a	5	0.0
Root	Fine 0-10 cm	0.08 ±0.01 ^c	6	0.31 ±0.03 ^b	6	0.47 ±0.04 ^a	5	36.6 ***
	10-20 cm	0.05 ±0.00 ^c	6	0.10 ±0.02 ^b	6	0.31 ±0.05 ^a	3	18.0 ***
	20-30cm	0.04 ±0.00 ^c	6	0.09 ±0.01 ^b	6	0.24 ±0.01 ^a	3	39.4 ***
	30-40 cm	0.02 ±0.00 ^c	6	0.07 ±0.01 ^b	6	0.23 ±0.02 ^a	3	39.4 ***
	0-40 cm	0.19 ±0.01 ^c	6	0.58 ±0.06 ^b	6	1.21 ±0.08 ^a	5	56.5 ***
	Coarse	1.29 ±0.14 ^c	6	2.58 ±0.57 ^b	6	6.06 ±0.47 ^a	5	24.9 ***
	Stump	2.83 ±1.22 ^a	3	3.57 ±0.61 ^a	8	5.33 ±0.38 ^a	7	3.5
N storage (kg ha⁻¹)								
AGB ⁽¹⁾	Woody, includ.	1.5 ±0.9 ^c	6	99.4 ±13.2 ^b	10	162.5 ±8.0 ^a	7	42.7 ***
	- trunk	nd		26.7 ±4.4 ^b	10	51.4 ±1.7 ^a	7	27.6 ***
	- twig	nd		19.7 ±2.6 ^b	10	32.6 ±1.3 ^a	7	33.1 ***
	- leaf	nd		53.0 ±7.5 ^b	10	78.5 ±5.9 ^a	7	7.8 *
	Herbaceous	57.1 ±4.1 ^a	6	40.9 ±10.1 ^b	6	12.8 ±1.4 ^c	5	20.2 ***
Litter		nd		11.0 ±2.2 ^a	6	10.4 ±2.7 ^a	5	0.1
Root	Fine 0-10 cm	4.1 ±0.4 ^c	6	7.0 ±0.1 ^b	6	10.3 ±1.0 ^a	5	19.3 ***
	10-20 cm	2.6 ±0.2 ^b	6	2.5 ±0.7 ^b	6	6.9 ±1.2 ^a	3	6.4 *
	20-30cm	1.7 ±0.1 ^b	6	2.2 ±0.5 ^b	6	5.1 ±0.3 ^a	3	5.8 *
	30-40 cm	1.1 ±0.1 ^b	6	1.7 ±0.4 ^b	6	5.1 ±0.6 ^a	3	11.3 **
	0-40 cm	9.4 ±0.7 ^b	6	13.4 ±2.5 ^b	6	26.8 ±2.0 ^a	5	12.6 ***
	Coarse	11.7 ±1.2 ^c	6	28.3 ±6.9 ^b	6	62.8 ±4.6 ^a	5	29.7 ***
	Stump	25.9 ±11.2 ^b	3	38.4 ±7.3 ^{ab}	8	57.6 ±4.1 ^a	7	4.5 *
P storage (kg ha⁻¹)								
AGB ⁽¹⁾	Woody, includ.	0.1 ±0.1 ^c	6	10.5 ±1.4 ^b	10	20.1 ±0.6 ^a	7	69.1 ***
	- trunk	nd		7.5 ±1.0 ^b	10	15.5 ±0.5 ^a	7	40.4 ***
	- twig	nd		1.79 ±0.25 ^b	10	2.96 ±0.12 ^a	7	23.4 ***
	- leaf	nd		1.19 ±0.18 ^b	10	1.68 ±0.12 ^a	7	3.6
	Herbaceous	3.20 ±0.25 ^a	6	3.86 ±0.98 ^a	6	1.27 ±0.10 ^b	5	11.7 **
Litter		nd		0.64 ±0.11 ^a	6	0.78 ±0.21 ^a	5	0.0
Root	Fine 0-10 cm	0.18 ±0.03 ^c	6	0.37 ±0.03 ^b	6	0.55 ±0.05 ^a	5	43.4 ***
	10-20 cm	0.11 ±0.02 ^b	6	0.13 ±0.02 ^b	6	0.36 ±0.06 ^a	3	5.7 *
	20-30cm	0.07 ±0.01 ^c	6	0.11 ±0.01 ^b	6	0.27 ±0.01 ^a	3	15.1 ***
	30-40 cm	0.05 ±0.00 ^c	6	0.09 ±0.01 ^b	6	0.27 ±0.03 ^a	3	40.5 ***
	0-40 cm	0.41 ±0.06 ^c	6	0.70 ±0.07 ^d	6	1.42 ±0.09 ^a	5	25.6 ***
	Coarse	0.68 ±0.07 ^c	6	1.68 ±0.55 ^b	6	6.02 ±0.80 ^a	5	15.7 ***
	Stump	1.49 ±0.64 ^b	3	2.26 ±0.47 ^b	8	4.20 ±0.30 ^a	7	10.4 **

nd: not determined. Mean ± SE.

$p\{H_0: F_{obs} > F_{th}\}$: * < 0.05; ** < 0.01; *** < 0.001.

See data in Table 1.3 and Appendix 7.

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

Mean amounts in plant biomass and net productivity (annual variation of the stocks) were summarised in Table 1.5. Fastest accumulation of elements generally occurred during the first year of fallow. This was not the case for below-ground N and P; fastest increases for these elements were achieved between one and 10 years of fallow. DM, C, N and P accumulation was 10 to 20 times slower beyond 10 years of fallow.

Anovas were performed on these three groups (Table 1.6). Significant increases of amounts of DM, C, N and P in woody AGB were found between GN and YF, and YF and OF. Herbaceous N and P values decreased through the succession, although highest biomass values were found in YF. Amounts in fine and coarse roots increased significantly along all steps of the succession, whatever the element. Although stump biomass strongly increased between YF and OF, differences were not statistically significant, except for P.

1.3.4. Post-fallow dynamics of above-ground plant biomass

Estimates presented below do not take into account possible translocation occurring during the dry season. Thus, N and P returns from AGB to the soil might be overestimated.

Herbaceous above-ground biomass. Estimates of potential returns of C, N and P from the herbaceous biomass to the soil would be 2.1 tC, 41 kgN and 3.9 kgP ha⁻¹ derived from a young fallow; 0.5 tC, 13 kgN and 1.3 kgP ha⁻¹ issued from an old fallow (Table 1.6). However, these are gross, upper estimates, as the returns of C and N to the soil at clearing heavily rely on fire occurrence.

Woody above-ground biomass (Figure 1.5). DM returns from a young fallow were estimated to be 8.4 t ha⁻¹ when setting combustion efficiency to 50 % of ABB, or 1.7 t ha⁻¹ under the 90 % hypothesis. Values computed for old fallows were 18.4 and 10.2 tDM ha⁻¹. This would mean an on-site recycling of 0.6-3.1/0.8-4.0 tC and 9-44/12-59 kgN ha⁻¹ depending on burning efficiency (90-50 %) and age of fallow (young/old). P returns to the soil would amount to 6.9 and 7.0 kg ha⁻¹, after clearing a young or an old fallow. Wood harvest occurring at clearing of an old fallow would lead to the following exportations: 50 % of DM and C, 27 % of N and 66 % of P contained in initial woody AGB.

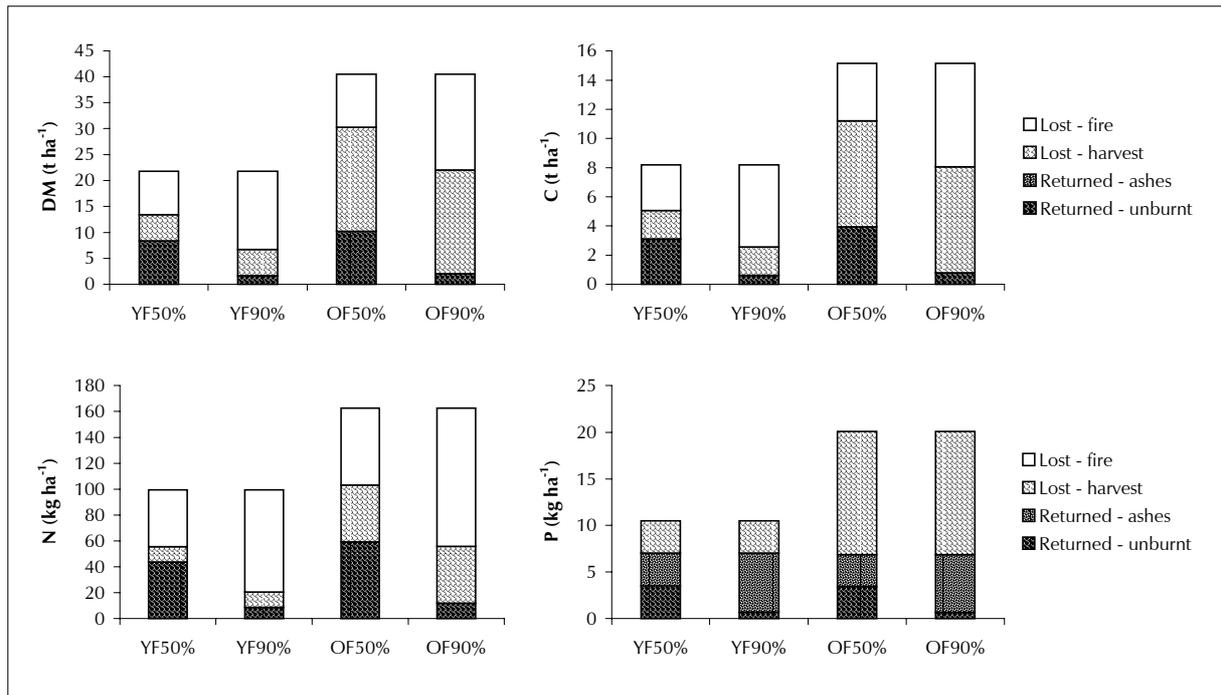


Figure 1.5 Fate of dry matter, carbon, nitrogen and phosphorus in above-ground woody biomass after clearing of a young (YF) and old (OF) fallow (young fallow: aged less than 10 years; old fallow: 10 years and more). Two scenarios are considered: 50 % and 90 % of available plant biomass for burning is burnt. Assumptions: ashes are DM-, C- and N-free; all P, except that exported for wood need, is returned to the soil both as ash or non-burnt biomass. See data in Appendix 8.

1.4. DISCUSSION

Plant biomass components show contrasted dynamics along the crop and fallow cycle. After crop abandonment woody and root biomasses increase at the expense of the herbaceous layer, while litter shows no clear pattern of evolution. These trends are consistent with observations made by Kotto-Same *et al.* (1997) under wetter conditions. However, even the highest amounts of carbon storage in plant biomass (29 t ha⁻¹) reported here are lower than the average values reviewed by Allen-Diaz *et al.* (1996) (118tC ha⁻¹) and Tiessen *et al.* (1998) (50tC ha⁻¹) for dry tropical forests and savannas. The potential for annual carbon sequestration in our study was similar to the work of Tiessen and his colleagues (5 t ha⁻¹) during the first year of fallow only. However, plant biomass and net storage productivity found in our study agreed better with those usually recorded in dry Miombo woodlands (AGB: 21-84 tDM ha⁻¹; BGB: 7-39 tDM ha⁻¹) (Desanker *et al.*, 1995). Meanwhile, amounts of nutrients in plant biomass were much lower than those reported by Singh and Singh (1991) in a dry Indian forest, higher than those reviewed by Lamotte and Bourlière (1983) (100-150 kgN and 19 kgP ha⁻¹), but roughly the same as an eight-year old fallow in a nearby area of Guinea (Sirois *et al.*, 1998).

Swift and Anderson (1994) have defined the concepts of productive biota – the community of plants and animals that provide peasants with valuable goods such as food or construction materials – and of resource biota – the body of “organisms which contribute positively to the productivity of the system”; this distinction will be the main backbone of the discussion.

1.4.1. Fallow as a productive ecosystem

Wood supplies 90% of the needs of rural population of the West African savannas for domestic energy and construction material (Bertrand, 1977; Breman and Kessler, 1995). However, estimates for wood standing stock values and productivity of fallows and woodlands of the sub-region are scarce and difficult to assess, because of uncontrolled fire, grazing, tree felling, and soil. For instance, Breman and Kessler (1995) report woody biomass values ranging 20-60 t ha⁻¹ in sub-Saharan Africa. Highest values of woody biomass found in our study were much lower than the mean estimates reported by Martinez-Yrizar (1995) in dry tropical forests (90 t ha⁻¹) and by Nye and Greenland (1960) in Ghanaian fallows and savannas (54 t ha⁻¹). This must be a consequence of pedohydric constraints due to shallow clay accumulation in soil and nutrient limited availability. Initial wood productivity averaged 2 tDM ha⁻¹ during the first ten years after crop abandonment; this is consistent with the estimates provided by Catinot (1994) (2-3 t ha⁻¹ y⁻¹) in managed savannas of the ecozone, though slightly lower than the figures reviewed by Alexandre and Kairé (2000) for West African secondary successions (2.5-4.7 t ha⁻¹ y⁻¹). In oldest fallows productivity dropped to 0.1 tDM ha⁻¹ y⁻¹, which is much less than FAO's findings (1989) for dry mature forests of the region (1.2 t ha⁻¹). Soil properties mentioned above may again be put forward for such a discrepancy. Tree felling by farmers, which cumulate value since crop abandonment was estimated to 2 tDM ha⁻¹ in local fallow fields (Kairé, 1999), has but little impact on woody productivity. To fulfil their need for domestic energy, peasants usually harvest dead wood rather than fell trees, because it saves labour. From Shackleton's work (1998) in south African savannas, local dead wood production might be estimated to 0.4 and 0.7 t ha⁻¹ in young and old fallows.

Pastoral usage of fallow usually conflicts with the need for woody products, as woody layer closure induces a fast decrease of herbaceous standing biomass in fallows older than ten years. Maximum grass biomass in youngest fallows averaged 6.5 t ha⁻¹, which compares fairly well with data of Nye and Greenland (1960) in savannas (1.5-7.6 t ha⁻¹), Fournier (1982) in Ivory Coast (3.5-9 t ha⁻¹) and Lamotte and Bourlière (1983) in a more humid savanna (7 t ha⁻¹). The herbaceous layer of fallow is a valuable source of forage for cattle, as it contributes to 75 % of the diet of local livestock (Delacharlerie, 1994). Recent results by Ickowicz (in press) suggest that fallows of intermediate age ensuring both forage quality and quantity have the best pastoral value among all vegetation facies of the uncropped plots of the study site.

1.4.2. Role of plant biomass in sustaining agro-ecosystem fertility

1.4.2.1. Cycling of nitrogen and phosphorus in plant biomass

The higher efficiency of plant communities of young fallows and pasture as compared to domestic plants for the restoration of substantial amounts of available nitrogen and phosphorus in soil, provided that

biological integrity has been maintained, has been demonstrated in several works and will not be discussed here (see Chapter 2). From an agro-ecological point of view, fallowing has been described as a process of organic matter and nutrient accumulation (Kowal and Kassam, 1978; Juo and Manu, 1996), something particularly obvious here during the year following crop abandonment (Table 1.5). Although removal of wood and grass during the fallow period -for purposes of energy and forage supply- remains locally negligible (Masse *et al.*, 1998), dramatic mineral losses from the ecosystem through felling or burning of woody and grass layers occur at clearing. Such practices imply the loss of 40-94 % of N contained in above-ground plant biomass (depending on combustion efficiency and fate of the herbaceous layer), and of 24-62 % of P (depending on the age of fallow). It may be hypothesised that N losses are of moderate consequences on yields of following crops, because groundnut is preferred to any other crop in the bush ring and it is a legume (although the N-fixation efficiency of local groundnut cultivars may be highly variable according to Pieri, 1989).

This is not the case with phosphorus, which is a non-renewable resource. Slash and burn practices can thus be justified only in a context where availability of labour power (human and motorised) is low (Nye and Greenland, 1960). Though often misstudied, the root component accounts for more than a third of total N and P storage in plant biomass. Considering P immobilisation in harvested groundnut biomass (2.8 kgP ha⁻¹), the clearing of a one-year old fallow could provide fairly enough P for three years of cropping, thanks to P returned to the soil both from cleared AGB and decaying root biomass (7.4 kgP ha⁻¹). As a matter of fact groundnut is never cropped longer than one year in High Casamance, indicating possible (1) pre-eminence of pest and weed problems, (2) asynchrony between nutrient release and plant needs throughout the first years of cropping, due to massive mineralization of plant biomass and SOM (Myers *et al.*, 1994), (3) fast conversion of P back to less available forms in soil. It must also be kept in mind that internal recycling (translocation) in tree was not taken into account in our calculations; it might lead to an overestimation of nutrient amounts stored in woody biomass at the end of the dry season (Breman and Kessler, 1995).

1.4.2.2. Carbon dynamics

Much evidence has been brought today about the non sustainability of strictly mineral fertilization in the tropics, and especially in West Africa (Pieri, 1989). Associated organic amendments are needed, since they maintain SOM levels and associated soil properties (Pieri, 1989; Tiessen *et al.*, 1994; Syers, 1997).

As mentioned above, only a small fraction of above-ground plant biomass returns to the soil at clearing and during the crop-fallow cycle. Therefore, soil organic inputs stem mainly from roots and, to a lesser extent, from litter. There is however a paucity of quantitative root dynamics studies in tropical savannas, especially in West Africa. In a drier site of Senegal, Chopart (1980) estimated groundnut fine root biomass to 0.3 t ha⁻¹, that is half of the values reported in this study. Mean fine root biomass of 20 Senegalese young grass fallows was estimated to 2 t ha⁻¹ by Charreau and Nicou (1971). In the Sudanian zone of Ivory Coast, César and Coulibaly (1993) also gave consistent values with our work (2.6 and 5.3 t ha⁻¹ of

fine roots in 10 and 15 years old fallows). General figures for woody root biomass in sub-Saharan Africa range 10-30 t ha⁻¹ (Breman and Kessler, 1995). The range of values of total root biomass found in this study compares well with estimates for less disturbed and more humid savannas (3.5 to 27 t ha⁻¹ according to Menaut and César, 1979) and for dry forests (23.4 t ha⁻¹ in Martinez-Yrizar, 1995).

Relative DM allocation to plant AGB as compared to BGB (shoot:root value) found in our study was 10 times less than that reviewed by Martinez-Yrizar (1995) for tropical dry forests, or that adopted by Delaney *et al.* (1997) for the estimate of BGB in dry forests of South America. Such a discrepancy might be explained by fire evenness. Advocating the fact that vegetation climax has not been reached after 25 years of fallow succession is not relevant: sacred, undisturbed woodlands found on the study site exhibit similar physiognomy to oldest fallows (unpublished observations).

Results of model adjustment (see 1.3.2.) indicate a time-lag of maximum growth rate between above- and below-ground components of the woody layer. Ecological implications of this time-lag are very important: it suggests that priority is given by woody plants to the development of autotrophic organs over rooting systems at the onset of the succession. Only later is more carbon allocated to below-ground biomass. This would result from competition for light according to Shukla and Ramakrishnan (1984), and for nutrients (mainly P) according to us. It demonstrates that the building of a strong rooting system in natural vegetation happens only in oldest fallows. This is of greatest importance to define sustainable rules of fallow management, because early fast plant biomass production -and soil improvement (Chapter 2)- recorded after crop abandonment must rely mostly on the resprouting capacity of woody plants.

In a more dynamic perspective, roots might account for 40 to 85 % of the net primary production of plant communities (Fogel, 1985). Root carbon originating from aerial parts returns to the soil through both exudation and decay of roots. Quantifying these inputs is a difficult task. Turn-over estimates under tropical dry climate range from 0.5 to 1.2 y⁻¹ (Menaut and César, 1979; Lamotte and Bourlière, 1983; Brown *et al.*, 1994). During the 1993-94 dry season, fine root biomass decreased by half in four local fallows (Manlay, 1994). Thus, using a turn-over value of 0.5 y⁻¹, C input from fine and coarse roots to the soil of young fallows would reach 1.6/3.6 tC ha⁻¹ y⁻¹. This is a rough evaluation of actual carbon flow, as it probably overestimates the turnover of coarse roots, but does not take into account root exudation.

1.5. CONCLUSION

From a strictly “productivist”, narrow point of view, appraisal of optimal length of fallow hangs more or less upon conflicting human needs and demographic context. In fallows disturbed mostly by fire, our results demonstrate the existence of an ecological threshold around 10 years after crop abandonment. A similar value was also recorded in the floristic and physiognomic studies of Stromgaard (1986) and Donfack *et al.* (1995) under equivalent climates; Brown and Lugo (1990) reviewed a higher value (15 years) in more humid successions. Beyond 10 years, the keeping of fallow for the production of valuable plant

biomass may be relevant under low population density only; from this study and findings of Shackleton (1998) indeed, old fallows would be more productive than the young ones only in term of dead wood production. Growing needs for both wood and forage would be met with 6-10 years old fallows at best. Nutrient budgets (N and P) indicate that such fallows might be of greatest efficiency to satisfy the needs of cropped plants during several years, although local practices of clearing lead to important losses of nutrients. However, the value of such an ecological threshold must rely largely on (1) the way local practices are applied at clearing, (2) the intensity of cropping, (3) the duration of human settlements. And much different patterns of vegetation dynamics are to be found in secondary successions, depending on how trees have to rely on resprouting capacity of stumps (low human pressure context) or on seedling strategies (high anthropisation scenario).

