

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.

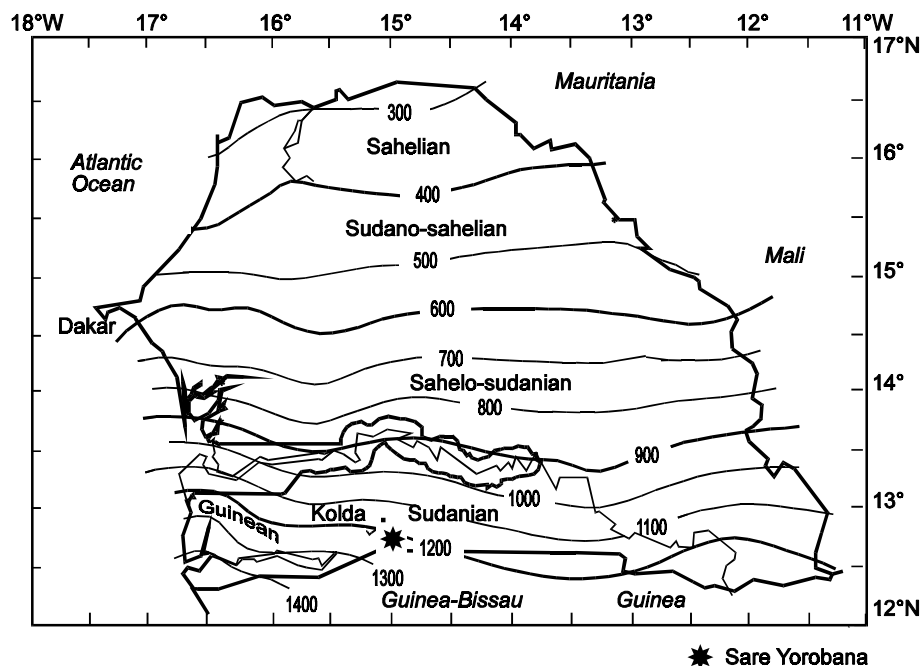


Figure 0.1 Location of the study site of Sare Yorobana (12°49'N 14°53'W) in Senegal, West Africa, and isohyets for the 1951-1980 period (Laboratoire d'Hydrologie, IRD-Dakar).