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 exsudation 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.).

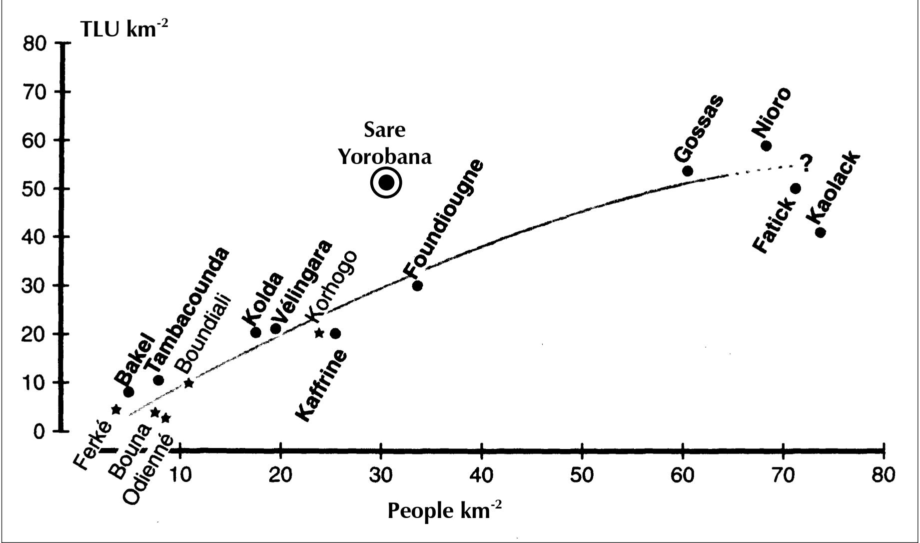

Figure 6.1 Human and livestock densities in Sare Yorobana as compared to other situations in Senegal and northern Ivory Coast (adapted from Landais and Lhoste 1993).
TLU: tropical livestock unit. 1 TLU= 250 kg of live weight.

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.

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)

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.

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 autonomous 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 crowed 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 CO_2 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.