On the other hand, all these “nutrient” and “productivist” considerations are fairly restrictive. The well-known decline of yields in the overcrowded Groundnut Belt of Central Senegal, just 200 km far from the study site, and after several decades of mining agriculture, must remind that the short fallow-groundnut rotation is seldom sustainable (Pieri, 1989). Our study suggests that, when unavoidable, substitutes for long breaks of fallow must at least ensure strong root biomass settlement, soil energy replenishment, and subsequent modifications of functional ecological organisation enabling pest control. Alternative techniques to prolonged fallowing can be aimed at accelerating succession with improved fallows (Peltier, 1993; Harmand and Njiti, 1998) or inserting fallow ecological mechanisms of soil fertility conservation in continuous cultivation systems through the adoption of “dispersed tree” plantation in cropped fields or live-hedges systems, and stump-saving, no-till practices.

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 Woome, 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 $5.5 \pm 0.3 \text{ g kg}^{-1}$ (\pm standard error) of soil in the 0-10 cm layer, $4.1 \pm 0.1 \text{ g kg}^{-1}$ in the whole profile (0-40 cm). Respective nitrogen contents were 0.44 ± 0.02 and $0.36 \pm 0.01 \text{ g kg}^{-1}$. Available phosphorus content was 2.7 ± 0.2 and $2.0 \pm 0.1 \mu\text{g kg}^{-1}$. Other main properties were: slight acidity ($\text{pHH}_2\text{O}: 5.5 \pm 0.1$); CEC: 2.5 ± 0.1 and $3.0 \pm 0.2 \text{ meq } 100\text{g}^{-1}$ of soil in the 0-10 and 30-40 cm layers respectively, with saturation rate decreasing from 85 ± 5 to $60 \pm 6 \%$ from the 0-10 to the 30-40 cm layer; pF 4.2: $3.1 \pm 0.2 \%$ in the 0-10 cm to $7.7 \pm 0.6 \%$ in the 30-40 cm layer; bulk density: $1.50 \pm 0.01 \text{ kg dm}^{-3}$ in the whole profile,
- (2) a glaxis, 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 glaxis. In each of them, four 16-m² 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-cm³ 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 CH₃COONH₄ at pH=7. CEC was measured by saturating soil with CaCl₂, 2H₂O 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.

<i>a. C (g kg⁻¹)</i>					
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

<i>b. N (g kg⁻¹)</i>					
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

<i>c. P_{OD} (mg kg⁻¹)</i>					
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

<i>d. C/N</i>					
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

<i>e. Bulk density (fraction [0-2000]μm) (kg dm⁻³)</i>					
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 H₂O 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 ($\alpha=0.05$).

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).

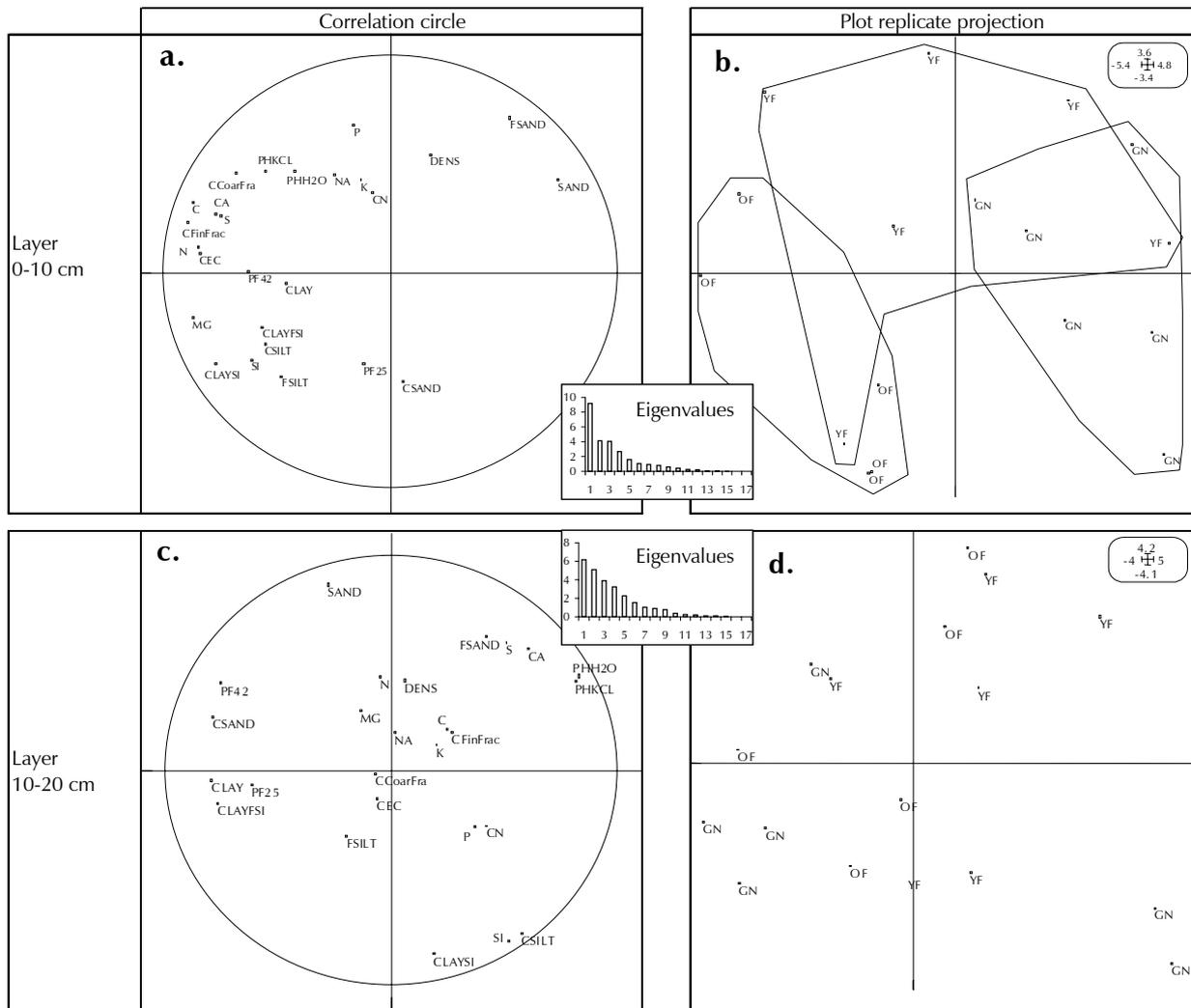


Figure 2.1 Principal components (PC) analysis of the soil properties of a chronosequence made of six cropped plots and 11 fallow plots. Correlation circles of the variables and projection of the plot replicates on plane PC1 x PC2: a.-b. layer 0-10 cm c.-d. layer 10-20 cm. Coding of variables: C: carbon. 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. PF2.5 and PF4.2: 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 (cm)	Groundnut field Mean (\pm SE) (n=6)	Young fallow Mean (\pm SE) (n=6)	Old fallow Mean (\pm SE) (n=5)	F		
				Management	Texture	Overall
Clay + fine silt content (%)						
0-10	11.3 \pm 1.2	12.4 \pm 0.8	14.1 \pm 0.5	3.2		
10-20	17.1 \pm 1.3	16.5 \pm 1.1	17.6 \pm 1.1	0.1		
20-30	22.5 \pm 2.5	21.7 \pm 1.7	24.9 \pm 2.3	0.5		
30-40	29.4 \pm 4.3	28.3 \pm 3.5	33.2 \pm 3.7	0.4		
0-40	20.1 \pm 2.0	19.7 \pm 1.5	22.5 \pm 1.7	0.4		
pF2.5 (gH ₂ O 100 g ⁻¹ soil)						
0-10	6.95 \pm 1.02 ^a	4.95 \pm 0.48 ^b	8.28 \pm 1.74 ^a	4.7 *	0.9	3.4
10-20	8.02 \pm 1.13 ^a	5.53 \pm 0.19 ^b	8.52 \pm 1.75 ^a	4.4 *	2.6	4.1 *
20-30	8.80 \pm 1.42	6.82 \pm 0.28	10.78 \pm 1.97	2.3	16.9 **	9.3 **
30-40	11.35 \pm 2.03	9.18 \pm 1.00	13.36 \pm 1.83	2.0	18.3 ***	9.1 **
0-40	8.78 \pm 1.20 ^{ab}	6.62 \pm 0.42 ^b	10.24 \pm 1.66 ^a	4.9 *	19.4 ***	12.6 ***
pF4.2 (gH ₂ O 100 g ⁻¹ soil)						
0-10	2.70 \pm 0.34	3.08 \pm 0.35	3.74 \pm 0.33	0.6	5.2 *	4.1 *
10-20	4.03 \pm 0.46	4.00 \pm 0.12	4.28 \pm 0.21	0.6	3.4	1.6
20-30	5.35 \pm 0.75	5.18 \pm 0.30	6.26 \pm 0.41	0.8	31.8 ***	13.2 ***
30-40	7.30 \pm 1.22	7.25 \pm 0.79	8.84 \pm 0.83	0.1	158.4 ***	56.6 ***
0-40	4.85 \pm 0.64	4.88 \pm 0.34	5.78 \pm 0.32	0.7	38.1 ***	15.1 ***
Bulk density (kg dm ⁻³)						
0-10	1.52 \pm 0.01	1.52 \pm 0.02	1.50 \pm 0.02	0.4	0.2	0.2
10-20	1.47 \pm 0.03 ^b	1.54 \pm 0.01 ^a	1.52 \pm 0.01 ^{ab}	4.2 *	1.1	3.0
20-30	1.54 \pm 0.03	1.51 \pm 0.02	1.48 \pm 0.02	1.1	0.5	0.8
30-40	1.45 \pm 0.03	1.51 \pm 0.01	1.50 \pm 0.05	0.6	0.0	0.5
0-40	1.50 \pm 0.01	1.52 \pm 0.01	1.50 \pm 0.02	1.3	0.1	0.8

$p\{H_0: F_{obs} > F_{tb} = 0\}$: * < 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 Appendix 11.

Table 2.2 (continued) b. chemical properties

Layer (cm)	Groundnut field		Young fallow		Old fallow		F		
	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} (10⁻³g 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⁻¹soil)									
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⁻¹soil)									
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⁻¹soil)									
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⁻¹soil)									
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⁻¹soil)									
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] 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 ± 0.2 g 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

Plot	Fraction 0-50 μm				Fraction 50-2000 μm				Fractionation recovery rate ((1)+(2))/C _t
	Mass (g 100 g ⁻¹ soil)	C content in g kg ⁻¹ of		C/N	Mass (g 100 g ⁻¹ soil)	C content in g kg ⁻¹ of		C/N	
		fraction	soil (1)			fraction	soil (2)		
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

Plot	Fraction 0-50 μm				Fraction 50-2000 μm				Fractionation recovery rate ((1)+(2))/C _t
	Mass (g 100 g ⁻¹ soil)	C content in g kg ⁻¹ of		C/N	Mass (g 100 g ⁻¹ soil)	C content in g kg ⁻¹ of		C/N	
		fraction	soil (1)			fraction	soil (2)		
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 (cm)	Groundnut field		Young fallow		Old fallow		F		
	Mean (\pm SE) (n=6)		Mean (\pm SE) (n=6)		Mean (\pm SE) (n=5)		Management	Texture	Overall
C/N on non-fractionated soil									
0-10	12.7 \pm 0.5	ab	12.1 \pm 0.8	a	12.3 \pm 0.9	b	0.3	0.6	0.3
10-20	11.9 \pm 0.9		12.3 \pm 0.3		10.8 \pm 0.3		3.7	0.0	2.5
20-30	11.3 \pm 0.3		11.6 \pm 0.5		10.5 \pm 0.2		2.0	0.0	1.4
30-40	10.8 \pm 0.4		11.1 \pm 0.5		10.7 \pm 0.7		0.1	1.4	0.6
0-40	11.7 \pm 0.4		11.8 \pm 0.4		11.2 \pm 0.4		0.1	4.3	1.7

b.

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

$p\{H_0: F_{obs} > F_{ib} = 0\}:$ * <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).

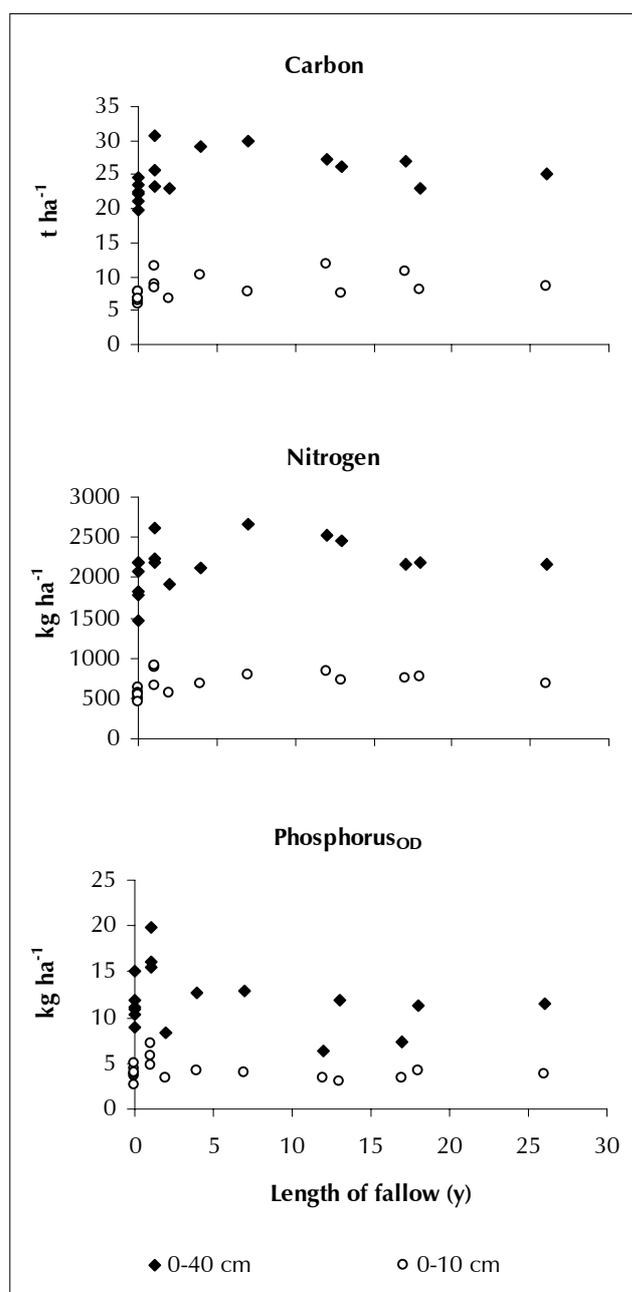


Figure 2.2 Evolution of soil C, N and P_{OD} storage in the 0-10 and 0-40 cm layers along the crop-fallow succession. See data in Appendix 13.

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.

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 (cm)	Groundnut field			Young fallow			Old fallow		
	Mean (±SE) (n=6)			Mean (±SE) (n=6)			Mean (±SE) (n=5)		
Carbon storage (t ha ⁻¹)									
0-10	6.8 ±0.3	b		8.8 ±0.7	a		9.2 ±0.8	a	
10-20	5.4 ±0.3	b		6.9 ±0.3	a		5.7 ±0.2	b	
20-30	5.1 ±0.3			5.8 ±0.5			5.2 ±0.2		
30-40	4.9 ±0.4			5.4 ±0.4			5.6 ±0.4		
0-40	22.3 ±0.7	b		26.9 ±1.4	a		25.6 ±0.8	a	
Nitrogen storage (kg ha ⁻¹)									
0-10	538 ±28	a		740 ±56	a		747 ±28	b	
10-20	458 ±24	b		563 ±27	a		530 ±25	a	
20-30	458 ±33			498 ±31			496 ±21		
30-40	466 ±46			487 ±43			527 ±37		
0-40	1920 ±114	b		2289 ±119	a		2300 ±81	a	
Phosphorus _{OD} storage (kg ha ⁻¹)									
0-10	3.8 ±0.3			4.8 ±0.5			3.6 ±0.2		
10-20	2.7 ±0.3	b		3.6 ±0.3	a		2.6 ±0.6	ab	
20-30	2.7 ±0.3			2.7 ±0.3			1.9 ±0.4		
30-40	2.2 ±0.2			3.0 ±0.5			1.6 ±0.2		
0-40	11.3 ±0.9	b		14.2 ±1.6	a		9.7 ±1.2	a	

b. soil size fractions

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

$p\{H_0: F_{obs} > F_{ib} = 0\}: * < 0.05; ** < 0.01; *** < 0.001.$

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

See data in 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.

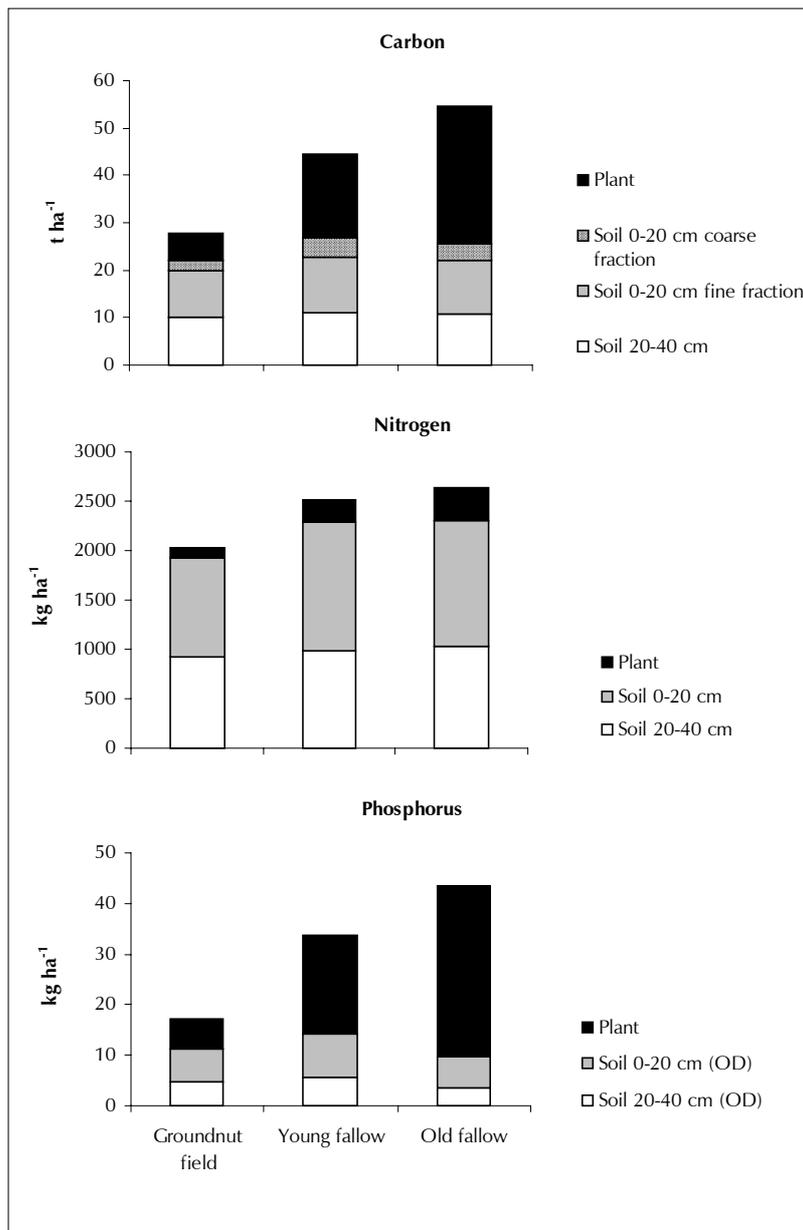


Figure 2.3 C, N and P storage in the plant-soil system at three main stages of the crop-fallow succession. Figures for plant biomass derived from Chapter 1. Young fallow: aged 0-9 years. Old fallow: older than 9 years. OD: available phosphorus (soil) as measured by Olsen's method modified by Dabin (1967).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

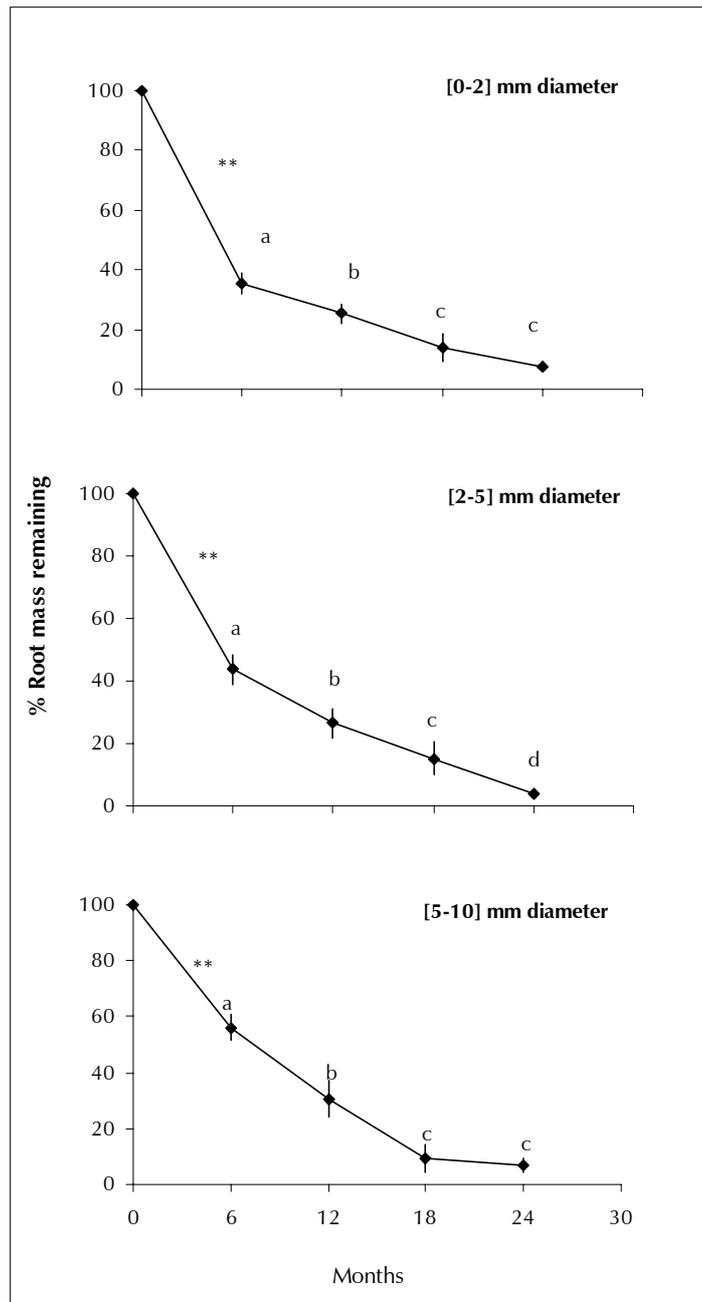


Figure 2.4 Root decomposition dynamics of *Combretum glutinosum* Perr. after clearing of a 15 years old fallow as measured during a mesh-bag experiment.

Vertical bars stand for SE. Results of Z- and SNK-tests ($\alpha=0.05$; $n=20$).

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.

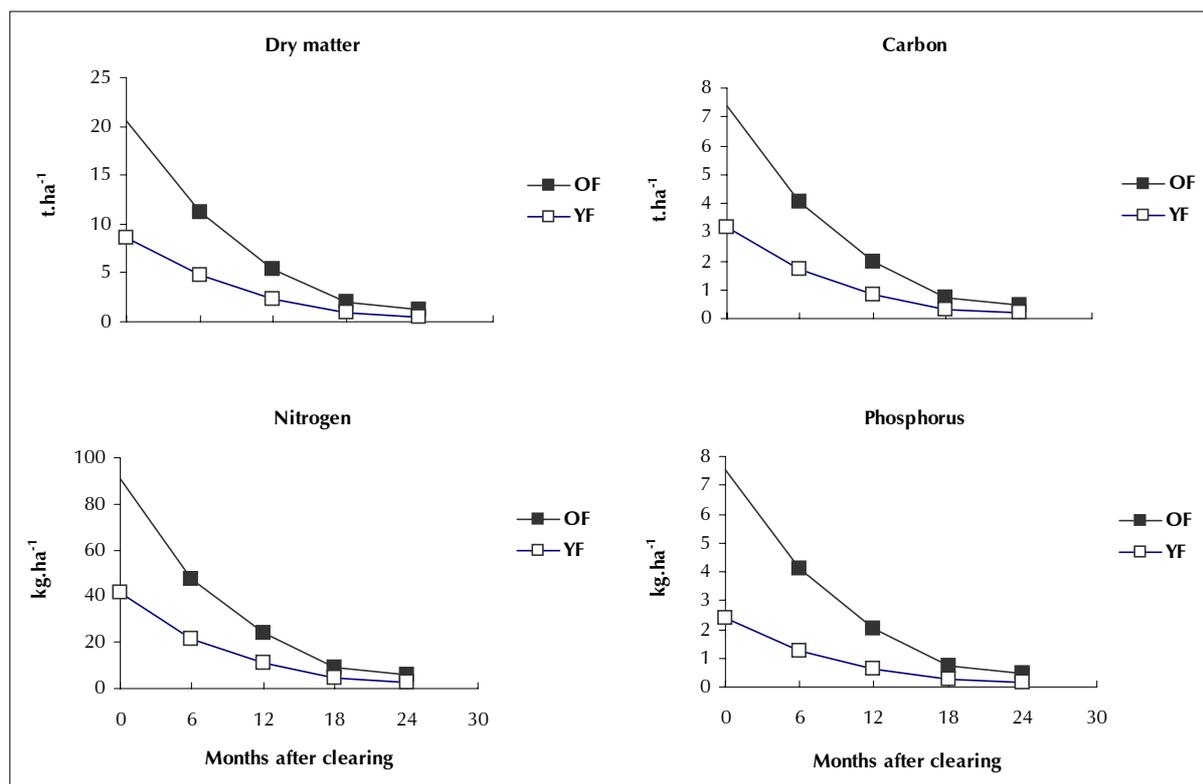


Figure 2.5 Estimated remaining amounts of dry matter, carbon, nitrogen and phosphorus from the decaying root component after clearing of a young (YF) and old (OF) fallow (stumps removed). See data in Appendix 16.

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 $60 \mu\text{g kg}^{-1}$, 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 ($7.2 \mu\text{g kg}^{-1}$, 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 $3.6 \text{ t ha}^{-1} \text{ y}^{-1}$ 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-CO₂ 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.

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

Chapter 3. CARBON, NITROGEN & PHOSPHORUS ALLOCATION IN AGRO-ECOSYSTEMS OF A WEST AFRICAN SAVANNA - III. THE PLANT & SOIL COMPONENTS UNDER CONTINUOUS CULTIVATION

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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 glacia 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 m²) 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-cm³ 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 H₂O 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 glaciais 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 ($\alpha=0.05$) 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_i content.

a.

Plot	Panicle / pod	Stover / haulm	Weed and woody advent	Fine roots per soil layer in cm					Coarse roots
				0-10	10-20	20-30	30-40	0-40	
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): $a=1.73*b + 2.95$; $R^2=0.6$; $p\{F_{obs}>F_{th}\}<0.05$; $n=9$ (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	Haulm or stover	Herb/woody advent	Roots	
				fine	coarse
	m ±SE	m ±SE	m ±SE	m ±SE	m ±SE
C (g 100g⁻¹DM)					
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⁻¹DM)					
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_i (g 100g⁻¹DM)					
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.

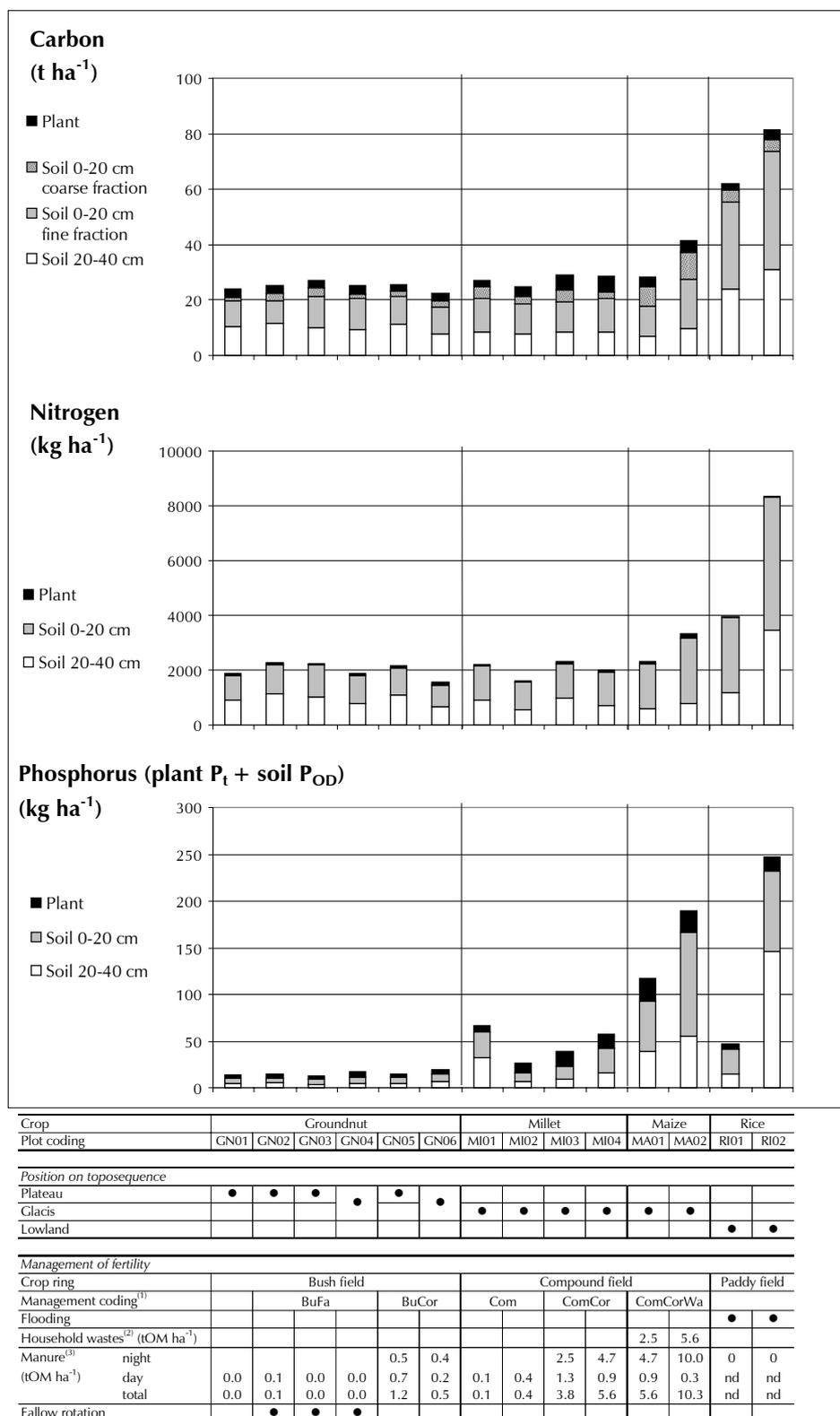


Figure 3.1 Plant and soil carbon, nitrogen and phosphorus storage in main cash and food crops along a typical toposequence in Sare Yorobana, southern Senegal.

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)						b. N (g kg ⁻¹)					
Plot	Soil layer (cm)					Plot	Soil layer (cm)				
	0-10	10-20	20-30	30-40	0-40		0-10	10-20	20-30	30-40	0-40
GN01	3.93	3.19	3.09	3.87	3.52	GN01	0.33	0.30	0.26	0.33	0.31
GN02	4.40	3.30	3.55	4.12	3.84	GN02	0.38	0.36	0.35	0.40	0.37
GN03	5.07	4.28	3.40	3.41	4.04	GN03	0.41	0.35	0.32	0.35	0.36
GN04	5.02	3.75	3.30	2.85	3.73	GN04	0.37	0.32	0.27	0.25	0.30
GN05	4.20	3.77	3.92	3.60	3.87	GN05	0.35	0.31	0.35	0.37	0.35
GN06	4.31	3.70	2.66	2.55	3.31	GN06	0.29	0.24	0.23	0.22	0.25
MI01	6.97	3.53	2.67	2.98	4.04	MI01	0.52	0.31	0.26	0.32	0.35
MI02	5.22	3.61	2.85	2.26	3.48	MI02	0.40	0.26	0.18	0.19	0.26
MI03	6.58	3.78	2.43	3.02	3.95	MI03	0.53	0.32	0.30	0.32	0.37
MI04	5.96	3.71	2.62	2.75	3.76	MI04	0.52	0.28	0.24	0.22	0.32
MA01	8.54	3.74	2.31	2.12	4.18	MA01	0.78	0.33	0.20	0.18	0.37
MA02	11.98	6.66	3.64	2.59	6.22	MA02	1.13	0.53	0.28	0.21	0.54
RI01	14.59	10.38	7.69	6.81	9.87	RI01	1.19	0.74	0.41	0.30	0.66
RI02	19.17	16.51	13.37	10.07	14.78	RI02	1.84	1.87	1.55	1.07	1.58

c. P _{OD} (mg kg ⁻¹)						d. C/N					
Plot	Soil layer (cm)					Plot	Soil layer (cm)				
	0-10	10-20	20-30	30-40	0-40		0-10	10-20	20-30	30-40	0-40
GN01	1.7	1.9	2.0	1.3	1.7	GN01	11.9	10.6	11.9	11.7	11.5
GN02	2.3	1.1	2.0	1.9	1.8	GN02	11.6	9.2	10.1	10.3	10.3
GN03	2.4	1.4	0.8	1.2	1.5	GN03	12.4	12.2	10.6	9.7	11.3
GN04	2.9	2.0	1.6	1.6	2.0	GN04	13.6	11.7	12.2	11.4	12.3
GN05	2.6	1.9	1.7	1.1	1.8	GN05	12.0	12.1	11.2	9.7	11.2
GN06	3.2	2.5	2.3	2.0	2.5	GN06	14.9	15.4	11.6	11.6	13.5
MI01	9.4	8.4	8.5	12.5	9.7	MI01	13.4	11.4	10.3	9.3	11.5
MI02	3.4	3.0	2.3	2.1	2.7	MI02	13.1	13.9	15.8	11.9	13.5
MI03	5.9	4.0	2.9	2.8	3.9	MI03	12.4	11.8	8.1	9.4	10.8
MI04	10.9	7.0	6.2	3.7	7.0	MI04	11.5	13.2	10.9	12.5	11.9
MA01	22.9	13.4	12.4	13.2	15.5	MA01	10.9	11.3	11.6	11.6	11.2
MA02	45.4	30.7	19.4	15.5	27.8	MA02	10.6	12.6	13.0	12.6	11.6
RI01	10.1	8.3	5.1	3.8	6.8	RI01	12.3	14.1	18.9	22.9	15.0
RI02	14.4	53.4	66.9	43.8	44.6	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).

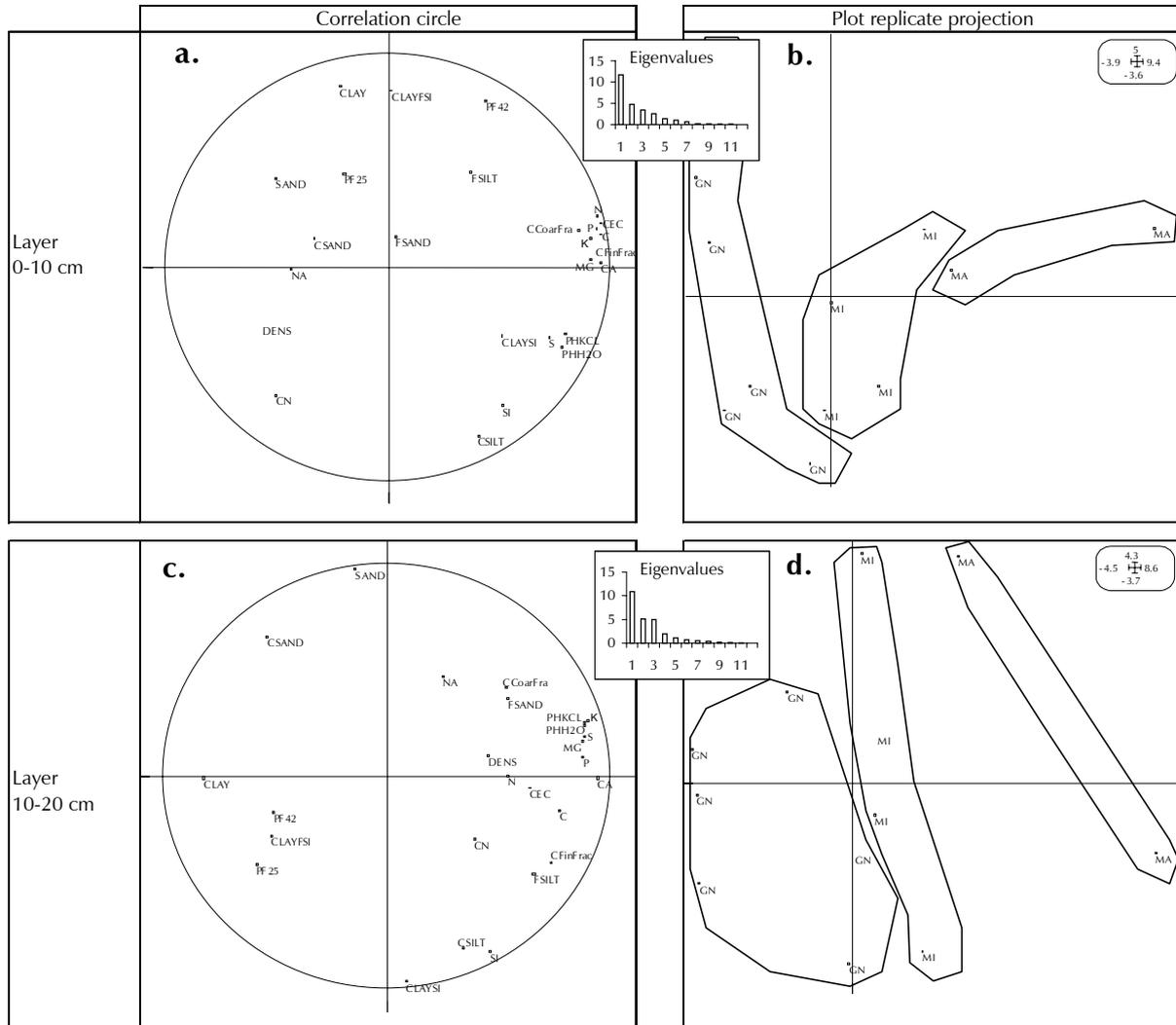


Figure 3.2 Principal components (PC) analysis of the soil properties of 12 cropped plots. Correlation circles of the variables and projection of the plot replicates on plane PC1xPC2: a,b: layer 0-10 cm; c,d: layer 10-20 cm.

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 (cm)	Bush fields Mean (\pm SE) (n=6)	Compound fields Mean (\pm SE) (n=6)	F		
			Cult. Intens.	Texture	Overall
Clay + fine silt content (%)					
0-10	11.3 \pm 1.2	10.6 \pm 1.0	0.1		
10-20	17.1 \pm 1.3	14.5 \pm 0.9	2.3		
20-30	22.5 \pm 2.5	18.0 \pm 1.2	1.3		
30-40	29.4 \pm 4.3	21.6 \pm 2.3	1.8		
0-40	20.1 \pm 2.0	16.2 \pm 1.0	2.3		
pF2.5 (gH₂O 100 g⁻¹soil)					
0-10	6.95 \pm 1.02	6.03 \pm 0.44	0.0	7.3 *	3.7
10-20	8.02 \pm 1.13	5.82 \pm 0.59	0.1	15.2 **	8.9 **
20-30	8.80 \pm 1.42	6.28 \pm 0.78	0.1	45.2 ***	26.1 ***
30-40	11.35 \pm 2.03	7.58 \pm 0.99	0.7	134.0 ***	83.6 ***
0-40	8.78 \pm 1.2	6.43 \pm 0.61	2.1	55.9 ***	30.0 ***
pF4.2 (gH₂O 100 g⁻¹soil)					
0-10	2.70 \pm 0.34	2.82 \pm 0.37	0.5	33.1 ***	16.6 **
10-20	4.03 \pm 0.46	3.03 \pm 0.23	0.1	24.9 ***	16.4 **
20-30	5.35 \pm 0.75	3.78 \pm 0.28	2.1	36.0 ***	24.9 ***
30-40	7.30 \pm 1.22	4.82 \pm 0.66	0.9	184.2 ***	114.6 ***
0-40	4.85 \pm 0.64	3.61 \pm 0.26	0.3	134.0 ***	79.5 ***
Bulk density (kg dm⁻³)					
0-10	1.52 \pm 0.01	1.47 \pm 0.02	5.1	2.6	3.6
10-20	1.47 \pm 0.03	1.54 \pm 0.01	5.2 *	0.3	2.7
20-30	1.54 \pm 0.03	1.54 \pm 0.01	0.7	0.1	0.4
30-40	1.45 \pm 0.03	1.56 \pm 0.01	23.9 ***	0.4	13.3 **
0-40	1.50 \pm 0.01	1.53 \pm 0.00	12.2 **	0.2	6.9 *

$p\{H_0: F_{obs} > F_{th} = 0\}$: * <0.05; ** <0.01; *** <0.001.

See data in Appendix 22.

Table 3.3 (continued) b. chemical properties

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

Plot	Fraction 0-50 μm				Fraction 50-2000 μm				Fractionation recovery rate ((1)+(2))/C _t
	Mass (g 100 g ⁻¹ soil)	C content in g kg ⁻¹ of		C/N	Mass (g 100 g ⁻¹ soil)	C content in g kg ⁻¹ of		C/N	
		fraction	soil (1)			fraction	soil (2)		
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

Plot	Fraction 0-50 μm				Fraction 50-2000 μm				Fractionation recovery rate ((1)+(2))/C _t
	Mass (g 100 g ⁻¹ soil)	C content in g kg ⁻¹ of		C/N	Mass (g 100 g ⁻¹ soil)	C content in g kg ⁻¹ of		C/N	
		fraction	soil (1)			fraction	soil (2)		
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 (cm)	Bush fields Mean (\pm SE)	Compound fields Mean (\pm SE)	F		
			Cultiv. intensity	Texture	Overall
C/N on non-fractionated soil					
0-10	12.7 \pm 0.5	12.0 \pm 0.5	2.0	10.9 **	6.1 *
10-20	11.9 \pm 0.9	12.4 \pm 0.4	0.1	0.1	0.2
20-30	11.3 \pm 0.3	11.6 \pm 1.1	0.6	4.5	2.2
30-40	10.8 \pm 0.4	11.2 \pm 0.6	0.0	1.9	1.1
0-40	11.7 \pm 0.4	11.7 \pm 0.4	0.7	5.0	2.5

b.

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

$p\{H_0: F_{obs} > F_{th} = 0\}$; * < 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] μ m 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 \pm 1.4 ν s. 6.8 \pm 0.3 t ha⁻¹) but only 16 % for the 0-40 cm layer (25.8 \pm 2.4 ν s. 22.3 \pm 0.7 t ha⁻¹) (Table 3.6). Similar differences were found for N: these were 950 \pm 150 in compound fields ν s. 540 \pm 30 kg ha⁻¹ in bush fields for the 0-10 cm layer, and 2210 \pm 220 ν s.

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 (cm)	Bush fields Mean (±SE) (n=6)	Compound fields Mean (±SE) (n=6)	F		Overall
			Cultiv. intensity	Texture	
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 (cm)	Fraction (µm)	Bush fields Mean (±SE)	Compound fields Mean (±SE)	F		Overall
				Cultiv. intensity	Texture	
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{H₀: 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 ($10.26 \pm 1.05 \text{ g kg}^{-1}$) > Com = ComCor ($6.27 \pm 0.63 \text{ g kg}^{-1}$) > BuFa = BuCor ($4.26 \pm 0.41 \text{ g kg}^{-1}$). 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 ($15.4 \pm 1.6 \text{ tC ha}^{-1}$) > Com = ComCor ($6.27 \pm 0.63 \text{ tC ha}^{-1}$) > BuFa = BuCor ($4.26 \pm 0.41 \text{ tC ha}^{-1}$). 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	Texture	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 ($\alpha=0.05$; pair-wise T-test). $p\{H_0: F_{obs} > F_{th} = 0\}$: * < 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.

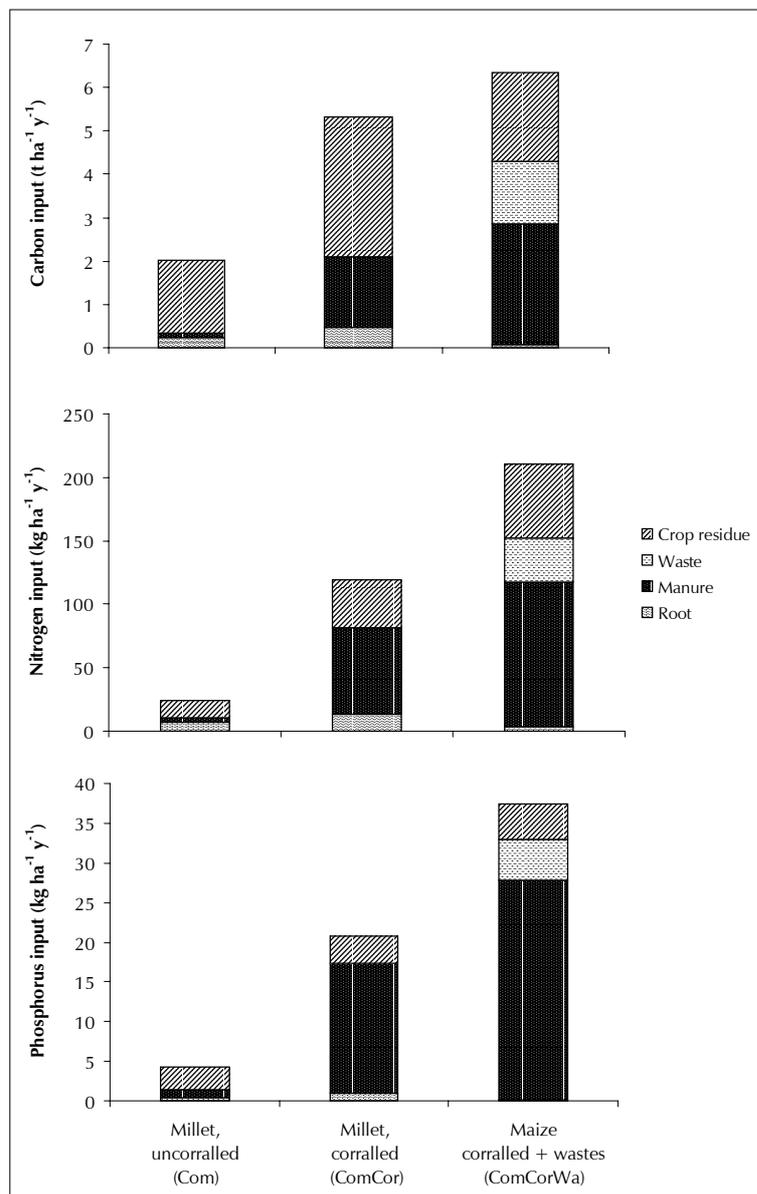


Figure 3.3 Carbon, nitrogen and phosphorus organic inputs in compound fields under three different patterns of organic management of fertility.

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.

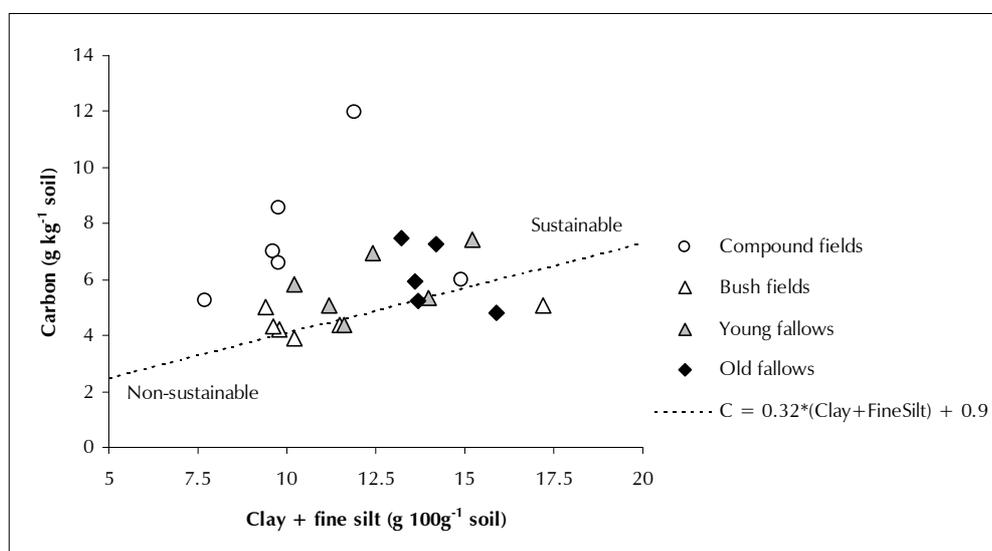


Figure 3.4 Assessment of soil quality of 23 crop and fallow plots (this study and Chapter 2) as predicted by Feller's criterion (1995b) based on carbon content and fine texture. Young fallow: aged 0-9 years. Old fallow: older than 9 years. See data in Appendix 27.

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 exudation and pre-harvest mortality of roots). Schaefer (1974) demonstrated that annual C-CO₂ 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 addressed. 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).

PART

II

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

THE VILLAGE TERRITORY
SCALE

CHAPTER 4.

CARBON, NITROGEN AND PHOSPHORUS

SPATIALIZED BUDGET OF A VILLAGE TERRITORY

OF THE WEST AFRICAN SAVANNA.

I. THE STOCKS



Millet field at harvest

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

ABSTRACT

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

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

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

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

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

KEY WORDS

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

4.1. INTRODUCTION

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

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

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

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

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

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

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

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

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

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

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

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

4.2. METHODS

4.2.1. Site characteristics

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

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

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

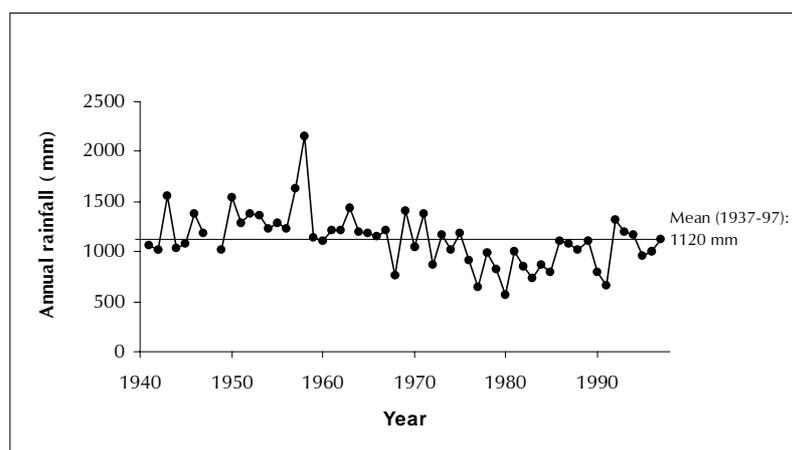


Figure 4.1 Mean annual rainfall over the last 60 years (Service de la Météorologie Nationale, station of Kolda).
See data in Appendix 28.

Kolda).

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

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

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

4.2.2. Characterisation of the farming system

4.2.2.1. Spatial organisation

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

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

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

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

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

4.2.2.2. Social organisation

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

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

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

4.2.3.1. On-field measurement of harvested plant biomass

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

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

biomass

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

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

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

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

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

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

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

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

Source: Chapters 2 and 3.

4.2.3.4. Establishment of a simplified agropastoral budget

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

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

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

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

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

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

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

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

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

4.3. RESULTS

4.3.1. Spatial organisation of the farming system

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

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

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

"Millet x maize" stand for millet intercropped with maize.

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

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

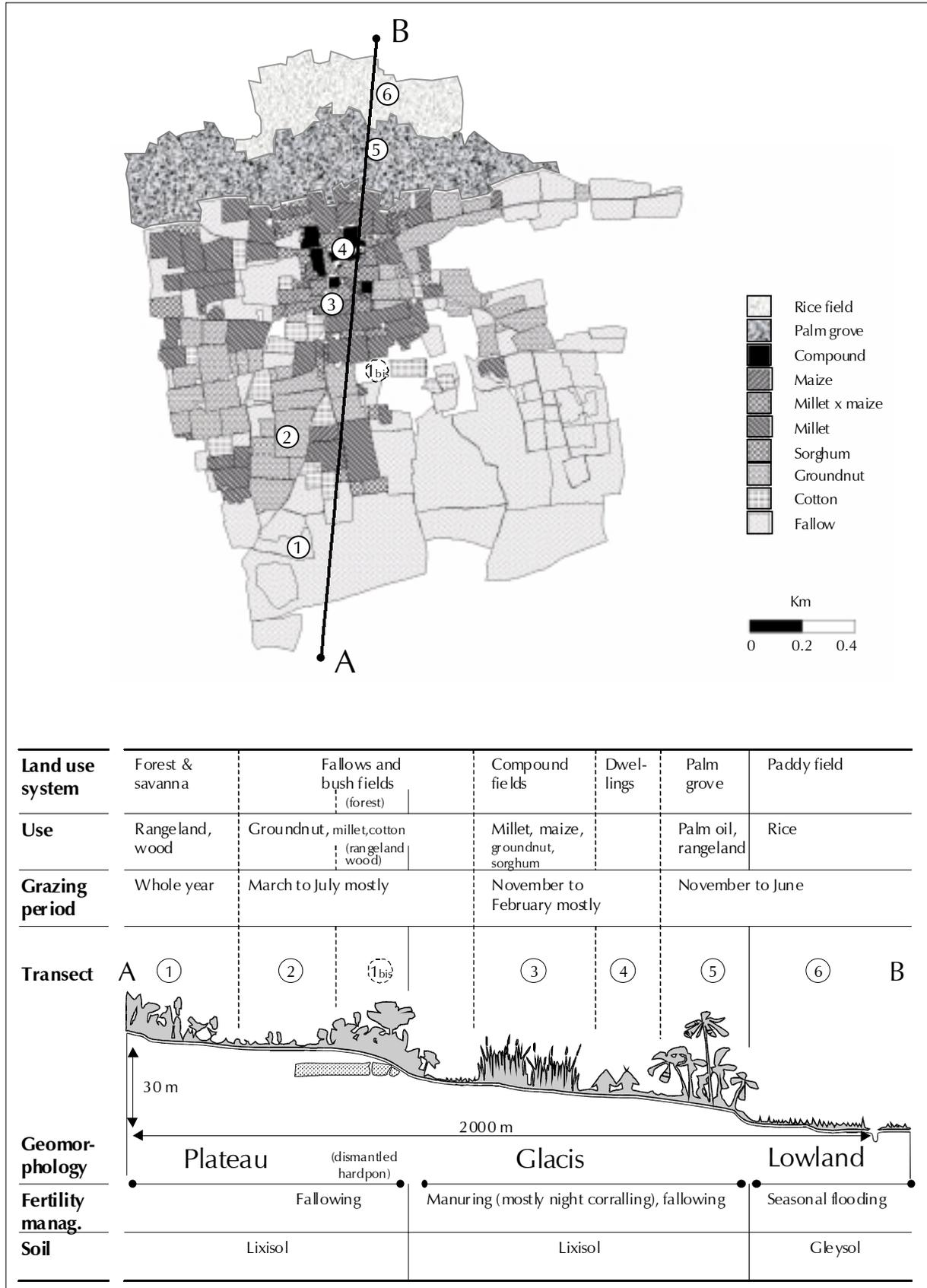


Figure 4.2 Spatial organisation and land use in the village of Sare Yorobana.

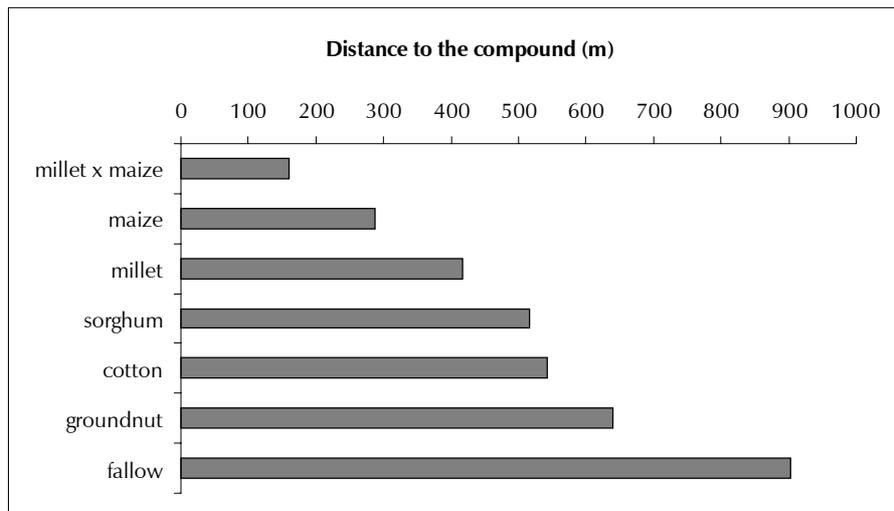


Figure 4.3 Spatial distribution of land use as illustrated by the distance of crops to the compound. See data in Appendix 29.

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

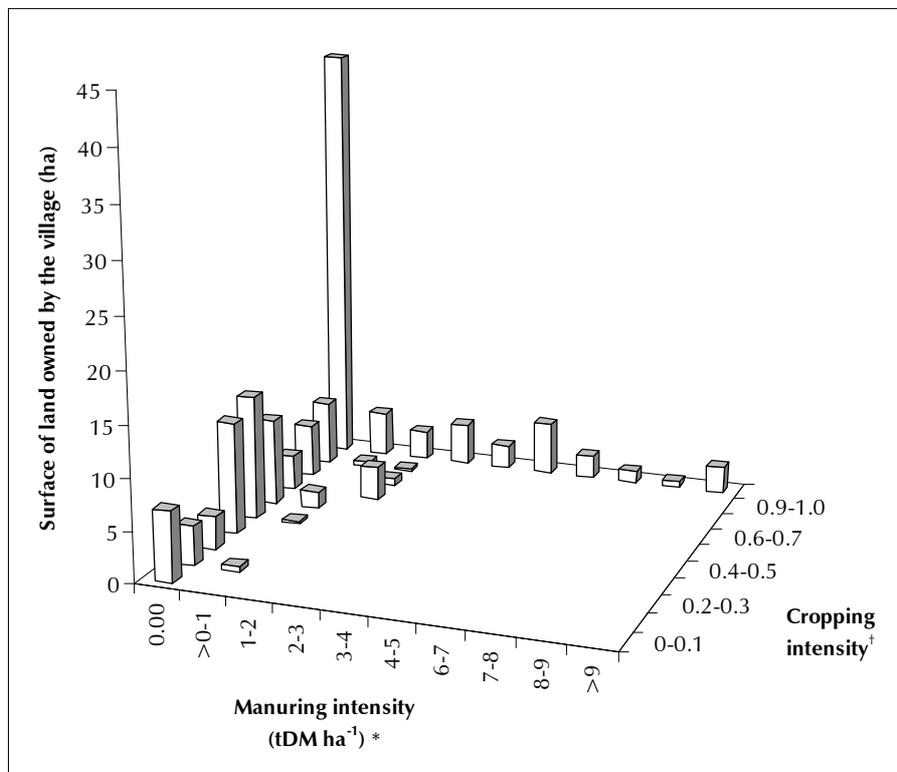


Figure 4.4 Spatial complementarity between cropping intensity and manuring in the mixed-farming system of the village of Sare Yorobana.

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

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

See data in Appendix 30.

4.3.2. Social organisation

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

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

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

(1) See 4.2.2.2. for definition

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

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

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

See more data in Appendix 31.

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

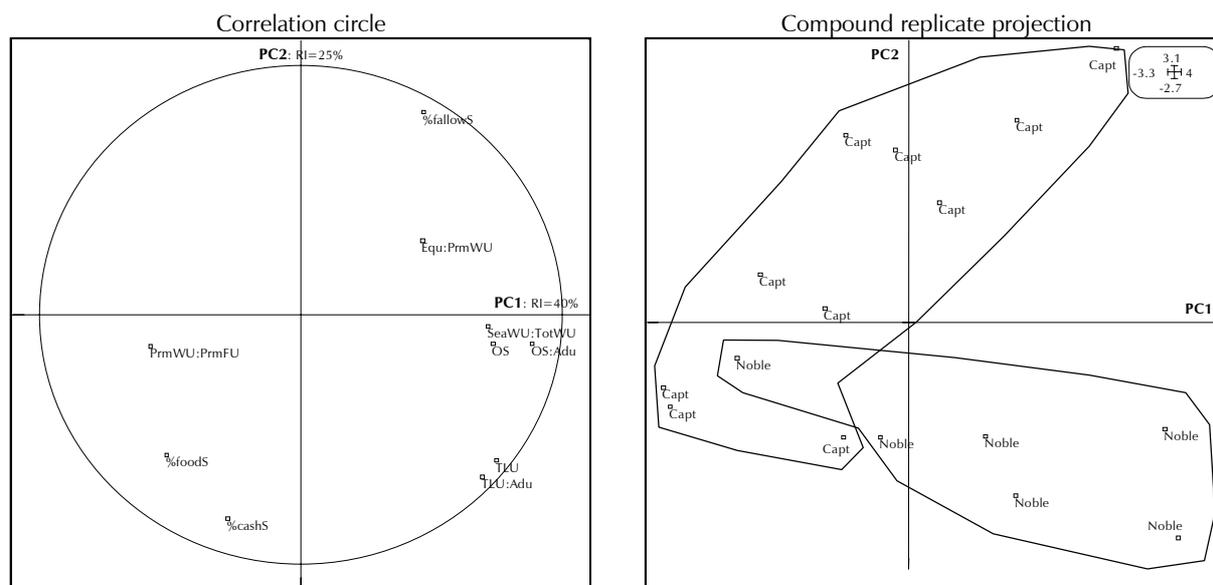


Figure 4.5 Principal component (PC) analysis of the structure of 16 out of the 18 holdings of Sare Yorobana: correlation circle of the variables and compound replicate projection (1st and 2nd PC).

“:” stands for “ratio”.

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

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

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

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

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

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

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

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

Data used for regressions are in Appendix 35.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

[†] set to 0

[‡] carbon content set to that of millet

* not including the palm grove

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

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

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

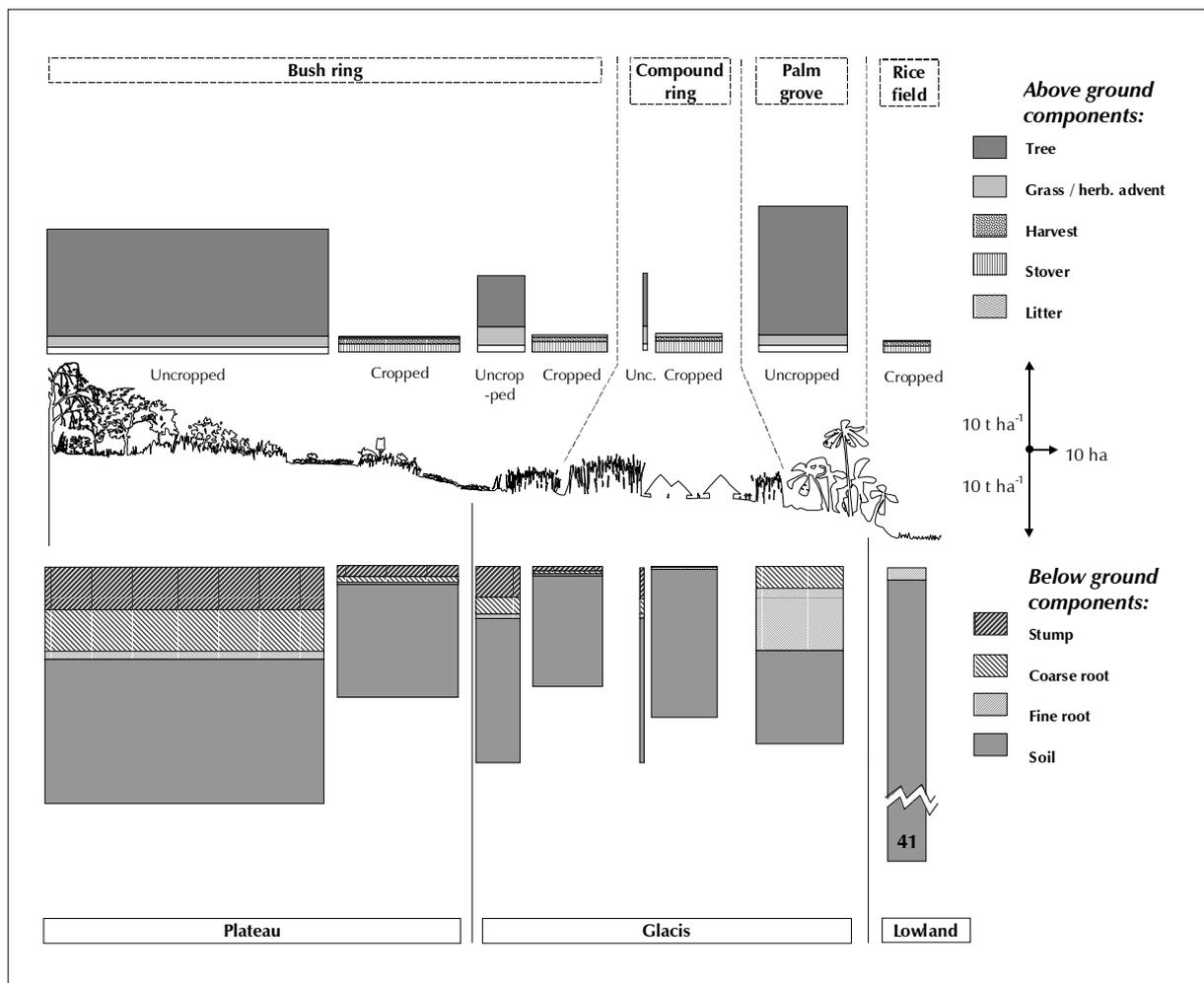


Figure 4.6a Carbon storage in plant biomass and soil of the territory of the village of Sare Yorobana with respect to geomorphology, ring and land use (cropped, non-cropped).

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

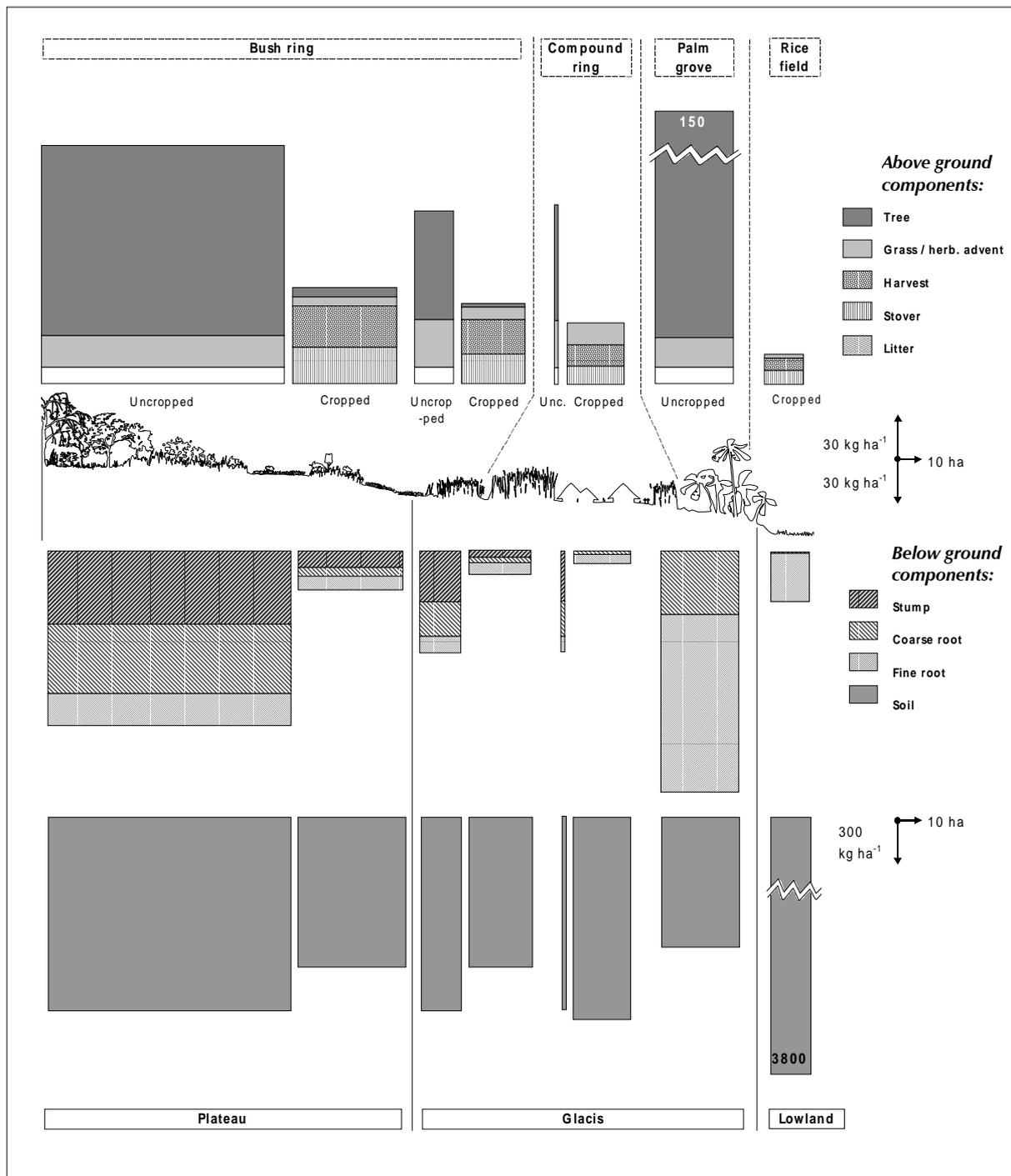


Figure 4.6b Nitrogen storage in plant biomass and soil of the territory of the village of Sare Yorobana with respect to geomorphology, ring and land use (cropped, non-cropped).

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

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

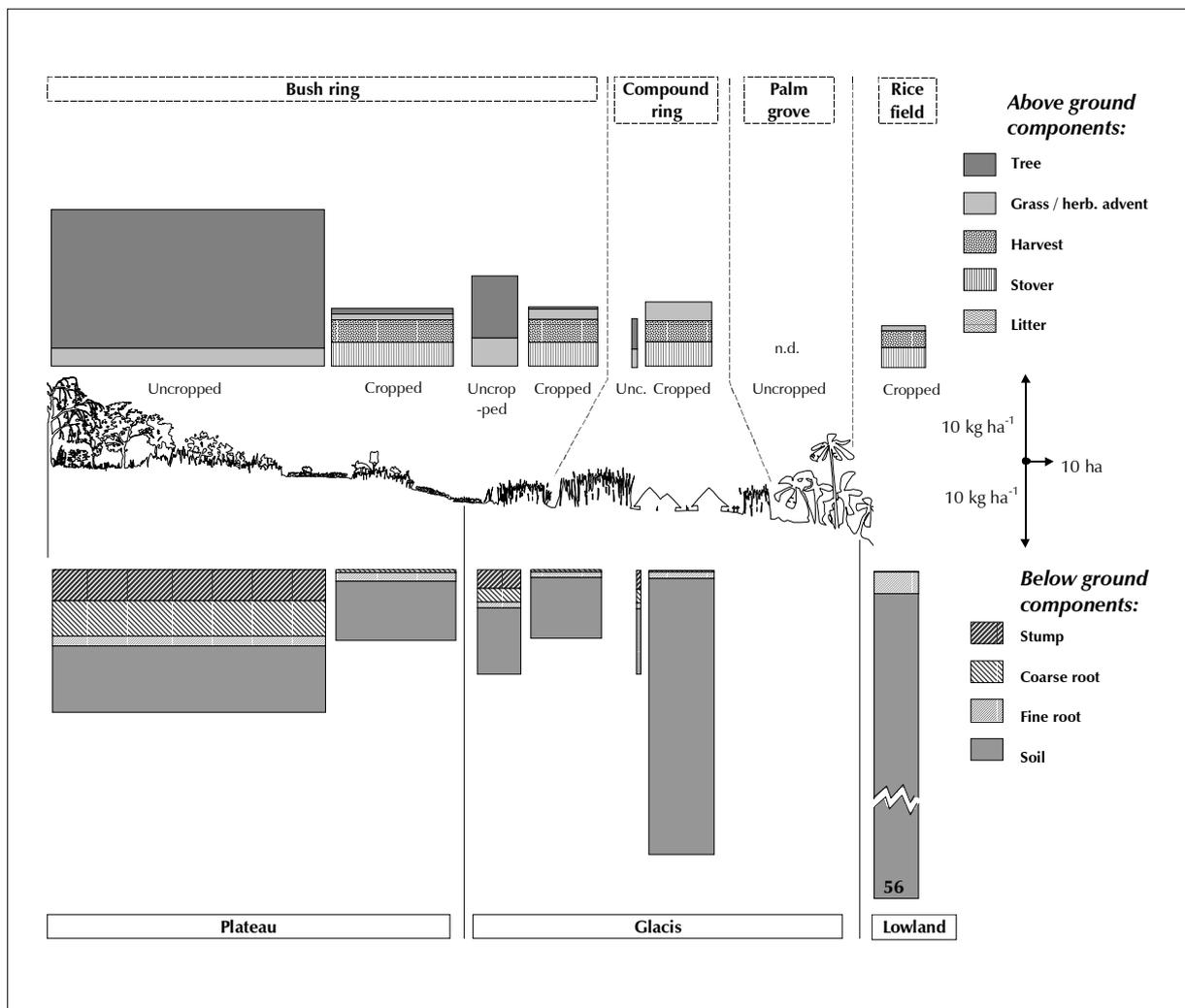


Figure 4.6c Phosphorus storage in plant biomass and soil of the territory of the village of Sare Yorobana with respect to geomorphology, ring and land use (cropped, non-cropped).

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

4.3.3.3. A simplified agro-pastoral budget

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

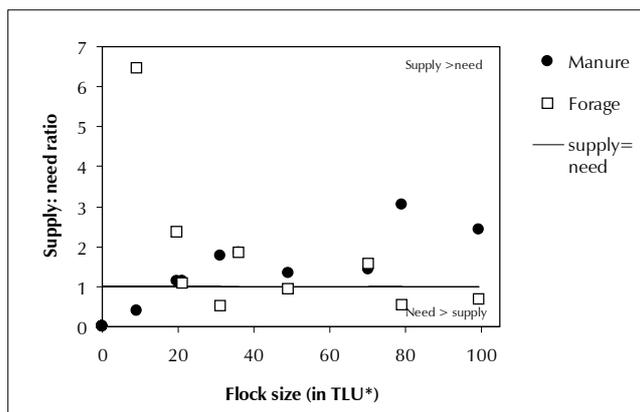


Figure 4.7 Self sufficiency in manure and forage availability in the holdings of Sare Yorobana as derived from a simplified agro-pastoral budget.

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

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

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

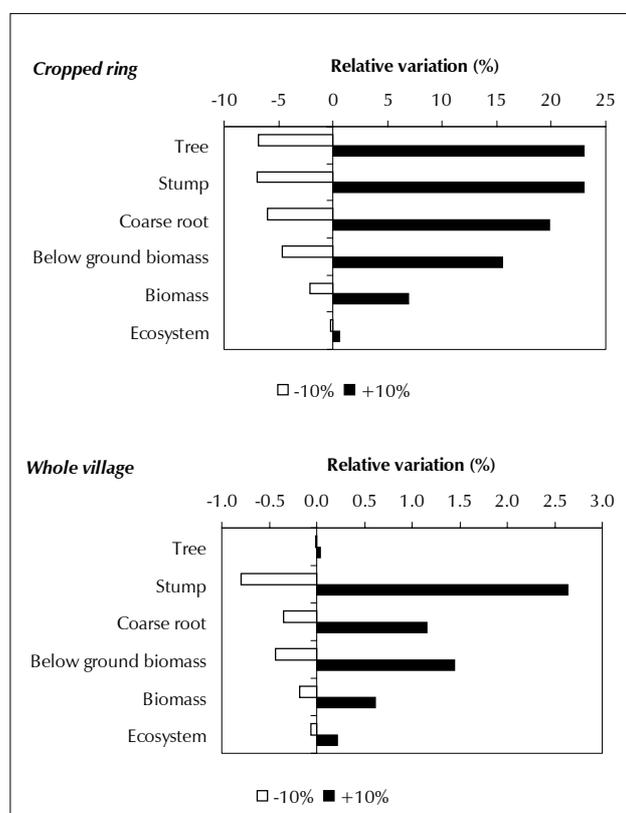


Figure 4.8 Analysis of sensitiveness of carbon storage calculation as related to the threshold value of cropping intensity driving woody advent biomass in cropped plots: impact of a variation of less or more than 10 % of this threshold value on C stock estimates.
See Appendix 38 for data.

4.3.4. Outlook on future C stocks

4.3.4.1. Land use

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

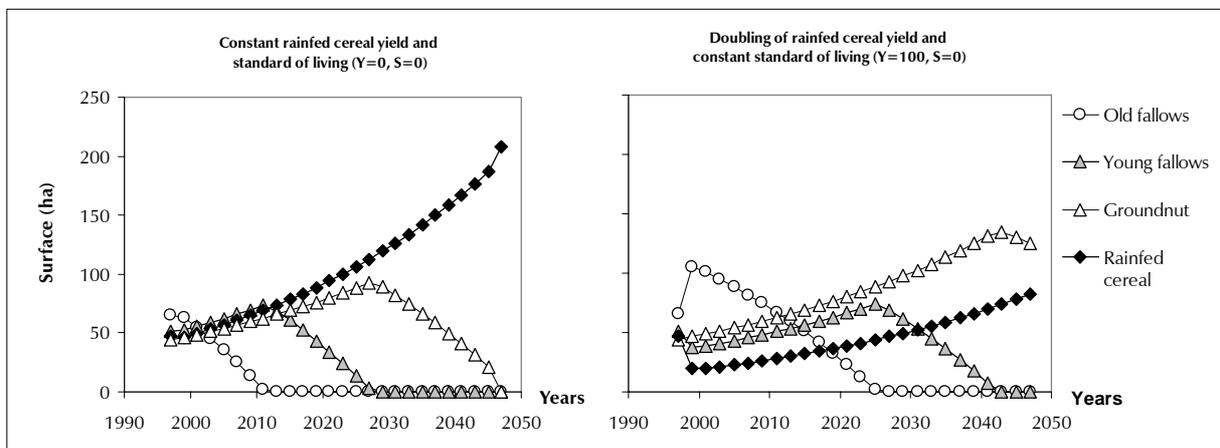


Figure 4.9 Evolution of land use in the village of Sare Yorobana for the 1997-2047 period as predicted by a static model (see description in text).

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

4.3.4.2. Carbon storage in the village territory

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

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

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

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

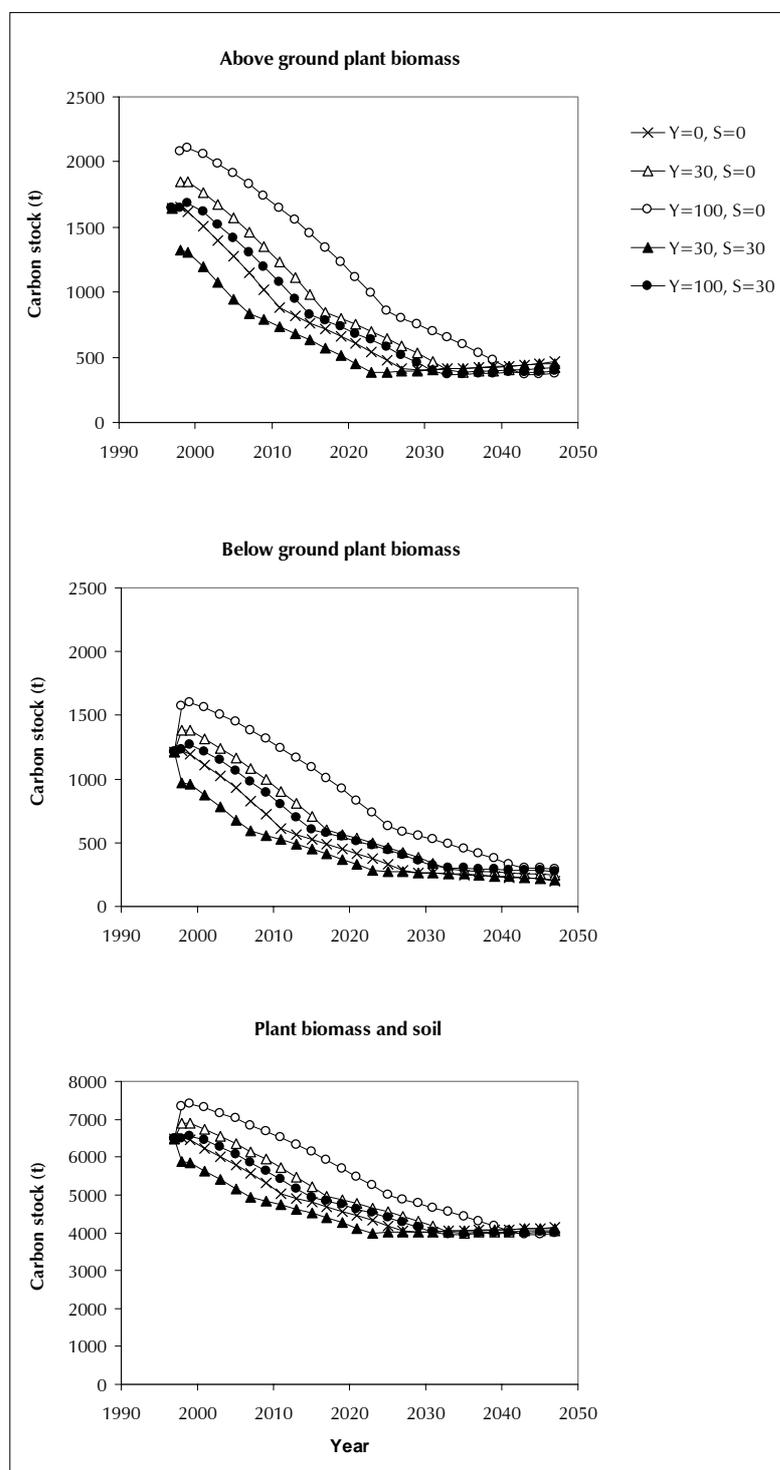


Figure 4.10 Evolution of carbon storage in the plant-soil system (soil: layer 0-20 cm considered only) of the territory of the village of Sare Yorobana for the 1997-2047 period as predicted by modelling (see description in text).

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

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

See Appendix 40 for data.

4.4. DISCUSSION

4.4.1. Social organisation & dynamics of the farming system

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

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

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

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

4.4.2.1. The bush ring

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

4.4.2.2. The compound ring

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

4.4.2.3. The palm grove

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

4.4.2.4. The rice fields

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

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

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

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

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

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

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

4.4.4. Future evolution of the carbon stocks

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

CHAPTER 5.

CARBON, NITROGEN AND PHOSPHORUS

SPATIALIZED BUDGET OF A VILLAGE TERRITORY

OF THE WEST AFRICAN SAVANNA

II. THE FLUXES



Drift pasture on millet crop residue

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

ABSTRACT

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

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

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

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

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

KEY WORDS

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

5.1. INTRODUCTION

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

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

A noticeable feature of the carbon dynamic in tropical farming systems is its highly seasonal pattern. Plant biomass production occurs mainly during the wet season, even in perennial vegetation, leading to peak storage of organic matter at the offset of rains (Kowal and Kassam, 1978). Plant productivity remains very weak during the following months, while the continuous activity of human beings and animals results in the progressive exploitation of the newly created resource. As a consequence, substantial vertical flows and horizontal transfers of carbon and related nutrients are set up till the return of rains. Farmers directly manage some of these flows. The main ones are linked to food harvest (grain and haulm), livestock-mediated organic fluxes, and collecting of wood and of other non-ligneous products in fallows and savanna.

Except for the works of Woomer *et al.* (1998), Dugué (2000) and Ngamine and Altolna (2000), attempts to quantify organic matter fluxes at the scale of the farming seldom encompass all the uses of organic matter. Crop-livestock integration has initiated several studies dealing with various roles of organic matter. The role of livestock in transfers of fertility at the village scale is widely acknowledged (Landais and Guérin, 1992; Landais and Lhoste, 1993; Fernandez-Rivera *et al.*, 1994; Buerkert and Hiernaux, 1998), but

spatialisation and quantification of livestock-mediated fluxes remain scarce (Murwira *et al.*, 1994; Hiernaux *et al.*, 1997; Achard *et al.*, 2000). Most of nutrient budgets for sub-Saharan are set at the field level (Bationo *et al.*, 1998) or at the regional scale (Stoorvogel *et al.*, 1993a; Stoorvogel *et al.*, 1993b); but few include the village level (Krogh, 1997; Defoer *et al.*, 1998). And when they do, carbon budgets miss.

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

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

5.2. METHODS

5.2.1. Site characteristics

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

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

The farming system (land use, spatial allocation of organic resources) was depicted in Chapter 4. This system exhibits a ring-like organisation scheme typical of West African human settlements. A compound ring surrounds the dwellings. It is devoted to food production through continuous cropping of cereals, mainly pearl millet (*Pennisetum glaucum* L.), maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench),

thanks to manuring and spreading of household wastes. Beyond, the bush ring encircles the compound ring. Various cropping patterns coexist (depending on manure availability), but semi-permanent cultivation dominates. Both staple and cash -groundnut (*Arachis hypogea* L.) and cotton (*Gossypium hirsutum* L.) to a lesser extent- crops are to be found there. The edge with the forest/savanna ring marks out the limits of the village on the plateau and glaciis; the village owns a palm grove (*Elaeis guineensis* Jacq.) and rice (*Oryza sativa* L.) fields in the lowland too.

In 1997, the surface owned privately or in common by the 268 inhabitants was 260 ha, of which 110 were cropped. However, the space used by the village spreads largely beyond these boundaries, because of extensive livestock breeding. In 1997, the village managed 410 tropical livestock units (TLU; one TLU being equal to 250 kg of live weight or LW). Taurine cattle consist of the *Bos taurus* species. The local *Ndama* race is trypano-tolerant but has rather poor zootechnical performances (Coulomb, 1976). Cattle is usually run by herdsmen in the savanna/forest ring during the cropping period, and they are left straying during the dry season (Richard *et al.*, 1991). Common grazing is the usual rule, but manuring during night corralling benefits to cattle owners only.

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

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

5.2.2.1. Flows at harvest

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

5.2.2.2. Livestock-mediated transfers

Space mapping

Two kinds of mapping were performed to spatialize organic matter flows related to cattle activity. Firstly, the subregion district of Dioulacolon, to which Sare Yorobana belongs, was mapped and scaled to 1:12000 thanks to a photo-interpretation of the physiognomic types of vegetation. For this study, seven vegetation types were distinguished: woody savanna (upper woody strata or UWS above 7 m high); bush

savanna ($2\text{ m} < \text{UWS} < 7\text{ m}$); grass savanna ($\text{UWS} < 2\text{ m}$); rice fields; rainfed fields and ponds (pooled as “Other” in what follows). This typology was used to characterise the flows occurring in the area outside the village (except for palm grove, which was pooled with bush savanna). Another mapping was performed for all the plots (cropped or not) owned by the village (see Chapter 4 for detailed method).

Livestock location

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

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

Estimate of plant biomass uptake and dung deposition by livestock

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

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

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

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

5.2.2.3. Energy and construction needs

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

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

5.2.3. Outlook on carbon flows

To predict how the organic flows of the village territory may evolve during the next decades, a simplified representation of its dynamics was made using a spreadsheet relating C amounts to land use, which in turn was linked to manure availability and human needs (see Chapter 4 for a detailed description of the model). Five scenarios were tested, combining three modality levels of increase of cereal yield (0, 30 and 100 %) and two modalities of increase of the standard of living (0 and 30 %). Output variables monitored were C flows (C intake by livestock, crop, wood and straw harvest). Ratio of C flow to C amount (as simulated in Chapter 4) was also examined as an indicator for the viability of the system under different constraint options.

5.3. RESULTS

5.3.1. Current C, N & P fluxes

5.3.1.1. Crop harvest

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

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

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

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

±: standard error.

See Appendix 35 for data.

5.3.1.2. Livestock-mediated flows

Uptake

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

Table 5.2 Dry matter, carbon, nitrogen and phosphorus budgets of the land use systems exploited by peasants of Sare Yorobana in and around the village territory, as related to crop harvest, livestock-mediated transfers, wood and straw harvest, and residue recycling. All data in mass per hectare, except for farmyard (computed in absolute amounts).

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

Table 5.2 (continued)

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

* data for fallows in the compound ring not detailed (less than 0.5 ha).

See Appendix 41 for absolute amounts and distribution.

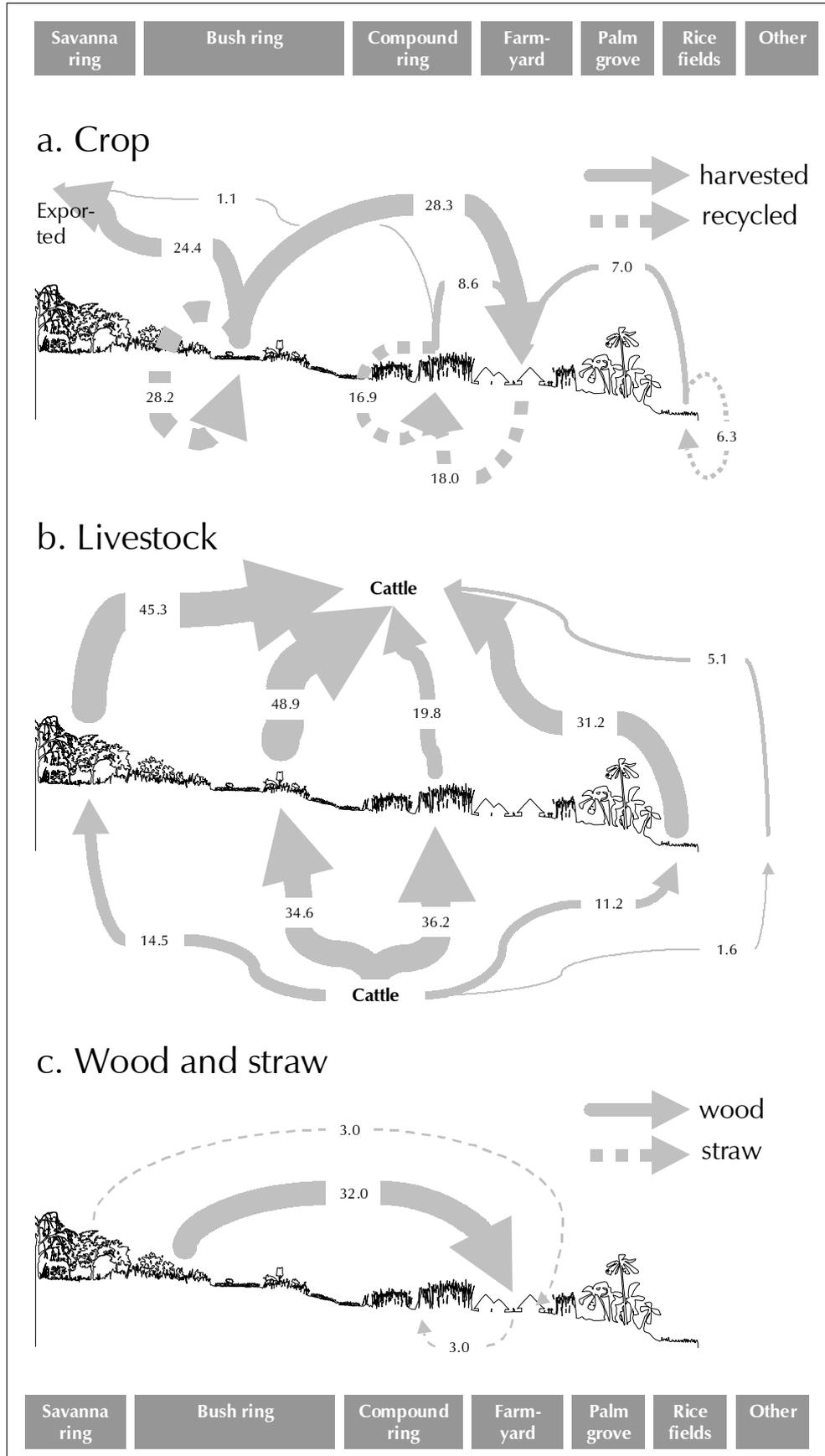


Figure 5.1 Anthropogenic flows of carbon (tons) established from November 1996 to November 1997 in Sare Yorobana. Livestock flows include the dry season only. Arrow width is proportional to flow value. See Appendix 41 for data.

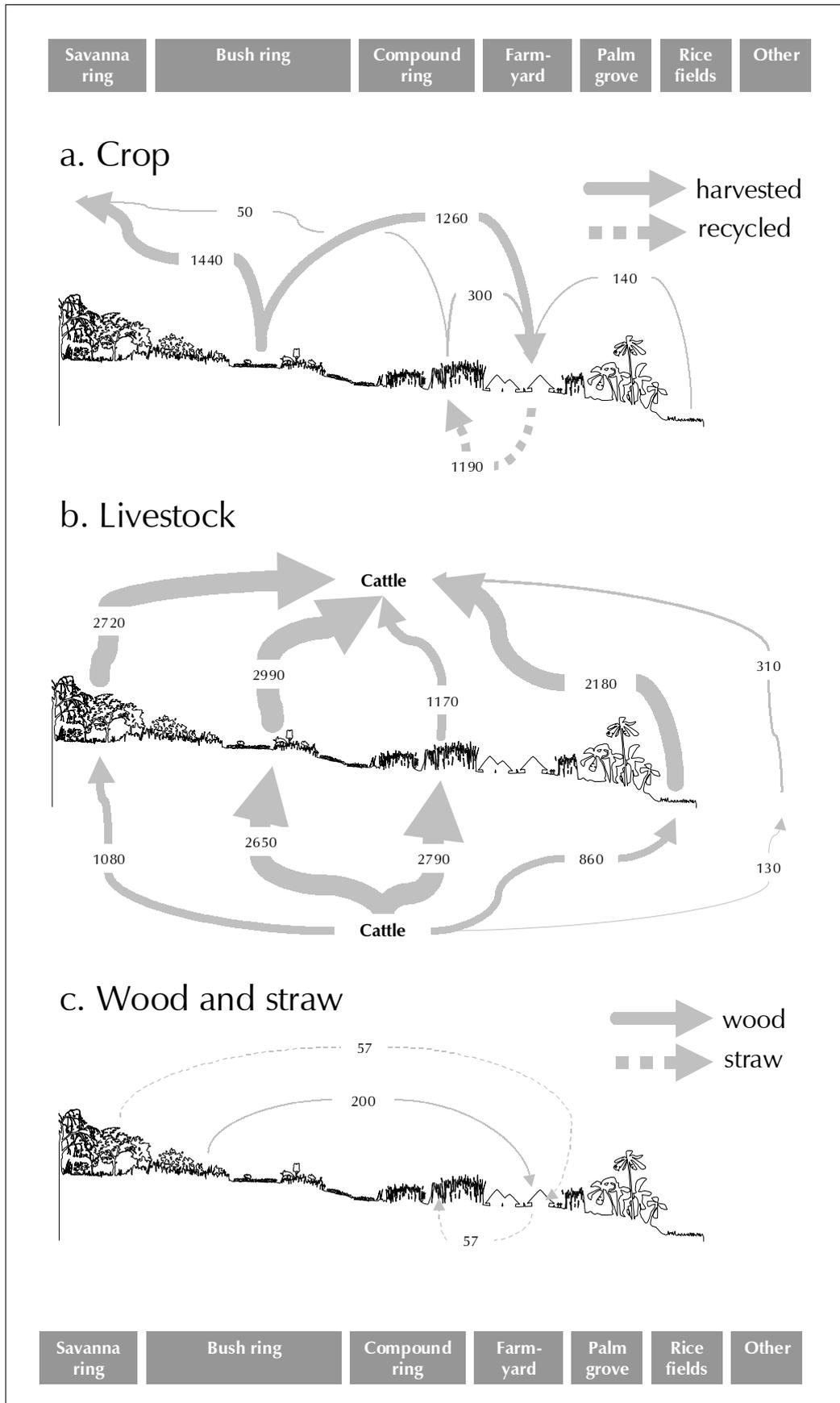


Figure 5.2 Anthropogenic flows of nitrogen (kg) established from November 1996 to November 1997 in Sare Yorobana. Livestock flows include the dry season only. Arrow width is proportional to flow value. See Appendix 41 for data.

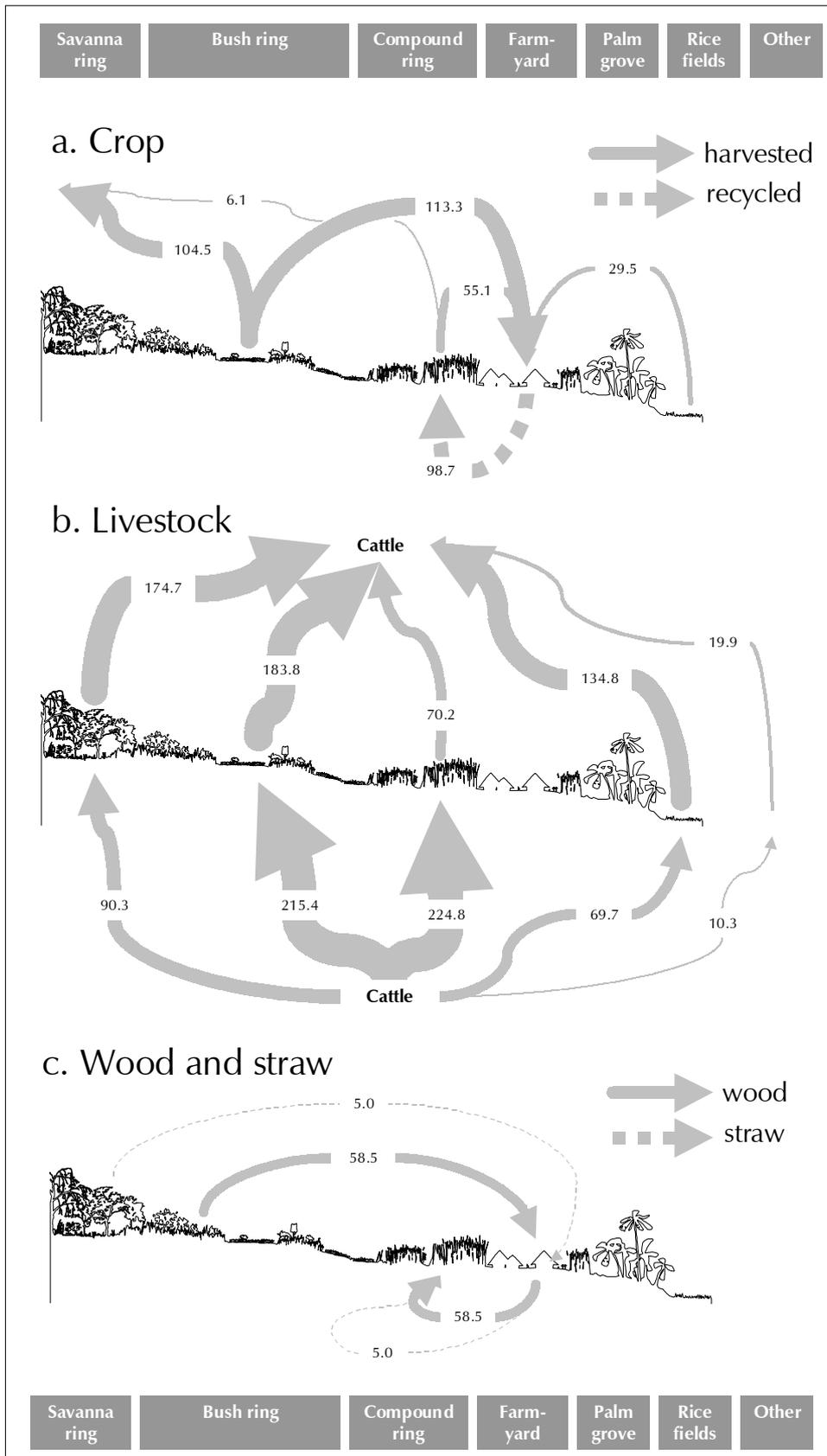


Figure 5.3 Anthropogenic flows of phosphorus (kg) established from November 1996 to November 1997 in Sare Yorobana. Livestock flows include the dry season only. Arrow width is proportional to flow value. See Appendix 41 for data.

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

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

All data expressed in g of element per day per kilo of metabolic weight.

Source: ISRA/CIRAD-EMVT, Program ABT (Ickowicz et al., 1998).

See Appendix 43 for carbon, nitrogen and phosphorus content of cow dung.

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

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

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

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

TLU: tropical livestock unit (1TLU=250 kg of live weight)

* includes the size of another herd managed by the holding (34.5 TLU).

See data in Appendix 44.

A clear influence of previous cropping and land use on frequentations by animals during day straying was also evidenced, as illustrated by the contrasted organic matter flow densities recorded among land uses (crop type) and LUS (ring management, physiognomy of the vegetation of uncropped areas) (Table 5.2, Figure 5.4). According to grazing intensity, previous cropping ranked in the following order in the area owned by the village: millet > maize > millet intercropped with maize > groundnut > sorghum > fallow. When considering the whole territory prospected by animals, ranking was: compound ring > rice field > grass savanna = bush ring > woody savanna > bush savanna. When computing absolute intake values, main forage sources were the bush ring and the savanna ring (61 % out of the 443 tDM removed,

equivalent to 63 % of 150tC) (Figure 5.1b); the compound ring ranked behind the rice fields. Nitrogen and phosphorus flows showed spatial patterns similar to C; they rose to 9.4 tN and 580 kgP (Figure 5.2b, Figure 5.3b).

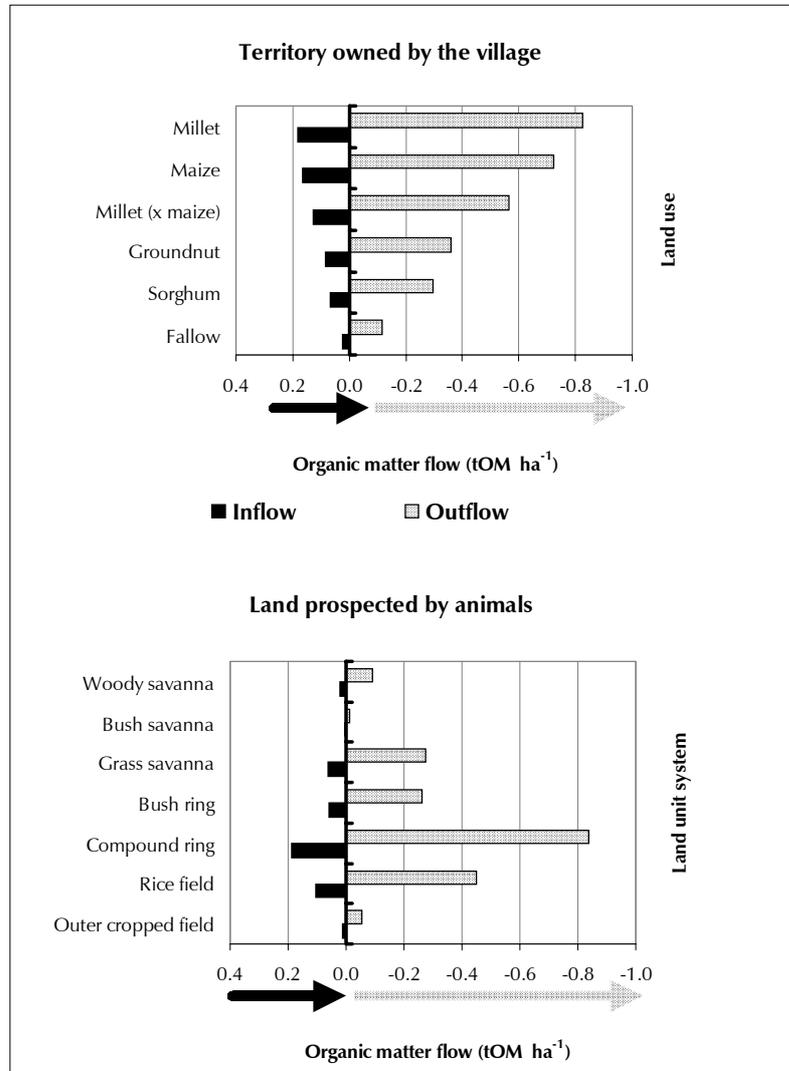


Figure 5.4 Organic matter inflows and outflows initiated by intake and faecal excretion of three herds during the 1995-1996 dry season. See Appendix 46 for data.

Faecal excretion

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

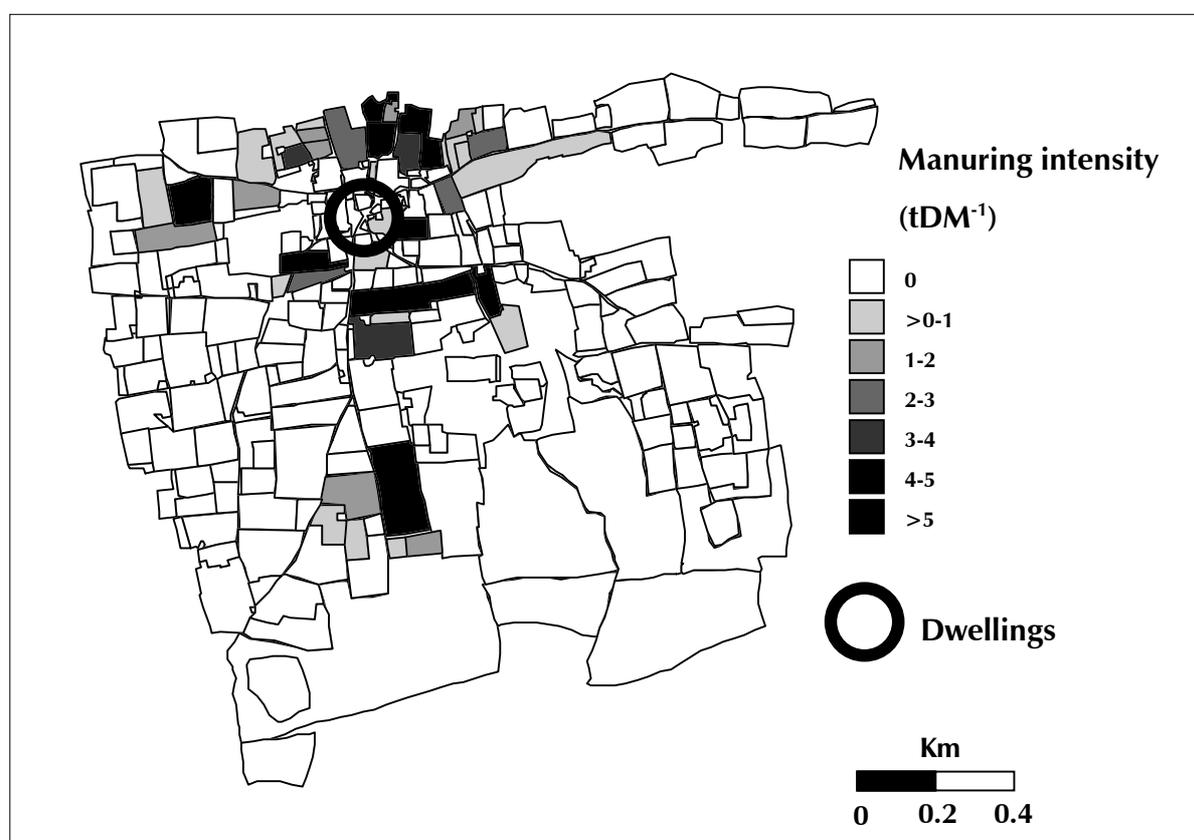


Figure 5.5 Manuring intensity from night corralling in the village of Sare Yorobana during the 1996-1997 dry season. See Appendix 2 for data.

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

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

±: standard error.

See data in Appendix 45.

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

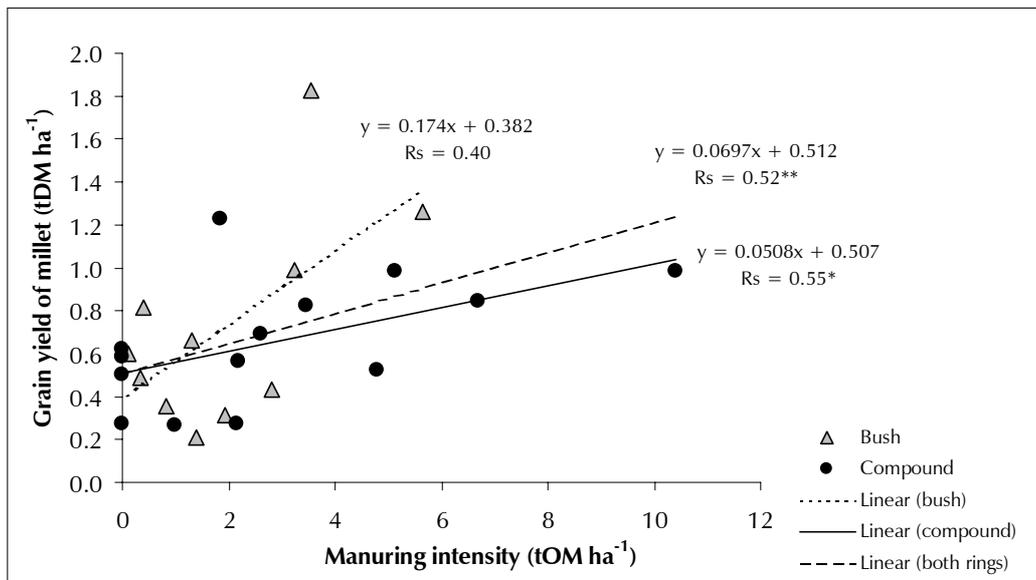


Figure 5.6 Millet yield as related to manuring practices in the compound and bush rings.
 $p\{R_{Spearman}=0\}$: * <0.05 ; ** <0.01 . See Appendix 47 for data.

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

5.3.1.3. Other anthropogenic fluxes

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

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

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

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

5.3.1.4. Global carbon and nutrient balance

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

Table 5.6 Participation of crop harvest, livestock, and collecting of wood and straw to anthropogenic carbon, nitrogen and phosphorus transfers due to farming activities.

	Crop (%)	Livestock (%)	Wood and straw (%)	Total (%)	(abs)
Removal					
C	27	59	14	100	255 t
N	25	73	2	100	12.8 t
P	32	61	7	100	956 kg
Return					
C	15	83	2	100	119 t
N	14	86	1	100	8.7 t
P	13	79	8	100	773 kg

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

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

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

5.3.2. Outlook on future carbon outflows

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

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

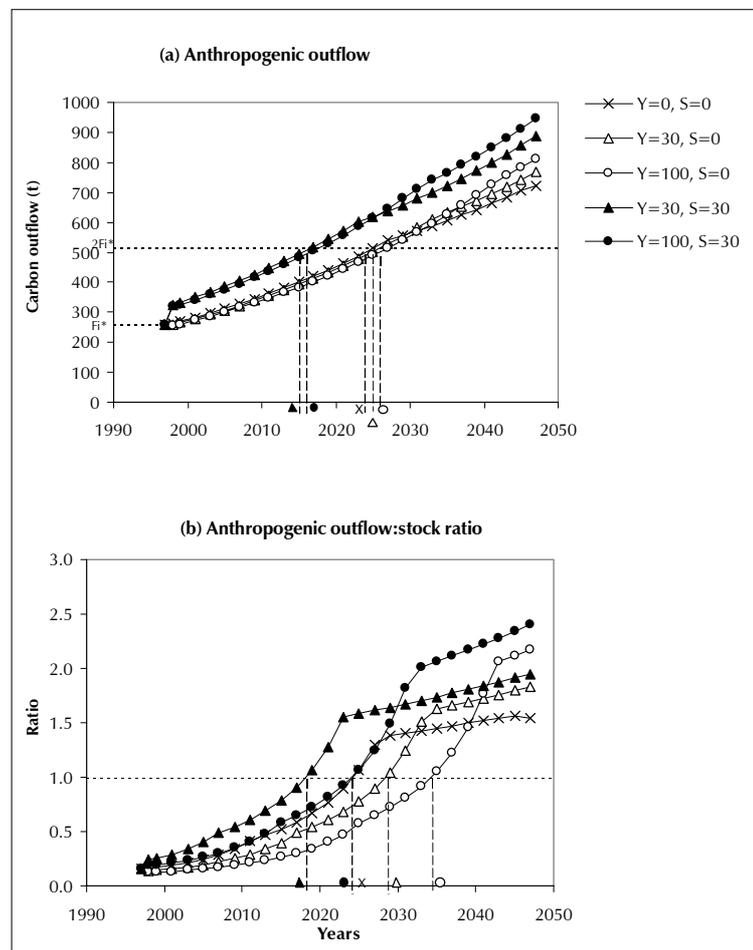


Figure 5.7 Evolution of (a) anthropogenic carbon outflows (b) ratio of C outflow to amount of C stored in plant above-ground biomass of the territory of the village of Sare Yorobana for the 1997-2047 period as predicted by modelling (see description of the model in Chapter 4). Outflows considered are: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

5.4. DISCUSSION

5.4.1. Control of stocks over flows: livestock mediated transfers

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

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

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

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

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

5.4.1.2. The human factor

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

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

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

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

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

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

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

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

5.4.3.1. On site recycling

As demonstrated above, common grazing leads to on-site recycling of half of herbaceous biomass produced on the cropped fields. From a pastoralist point of view, common grazing thus saves labour but not forage resource. On an agricultural perspective, organic matter recycling through animals speeds up biogeochemical cycles (Landais and Guérin, 1992), but leads to the withdrawal of a third of carbon from the system through animal respiration. Assessment of soil C, N and P status at the plot scale in various agroecosystems of the study site have pointed out the necessity of setting steady C flows through the soil to maintain soil quality (Chapters 2 and 3). Thus propositions aimed at improving manure availability and quality through herd expansion and stalling of cattle (Bosma *et al.*, 1999) should also take into account the energetic (carbon) cost of such practices for the farming ecosystem. Organic matter/energy loss is all the more likely to happen, since the return of manure from stall to field is often limited by transport means and labour availability (Schleich, 1986). Such a loss may seriously threaten the sustainability of traditional farming systems, since fast beneficial effects of on-site recycling of crop residues on soil quality by the doing of below-ground macrofauna for instance are now well documented (Mando, 1998; Mando and Stroosnijder, 1999).

5.4.3.2. Spatial organic transfers, C inputs and nutrient balances

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

Considering nutrient dynamics, N and P outflows were well balanced between rainfed cropped fields and other land use systems, but these cropped fields represented 74 % of the N and P sinks, of which nearly all benefited to staple crops, resulting in positive N and P balance. Thus, the current system acts as an

impluvium for carbon and nutrient elements, since it taps organic resources from the peripheral areas to the rainfed food crops. By this way, ring like organisation scheme enables sustainable continuous cultivation of cereals at relatively high yields on 7 % of the surface owned by the village. In the compound ring (8 % of the territory) of a village of the Sahelian zone, N and P inputs were reported to amount to 7.7 kgN ha⁻¹ and 1.1 kgP ha⁻¹ under a stocking rate of 12 TLU ha⁻¹ (Buerkert and Hiernaux, 1998). This is less than our findings (+87 kgN ha⁻¹; +8.3 kgP ha⁻¹), even taking into account the difference in stocking rate, and it indicates possible impact of climate on potential nutrient transfers by livestock.

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

From a nutrient point of view, the system as a whole might be considered close to sustainability. However, one of the major prerequisites is high livestock availability, through which most of C, N and P flows to the village occur. The potential of higher herd densities to sustain agricultural systems through manure production has been well demonstrated in West Africa (Schleich, 1986; Williams *et al.*, 1994; Bosma *et al.*, 1999). But unless switching to more intensified farming patterns such as fertilised ley and improved fallow (Hoefsloot and VanDerPol, 1993), forage availability quickly impedes the maintenance of animal husbandry in crowded areas. Another condition driving the sustainability of the farming system of Sare Yorobana is thus good land availability. The keeping of wide peripheral rangelands (1) ensures forage availability during the cropping period, thus avoiding the seasonal –and most of time definitive- migration of livestock as largely experienced in the Groundnut Belt of Central Senegal (Lericollais and Milleville, 1993) (2) lessens competition between human and animal needs for plant biomass, since large amounts of fuel wood are stored in the fallow and savanna ring (3) compensates for nutrient losses of the system at a low mineral depletion rate. Reporting good carbon and chemical status of soils of the compound ring in villages under various climates of Burkina Faso, Prudencio (1993) concludes that the evolution toward more permanent cultivation systems will mine the fertility of fields of the outer ring, but not that of the chemically well endowed soils of the compound ring. From what is presented here, we cannot strictly subscribe to his point of view, since soil quality of plots neighbouring the compounds relies on organic mining flows from the bush and savanna rings. Intensification is likely to reduce the surface of nutrient sources, weaken the biological mechanisms of mineral repletion and questions the maintenance of the means to transfer these nutrients to the staple crop area (Giller *et al.*, 1997).

5.4.3.3. Other C, N and P flows

Only organically mediated C, N and P inputs and outputs are reported here. Actual C inflows to the soil should also take into account root exudation and decay, and litter production in fallows. C transfers through erosion, runoff and leaching should remain limited. Assuming such water-mediated C flows to be 20 and 84 kgC ha⁻¹ y⁻¹ in fallow and cropped fields respectively (Roose and Barthes, accepted), C transfers would amount to 10.6 t ha⁻¹ on the whole surface owned by the village, which is less than 2 % of the flows mediated by plant biomass. Factors affecting N and P balances not taken into account in our study are: atmospheric deposition, nitrogen biological fixation, leaching, gaseous losses and erosion. For cropping fields under uncertain rainfall in Senegal, Stoorvogel and Smaling (1990) estimate the net balance of these factors to be -3.5 kgN and -1.5 kgP ha⁻¹ y⁻¹, and biological N and P accumulation in fallow to +2.0 kgN and +0.87 kgP ha⁻¹ y⁻¹. Applying these figures to the village, final nutrient balance of the system would be -4kgN and -1 kgP ha⁻¹ y⁻¹, which is closer to equilibrium than the findings of these authors (-14 kgN and -9kgP ha⁻¹ y⁻¹).

5.4.4. Future trends in the use of the carbon resource

5.4.4.1. Evolution of the carbon flows

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

5.4.4.2. Methodological considerations: limits of the model

The C flow: C stock ratio as defined in the simulation here could be seen as a first step towards building an accurate carbon-based indicator of the viability of the farming system. Viability is understood here as the aptitude to provide products (food, forage, livestock, wood...) and means of production (livestock, manure, household wastes) in a given range of values, for a given initial state (here 1997), under various scenarios (demographic growth, crop yield, goals defined by peasants). At this step of the modelling approach, we restrict to the concept of viability, which refers to an objective mathematical concept. Main

refinements of the model should include (1) representation of human (means of production, needs) diversity (2) representation of spatial heterogeneity and constraints (3) integration of multiple scales of space and time, (4) autonomisation of actors (holding individual strategies, animal choice for feeding trajectory during the day, vegetation dynamics) as well as their socialisation (for instance, common decisions for land management, vegetation dynamics as influenced by plant biomass intake by human/animal). The adoption of a flexible, object-oriented programming tool and the creation of a multi-agent system for the formalised representation of carbon dynamics at the village scale would be a more accurate tool than the spreadsheet (Manlay *et al.*, 2000a). Only then could modelling be used to assess the evolution of the organic status of the village farming system and thus evaluating its sustainability as understood in the pragmatic meaning of Izac and Swift (1997a).

Chapter 6. GENERAL DISCUSSION & CONCLUSION

6.1. AGROECOLOGICAL BASEMENTS OF THE VIABILITY OF THE PRESENT

MIXED-FARMING SYSTEM OF SARE YOROBANA

From this study, a few features about the way peasants achieve viable production of food, forage and wood with low exogenous inputs can be distinguished.

6.1.1. Carbon & nutrient storage

Fallowing and manuring, the major tools for maintaining the fertility of agroecosystems of Sare Yorobana, are efficient means to store carbon (C), nitrogen (N) and phosphorus (P) above and below ground, and to modify soil properties (mostly chemical) in the 0-20 cm layer only.

Stocks in biomass

Fallowing raises plant biomass from 15 t ha⁻¹ of dry matter (DM) in cropped fields to 80 tDM ha⁻¹ within 15 years of crop abandonment. Manuring clearly stimulates plant productivity (+ 70 kg of DM millet grain per ton of dung DM added to the soil per ha; Chapter 5).

Stocks in soil

Trends in soil storage are less clear. While highest C amounts were found in rice fields as a result of clay texture, fallowing increased values of C and N by only 20%, from 12.2 t.ha⁻¹ in cropped fields of the bush ring to 14.9 t.ha⁻¹ in fallows aged more than 10 years (layer 0-20 cm). Organic status of these cropped fields could be slightly improved by manuring too (+2.6 tC.ha⁻¹), but high increases (+10.6 tC.ha⁻¹) in plots adjoining dwellings could be only spatially restricted to small surface, since large amounts of nutrient-rich organic inputs are needed (Chapters 3 and 5).

At the village territory scale, mean amounts of carbon manageable by farmers (29.7 tC.ha⁻¹, of which half is stored in the soil) remained low as compared to values usually reported under similar or wetter tropical climates (Nye and Greenland, 1960; Tiessen *et al.*, 1998). However, this study suggests that the “static” contribution of carbon stored in the living-plant biomass component to the productivity of the farming system is at least as high as that of non-living carbon stored in the soil clayey-humic matrix.

6.1.2. Flows & cycles

Plot level

The role played by non-living carbon to maintain good soil quality thanks to fallowing and manuring may rely more on the transient forms of carbon than on steady associations with the mineral matrix (Chapters 2 and 3).

Indeed, lower estimates of C inflows (not taking into account root exudation and, for compound plots, root decay) were 3.6-3.8 t ha⁻¹ y⁻¹ in old fallow fields and staple crops of the compound ring. This is a fourth of soil carbon stocks found in the upper 20 cm. Limited soil organic carbon (SOC) increase due to fallowing and manuring, and fast root decomposition evidenced from mesh-bag experiment indicate the existence of major biological sinks of carbon throughout all agroecosystems of the village. Although our work did not include measures of biological activity in soil, several studies carried out on the study site by the Program for the Improvement of Fallowing in West and Central Africa (Floret, 1998), and elsewhere in sub-Saharan Africa (SSA) underline the strong relationship between land use, plant-C cycling and macrofaunal and microfloral activities. The below-ground heterotrophic biota redirects most of C flows for its metabolic and construction needs. Such intake is detrimental to increase of SOC content but yet beneficial to plant biomass production, since macrofauna improves soil physical properties and stimulates microfloral activity (Lavelle *et al.*, 1998; Mando, 1998), while microflora safely stores and cycles nutrients in the rhizosphere.

In coarse-textured local soils, biological organisation compensates for the low capacity of C storage, and limited build-up of CEC and aggregated structures. In this context, rooting systems play a vital role: they stabilise the soil, enhance porosity, and supply C-mediated energy to soil biota. Thus, in these tropical sandy soils, soil fertility assessment must focus on living forms of below-ground C, as well as on intensity and temporal and spatial patterns of C flows.

We acknowledge that the conceptual plant-soil model suggested here is a kind of “extreme” one, since it gathers:

- low intrinsic chemical and physical buffering capacity of the coarse-textured matrix,
- high biological activity initiated by tropical temperature and rainfall patterns and by proximity of large reservoirs of live plant and faunal biomass around the village.

However, the control of plant productivity by patterns of C and nutrient flows is a matter of great concern throughout the tropics (Myers *et al.*, 1994). Things may be slightly different under mesic and frigid conditions, under which fair chemical status, slowdown of biological processes, and buffering capacity of the organo-clayey complex may relieve the dynamic and biological role of carbon in soil. However, all soils, including those developed under temperate conditions, result from the biotic transformation of a

mineral matrix. A soil is thus subjected to universal thermodynamics laws that rule the living systems, among which the establishment of steady C-mediated flows of energy. Thus, even in temperate soils the dynamic role of carbon should be better scrutinised as an environment-friendly biological tool to control some of soil properties at low actual economic cost (see below).

Village level

From a biogeochemical point of view, fallowing and manuring differ in the sense that fallowing is a vertical process of net accumulation of carbon and, to a lesser extent of nitrogen and phosphorus, while manuring is a simple, redistribution of matter. However, the establishment of steady flows of energy, carbon and nutrients sustains the mixed-farming system of Sare Yorobana at broader levels than plot. As shown in Chapter 4 and 5, significant transfers of organic matter are needed from the peripheral areas to enable nutrient balancing of continuous cultivation in the compound ring.

6.1.3. Functional & spatial diversity

The establishment of multi-scale flows hangs on the conservation of diversity, understood here in its functional and spatial (heterogeneity) dimensions (species diversity also plays a great role in sustaining the farming system, but it was not studied here).

. *At the microlocal level*, fallowing tends to generate patches of fertility below trees (alone or in coppice) and termite mounds. Gradients and flows of C, N and P set reciprocal causal relationships. Fallow ecosystems of the region act like any ecosystem submitted to stress (here nutrient and water limitations), thus setting the development of contracted, patchy spatial structures, and the enhancement of biodiversity (Fittkau, 1997; Toussaint and Schneider, 1998; Guillaume *et al.*, 1999). When converting fallow to cropping, man disrupts organic matter flows, eliminates ecological niches and lessens spatial and functional diversity of the plant-soil system. Provided that long breaks of fallows are maintained, semi-permanent cultivation can keep some of the specific and functional complexity of the original savanna ecosystem.

. *At the farm-holding level*, peasants set a gradient of fertility leading to identification of distinct land use systems; the keeping of a continuous cultivation ring owes it to the maintenance of bush and savanna rings. These rings act as sources of energy and nutrients, compensating for the compound field sinks; they are reserves of arable land too.

. *The village community* is itself a mosaic of different types of holdings. Socio-economic diversity among holdings ensures the viability of the system. Small livestock owners feed animals of big owners with stover and weed forage produced on their fields, during common grazing. Meanwhile, they get some of the manure produced during the day by animals, which thus act as biogeochemical accelerators and nutrient vectors.

Conservation of diversity at several levels can be viewed as a strategy implemented by ecosystems and people to reduce climatic and pest hazard, the risk being shared among different plant species (intra- and interspecific diversity) and growth environments (microlocal and fields scales).

6.1.4. Land & animal availability

As evidenced in Part I, a major feature of the systems is the width of area needed to sustain the system, which is also a constraint to its viability. Peripheral land acts as the true main source of nutrients of the system (together with biological fixation of nitrogen in groundnut fields). Sustainable fallow rotation requires low rotation intensity (R, as defined by Ruthenberg 1971), and thus wide areas of uncropped land (Nye and Greenland, 1960; Floret *et al.*, 1993). Land availability is also a prerequisite for the maintenance of extensive livestock activity, which is pivotal for the nutrient balance of the farming system of Sare Yorobana. High livestock availability is another pillar of the proper functioning of the village. With 51 TLU km⁻² (TLU: tropical livestock unit), Sare Yorobana is well beyond the densities usually recorded in West Africa (Figure 6.1). This of course raises the problem of representativeness of our study site, and of opportunities for other villages to reach such herd size (see 6.2.).

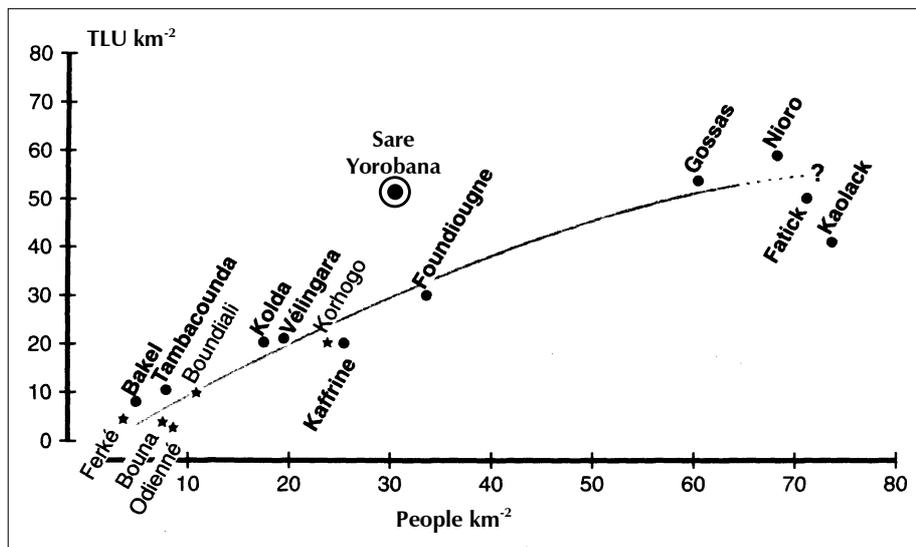


Figure 6.1 Human and livestock densities in Sare Yorobana as compared to other situations in Senegal and northern Ivory Coast (adapted from Landais and Lhoste 1993).

TLU: tropical livestock unit. 1 TLU= 250 kg of live weight.

6.1.5. Efficiency

Energy use

From heat combustion values reported in Table 6.1 and figures of Chapter 4, energy mobilised by human labour (that is, energy contained in cereals consumed on site) was estimated to 0.68 kJ per kJ of grain produced (cereals and groundnut) in 1997 in Sare Yorobana. Since animals provide the farming system with many services, energy contained in their intake (biomass computed in Chapter 5) should be taken into account for actual estimate of energy consumed by the farming system for food production. When doing so, one reaches 12.4 kJ consumed per kJ of grain produced.

Land use

Land use efficiency (as measured by above-ground productivity of all biomass components) in the cereal fields of Sare Yorobana is high and averaged 5.2 t ha⁻¹ (not including weeds; see Chapter 4). In this village, low harvest indexes (grain biomass: total above-ground biomass ratio) of millet (0.13) and of other local cereals such as sorghum have an agroecological function. The high allocation of matter to vegetative components can be viewed as a necessity for smallholders of the WAS, since it compensates for low access to exogenous energy.

6.1.6. Conclusion about the present system

At all spatial and functional scales, there is a perceptible invariance of the role of flows and heterogeneity in sustaining accumulation and redistribution functions needed for maintenance of agroecosystems of Sare Yorobana (plot to village territory). We suggest that the village system itself be viewed as a living metastructure. This biologically centred vision is supported by the preeminence of biological over substitutional maintenance (in the sense of Izac and Swift 1994) for the viability of the farming system. The kind of work presented here brings hints for the definition of local new cropping patterns and viable farming systems for the region.

Table 6.1 Heat combustion data (MJ kgDM⁻¹) of grain and vegetative biomass.

Component	Heat combustion
Grain [†]	
Maize	18.3
Rice	18.1
Sorghum	15.8
Millet	17.7
Groundnut	28.1
Vegetative parts [‡]	18.0

Sources: † Watt and Merrill (1963) and FAO (1997) ‡ Smil (1999)

6.2. FUTURE TRENDS IN THE EVOLUTION OF THE FARMING SYSTEM OF SARE YOROBANA

The system of Sare Yorobana is rather sustainable in term of nutrient budgets, but this feature should be considered only as transient. As suggested by simulations presented in Part II, the viability of the system could indeed be questioned during the next decades, and lead to mining agriculture if increasing human pressure is not followed by a shift towards more intensified practices (van der Pol, 1992).

6.2.1. Technical management options

From the findings of Part I, technical recommendations for the improvement of agricultural practices in the savanna should strive to mimic natural systems in the way they cycle C, N and P. These systems have indeed set reliable strategies to face climate harshness and soil local constraints. Another objective of these innovations should be the *“enhancement of local resources and the search for patterns of management of organic fertility of soils as much autonomously as possible, [which] condition the securisation of farming systems”* (Landais and Lhoste, 1993).

Two types of technical improvements can be distinguished. A first set implies light changes in the system. In fallows, C and N losses due to burning of 17-20 tDM ha⁻¹ of woody branches and leaves could be avoided. Although ashes straight increase soil pH and nutrient availability, the positive effect of woody mulches (branches or leaves, chipped or not) on soil physical properties and crop yields is now well documented in West Africa (Ong, 1996; Wezel and Bocker, 1999; Aman *et al.*, accepted). Hay-making before the offset of rains should also be considered as a transient means to increase supply of forage with high feed value during the dry season, but at only low exploitation rates if no fertilizer is to be brought (Fournier, 1996; Ickowicz *et al.*, 1998). A better crop-livestock integration could be achieved by collecting manure produced during the wet season. It represented 60 % of the dung production measured during the 1996-97 dry season. Since livestock ownership varies widely between farms, and since cattle owners fertilise staple crops at excessive manuring rates, corralling agreements between holdings could improve the productivity of the whole system.

Heavier modifications implying land tenure reform and perennial improvements would be: hedgerow settlement, planted fallow, ley farming (Hoefsloot and VanDerPol, 1993; Bosma *et al.*, 1999), increase of animal herd size, and stalling, which improves animal health and reduces volatilisation of N losses (Murwira *et al.*, 1994), investment in non-renewable resource such as local rock phosphate for soil improvement.

The feasibility of proposals presented here relies to a large extent on non-technical factors such as availability of labour, animal and equipment, which in turn depend on human local conditions and on economic and politic context at a broader scale.

6.2.2. Local human determinants

6.2.2.1. Demographic growth

The sudanian zone of Senegal shows a noticeable, sharp decreasing gradient of population from northwest to southeast (Groundnut Basin *vs.* High Casamance and eastern Senegal), within quite similar climatic conditions. Annual reports of the SODEFITEX, the company in charge of passing on cotton cropping systems (including chemical and organic fertilization intensification) in traditional agricultural systems in Senegal, indicate a better adoption of stalling in the overcrowded Groundnut Basin than in southern and eastern Senegal. Thus, Boserup's theory (1978), according to which every stage of agricultural intensification is reached only when a threshold of demographic density is attained, and which has proved to apply to manuring practices in the WAS (Schleich, 1986), should be relevant for Southern Senegal in the next few decades.

There is little doubt that population of High-Casamance will keep on increasing during the coming years. However, the growth rate for the Region is uncertain, and the 2.5 % y⁻¹ value adopted for simulations in Part II is rather academic. On the one hand, migrations to other less crowded areas of the subregion or to the capital may partly compensate for natural growth of local population (Fanchette, 1999b). On the other hand human pressure could be hastened by the settlement of northern maraboutic villages on plateau rangelands, which seriously threaten extensive pastoralism and may already raise land conflicts between migrant farmers and local herders (Fanchette, 1999a).

6.2.2.2. Social organisation

Cultural reflexes, especially concerning animal ownership, drive intensification patterns of mixed-farming systems too. In West Africa, spatial density of livestock is a rather linear function of human density (Figure 6.1). Farmers' investments in livestock ("*a bank on the hoof*") is a general feature of African smallholder agriculture, and is often detrimental to investment in other means of production such as equipment and soil improvement (Ker, 1995). Livestock density increase will be prejudicial to the whole farming system, if herding practices do not quit extensive pastoralism, which invariably leads to overgrazing (Meertens *et al.*, 1996). But cattle acquisition can also lead to improved securisation of the farm holding, if animals are fed at stall with private forage production (Landais and Lhoste, 1993).

In Sare Yorobana, as in many other villages of the region, big livestock ownership has impeded the village from adopting cotton instead of groundnut. And here, the existence of big cattle owners, who more than others benefit from the practice of common grazing, may also delay the privatisation of land and

resources required by intensification schemes such as ley farming, soil improvement and planting of perennial vegetation.

6.2.2.3. Land tenure

In Senegal, like in most SSA countries, the land is State-owned. Rural councils and village leaders can only grant holdings with a right of usage on fields they have cleared (“*right of the axe*”). Until recently, land use systems, which relied on rather communal land tenure, were compliant with such constraints. However, when land becomes scarce, farmers try to secure their access to land by extensive cropping on which the lineage will be allowed to claim its “*right of the axe*”. So, land tenure hastens biomass depletion. Meanwhile, heavy intensification options such as soil improvement and tree or hedgerow planting require financial funding, and farmers do not benefit from them immediately. Thus, land title securisation is needed to avoid mining extensive cropping strategy and favour investment in perennial means of biomass conservation; unfortunately, farmers have nearly no hold on national land tenure policy.

6.2.3. Sare Yorobana in a global perspective

6.2.3.1. Challenges of African agriculture and society

African agriculture is faced with the need to feed growing population with limited access to substitutional maintenance. Furthermore, it has to compete with industrialised Northern agriculture, which benefits from a better agricultural legacy and access to the manufactured inputs needed for substitutional maintenance (Mazoyer and Roudard, 1997). Thus, management options for viable African farming systems are more and more driven by agricultural policies implemented by governments and by the dynamism of technical advisory structures (Mwangi, 1997; Naseem and Kelly, 1999). Research in ecological economics brings evidence that improvement of soil fertility capital should be shared by the whole society (Izac, 1997b). Investment in agricultural capital (soil, animal, and equipment) is the basement of intensification. Farmers alone will not achieve it. The State must initiate a priming effect by subsidising means of production and re-evaluating trade prices of local food productions. Support to farmer is all the more important in tropical SSA since climatic hazard hampers economic profitability of shifting towards substitutional maintenance of agricultural systems.

6.2.3.2. Comparative efficiency of traditional African farming systems and modern agriculture

About 10 kJ of fossil fuel are needed for the production of one kJ of food consumed by an American (Steinhart and Steinhart, in Hall and Hall 1993). The estimate found for Sare Yorobana (12.4 kJ kJ⁻¹; see 6.1.5.) compares fairly well with Steinhart and Steinhart’s figure. Our simplified calculation suggests that industrialised agriculture might not be more energy-efficient than mixed-farming systems of the West African savannas (WAS), whatever labour-efficient it may be. Energy waste in temperate conventional

agriculture as compared to tropical low-input farming systems has been well established as a general fact by Hall and Hall (1993).

Land use efficiencies in the cereal fields of Sare Yorobana and of industrialised countries are close too. In the European Union, indeed cereal grain yield averaged 5.4 t ha⁻¹ in 1997 (FAO, 2000). Using a harvest index of 0.45 (Smil, 1999) and a water content of 10 %, one arrives at 11 tDM ha⁻¹ of above-ground biomass produced in Europe, which is only slightly more than twice the above-ground biomass yields found previously for millet in Sare Yorobana. In fact, the higher investment in non-edible biomass in Sare Yorobana than in farming systems of northern agribusiness should be seen as a way to compensate for differential access to exogenous energy, on which conventional modern agriculture heavily relies.

The competitiveness of modern agribusiness hangs on the consumption of non-renewable resources such as fertilisers, pesticides and fossil energy, which allow high labour efficiency. It is thus supported not only by grants from western agricultural policy, but to a larger extent by the consumption of these non-renewable resources. The use of non-renewable resources leads to ecological-economic dumping indeed, since (1) natural capital depletion (unlike manufactured capital depreciation) is scarcely taken into consideration for calculation of the actual economic cost of manufactured goods (Costanza *et al.*, 1997; Izac, 1997b), (2) yet, environmental costs of pollution of water and air in industrialised countries are not fully billed to polluters.

6.2.3.3. Global change considerations

The support to African agriculture is unavoidable to get smallholders out of the dead end to which they were thrown by unfair competition with industrialised agriculture (Mazoyer and Roudard, 1997).

Who should pay for supporting low-input agriculture in Africa and elsewhere? Local governments may be all the more reluctant for this, since (1) keeping low food trade prices ensures social peace in towns, (2) structural adjustment programs are hostile to any attempt to protect local agriculture, (3) funds are lacking.

In fact, some of the solution may come from the changing position of scientists and decision-makers on how actual value of agricultural activities should be assessed. This value should encompass not only food production, but all the by-products and services supplied by agriculture to the whole society, such as water and air quality, soil stabilisation, or carbon sequestration and mitigation too; it should also integrate the actual cost of depletion of natural capitals such as nutrients and fossil fuel, and its consequences on environment quality (Cole *et al.*, 1996; Izac, 1997b). This shift should be beneficial to African traditional low-input farming systems, which are more environmental-friendly than conventional agriculture in Europe and North America. Funding of agricultural intensification in Africa might soon be enabled by the trade of pollution permits aimed at controlling global release of carbon in the atmosphere. The sale of these permits by African countries could raise funds for those of their farmers who sequester carbon in soil and plant biomass thanks to enhanced agricultural practices and perennial investments. But peasants

should also be rewarded for fossil carbon they mitigate, since their energy need is supplied by renewable biomass.

6.3. LIMITS OF THE STUDY & RESEARCH AGENDA

6.3.1. Some overlooked factors driving the viability of the system

The global approach adopted in this project implied gross simplifications concerning some of the factors controlling the dynamics of the village agroecosystem. The main points still needing further investigation are:

- role of interannual climatic variability, mostly distribution of rainfall throughout the rainy season. Climatic data (Figure 4.1; Appendix 28) suggest that 1997 was agroclimatically representative of the last few years. However, even in Sudanian regions well endowed with rainfall, farmers' strategy may be influenced by interannual variations of yields due to climatic hazard,
- functions of animal husbandry. We considered livestock activity mostly as a means to improve the fertility of soils. This reductionist commitment certainly left some of the main determinants of the farming system dynamics misunderstood (Landais and Lhoste, 1984). In southern Senegal, the reluctance of some of pastoral villages to adopt cotton rather than groundnut as a cash crop, and the priming effect of potential income from dairy products on the adoption of livestock stalling bear evidence of the priority given frequently by pastoral farmers to animal husbandry over cropping strategies,
- social determinants. Among these, balance of power between holdings, timetable constraints and technical know-how, were only partially assessed, although inter-holding diversity has shown to be a structuring element of the village agroecosystem.

6.3.2. New needs for agroecological research

Our study has raised many questions about the ecological determinants of plant biomass production and organo-mineral status of local soils. A few hints have been given for methodological precautions to be observed when using below-ground carbon as an indicator for soil quality. Clearly, comparative seasonal variations of carbon stocks and fluxes (through on-site CO₂ release measurement and faunal and microbial inventories) in cropped and uncropped ecosystems must be further investigated. Organic status assessment should be judged with regard to the nature of carbon inputs (quantity, quality, temporal and spatial patterns of distribution) at the plot scale. Any comparative study with other sites should also take

into account the biological status of the small region as expressed by the share of uncropped area, which certainly influences the overall intensity of microlocal biological activity, and thus SOC turnover rate.

Identifying the determinants of stump dynamics as related to rotation intensity is definitely of utmost importance, since stumps clearly control many chemical properties of local sandy soils and drive tree regrowth. However, this kind of study raises considerable methodological -mainly sampling- difficulties. The study of post-fallow decomposition of woody roots is easier. Data presented here (Chapter 1) should soon be completed by on-going data analyses from experiments carried out on the study site and in the drier region of Sine Saloum (Central Senegal). These experiments should yield further information about the role of climate, soil fauna, and tree species on decomposition patterns following clearing of vegetation.

In a global change perspective, our study gives only a gross estimate of carbon sequestration potentials of local agroecosystems, even at the plot scale. Indeed, the work of Denich *et al.* (2000) dealing with shifting cultivation systems of eastern Amazonia brings evidence that seasonal variations of carbon storage in the soil-plant system have to be taken into account to assess the actual efficiency of agricultural management options to sequester carbon.

6.3.3. Exploratory research

Assessing today's organic status of a village agroecosystem generates valuable conceptual and operational information. Since the human and economic context is likely to change quickly in southern Senegal during the coming years, the prediction of possible trajectories followed by the village system under various scenarios is an interesting challenge and a logical outcome of the work presented here. Any formal representation of the village system is a complex object, which has to take into account the multiplicity of actors (people, animals, plant, and soil to a certain extent), their interrelations and hierarchical structure at several temporal scales and space and functional levels. Computer modelling is unavoidable to manage such an object. The modelling attempt carried out in Part II of this work yielded predictions that were worth to be used to compare effects of different scenarios on the village organic status. However, simplistic assumptions commanded by the choice of the spreadsheet tool impart too much uncertainty to output data for accurate absolute interpretation.

An on-going work with C. Cambier (ISRA/IRD Dakar) should soon significantly improve predictions about the organic status of Sare Yorobana (Manlay *et al.*, 2000a). A multi-agent system model based on object-oriented programming is being built. Agents (autonomous entities such as farm holdings and animals) interact with each other (ruling or cooperation) and with "situated objects" (plot, vegetation) to satisfy their food, wood, forage and cash needs. Spatial constraints on cropping schemes, yields and livestock search for forage are taken into account. The organic status of each plot (plant biomass, SOC stock) is defined by past and present land-use, fertility management, and withdrawing rates of biomass by people and animals. Land tenure securisation strategies are also taken into account.

Such a tool could be of great methodological and conceptual utility, although its use for decision-making will require much carefulness.

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ABBREVIATIONS

ABB	available biomass for burning	FU	feed unit
ABT	Alimentation du Bétail Tropical (Program for the “Improvement of Feeding Systems of Tropical Livestock”, ISRA/CIRAD-EMVT)	GHG	green house gas
Adu	adult	GLM	general linear model
AGB	above-ground biomass	GN	groundnut
BGB	below-ground biomass	INRA	Institut National de la Recherche Agronomique (French Institute for Agronomic Research)
CEC	cationic exchange capacity	IRD	Institut de Recherche pour le Développement (French Institute for Research and Development, formerly ORSTOM)
CI	cropping intensity	ISRA	Institut Sénégalais de la Recherche Agricole (Senegalese Institute for Agricultural Research)
CIRAD	Centre de Coopération Internationale en Recherche Agronomique pour le Développement (French International Centre for Agricultural Research in Hot Regions)	LS	least square
CNRS	Centre National de la Recherche Scientifique (French National Centre for Scientific Research)	LUS	land use system
Com	compound	LW	live weight
Cor	corralled	MA	maize
DM	dry matter	MI	millet
DMI	dry matter intake	MW	metabolic weight
EMVT	Département Elevage et Médecine Vétérinaire (Department of Animal Production and Veterinary Medicine)	NF	non-fractionated
ENGREF	Ecole Nationale du Génie Rural des Eaux et des Forêts (French Institute of Forestry, Agricultural and Environmental Engineering)	OF	old fallow
Equ	equipment	OM	organic matter
FA	fallow	OMI	organic matter intake
FOME	faecal organic matter excretion	OS	owned surface
		PC	principal component
		PCA	principal component analysis
		PET	potential evapotranspiration
		Pm	permanent
		POD	available phosphorus (Olsen method modified by Dabin, 1967)

P _t	total phosphorus	SOM	soil organic matter
RI	rice	SSA	sub-Saharan Africa
RI	rice	TLU	tropical livestock unit
R _s	correlation coefficient of Spearman	UWS	upper woody strata
SAS	statistical Analyses System	Wa	household waste
Sea	seasonal	WAS	West African savanna
SOC	soil organic content	WU	working unit
SODEFITEX	Société des Fibres Textiles	YF	young fallow

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Organic matter
dynamics
in mixed-farming
systems
of the West African
savanna:
a village case study
from south Senegal
RAPHAËL MANLAY

Organic matter (OM) is a multi-purpose tool in West African smallholder mixed-farming systems, but its supply has been decreasing for several decades. To assess the viability of a mixed-farming system of south Senegal, carbon (C), nitrogen (N) and phosphorus (P; available in soil and noted P_{OD}) budgets (stocks and flows) were thus quantified.

The village territory of the study showed a ring-like organisation with growing intensification of fertilization and cropping practices from the periphery (bush ring) to the compounds (compound fields).

Stocks in plant and soil averaged 55 tC, 26 tN and 43 kgP ha⁻¹ in old fallows. They were 100, 30 and 250 % higher than in the bush cropped fields, plant biomass accounting for nearly all of the rise. C, N and P amounts recorded in the soil of compound fields were higher than those of the bush field, but the increase was restricted mainly to the 0-10 cm layer. However, the rather weak response of local sandy soils to management can be interpreted only by reassessing the bio-thermodynamical signification of soil organic carbon cycling in the maintenance of the integrity of local agroecosystems.

Manageable stocks of the whole village territory were estimated to 30 tC, 1.5 tN and 26 kgP ha⁻¹ in 1997. Carbon was stored mainly in soil. Livestock, crop harvest and wood collecting were responsible for respectively 59, 27 and 14 % of the C uptake on the village territory. As a result, large C flows were set towards the compound ring (3.8 tC ha⁻¹ y⁻¹). N and P depletion of the system amounted to 4 kgN and 1 kgP ha⁻¹ y⁻¹, suggesting that the system was close to nutrient balance.

Under current demographic growth rate, C depletion may reach 0.38 tC ha⁻¹ y⁻¹ and C demand may double during the next three decades. Without any intensification of farming practices, the viability of the system might soon be called into question.

DOCTORAL THESIS

ENVIRONMENT