

CaTMAS: A multi-agent model for simulating the dynamics of carbon resources of West African villages

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ARTICLE INFO

Article history:

Received 16 February 2011

Received in revised form 26 July 2011

Accepted 28 August 2011

Keywords:

Generic model
Modeling and simulation
Organic matter
Farming system
Global change
West African savanna
Century

ABSTRACT

Carbon is an important determinant of the sustainability of West African farming systems and of the atmospheric greenhouse effect. Given the complexity of C dynamics, various simulation models have been developed. Few include socioeconomic factors or handle system heterogeneity. This study proposes a generic, multi-agent model for the analysis of C dynamics at village level. It assumes that a better analysis of carbon dynamics at village level requires account to be taken of social, economic, physical and biological factors as well as of the actions of individuals and their interdependence. The Carbon of Territory Multi-Agent Simulator (CaTMAS) model is based on the Organization-Role-Entity-Aspect (OREA) meta-model and the Multi-Agent Systems (MAS) approach. OREA enables C dynamics to be studied from various points of view through the roles played by entities within organizations and also allows various entities to play the same role in various ways through the notion of aspects. The model was coupled with the Century model and a geographical information system to provide a realistic representation of C dynamics. CaTMAS provides not only a framework for the explicit description of the carbon dynamics of farming systems but can also be used to assess the viability of farming systems using various socioeconomic and biophysical scenarios. The model includes interactions between human activities and the environment. Simple simulations involving two cropping systems and focusing on the impact of population growth and different climate regimes on the C dynamics indicate that CaTMAS accounts realistically for the relationships between population, agriculture, climate and SOC dynamics. In simulation, population growth, which drives food demand, leads to agricultural expansion, land scarcity and decrease in fallow duration. These effects are accentuated by increasing temperature and decreasing rainfall which affect the SOC dynamics controlling soil fertility and thus crop production. Improvements to the model should make it possible to extend the scale of the simulation of C dynamics and include refinements such as the inclusion of the trading of carbon credits.

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1. Introduction

The carbon (C) cycle plays an important role in ecosystem functioning and climate regulation. In the continental biosphere, a third of the C stock is stored in vegetation and the remainder is stored in the soil and in litter (IPCC, 2007). Vegetation and soil contain active carbon pools, whose dynamics are complex and result from natural and human-driven processes.

The farming systems of smallholders in sub-Saharan Africa rely particularly heavily on the management of C resources, as endogenous organic matter (OM) is a vital economic good, essential for

production (Dixon et al., 2001; Kowal and Kassam, 1978). Sixty percent of sub-Saharan Africans depend directly on locally grown food harvested from their environment (Dixon et al., 2001). The improvement of food production and other ecosystem services in the short and medium term requires better management of OM resources, nutrients and soil organic carbon (SOC) (Bationo et al., 2007).

Shifts in agriculture, forestry and land use have a global effect on the concentration of greenhouse gases (GHG) in the atmosphere, which is one of the factors that controls global climate. Changes in land use in the tropics (mostly deforestation) account for 12% of the anthropogenic release of C into the atmosphere (Friedlingstein et al., 2010). The environmental effects of change in land use (e.g. on climate or soil quality) are not necessarily immediate. They may occur over a much longer period than the effects of agricultural processes.

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Local agro-ecological and global environmental issues, therefore, call for in-depth analysis and prediction of C dynamics in West African savannas.

The village (understood here as the “share of land that is appropriated, managed and used by the group that lives on it and from it” according to Sautter and Pélissier, 1964) is an operational spatio-functional level for this as many decisions on land use and OM management are driven by communal rules (Manlay et al., 2004b). Carbon dynamics at village scale are complex and specific tools are required to deal efficiently with this complexity. Appendix A illustrates this complexity by describing the C dynamics of village territory in West Africa at multiple scales. Many computer models have been developed to simulate and predict carbon dynamics. These models are mathematical, process-based (Balesdent et al., 2000; Coleman and Jenkinson, 1996; Parton et al., 1994) or agent-based (Belem et al., 2006; Schreinemachers et al., 2007). Few include socioeconomic factors or handle system heterogeneity. These models do not provide an explicit spatial and temporal representation of carbon dynamics at a large scale such as community level. This study proposes a generic model – CaTMAS – that allows for multiple points of view and multi-level analysis and deals with system heterogeneity as well as including social, economic, physical and biological factors. CaTMAS is an integrated model, which focuses on C resources to analyze the interactions between human activities and the environment on the basis of the Malthusian (Malthus, 1817) approach since the decline of C resources is assumed to have no effect on the families’ strategies. CaTMAS is a generic model as it is intended to describe not just a specific site but a range of situations in the West African savanna. In other words, the model is independent of the characteristics of the villages simulated. The descriptions of the family typologies, cropping systems, crops and the environment (spatial and biophysical properties) are independent of the model structure.

The CaTMAS (Carbon of Territory Multi-Agent Simulator) model is based on a multi-agent system (MAS) (Ferber, 1999). The model analysis, design and implementation were carried out using the OREA framework (Belem and Müller, 2009) which provides a meta-model and methodology for the multi-scale and multi-point of view description of complex systems.

The model was coupled to the Century model, a process-based model (Parton et al., 1994) which can simulate C dynamics at plot level as result of interactions between biophysical processes, climate, cropping systems and animals (grazing, transfer of faeces and urine). A Geographical Information System (GIS) was coupled with the model, providing an explicit representation of the soil map, land use and spatial distribution of carbon, nitrogen and phosphorus. CaTMAS was implemented using Mimosa, an event-based platform that can take account of multiple simulation timescales.

This paper presents the materials and methods, describes the structure and architecture of CaTMAS and gives some outputs of CaTMAS simulations. It discusses the results and outlines promising lines of research for future development.

2. Materials and methods

2.1. Method

Using a MAS as a basis for CaTMAS makes it possible to take account of the heterogeneity within and among farming systems, the self-adaptive behavior of the farmers and the effect of social changes on C dynamics. Since it can support an explicit representation of the environment, a MAS is an effective means of studying the spatial variations of C dynamics (including the distribution of C pools, pastoral dynamics and land use) and the interactions between human activities and the environment. Many studies have

shown the potential of MASs for the simulation of ecosystem management (Bousquet and Le Page, 2004; Matthews et al., 2007).

The OREA framework (Belem and Müller, 2009) made it possible to define a very detailed, modular, abstract and generic conceptual model which provides a multiple point-of-view description of carbon dynamics at plot, farm, village, family and herd levels. It takes account of land tenure, plant and animal production, flows and transformation of carbon resources. Based on this conceptual model, the simulation model was implemented using Mimosa (numerical method for agent-based modeling and simulation), a multi-formalism platform that provides a framework for (1) conceptual modeling and simulation and (2) integration of various models using different formalisms (Müller, 2004). Mimosa is based on a Discrete Event System Specification (DEVS) formalism (Zeigler et al., 1995) which can take account of multiple simulation timescales. Using Mimosa makes it possible to simulate simultaneously several entities evolving at different time scales.

The resulting simulation model has four modules. The first module is the multi-agent system model. It includes population dynamics, crop production, changes in land use and animal husbandry. The second module is used to couple the MAS module with the Century model. This provides a realistic representation of C dynamics at plot level and the relationship between climate (temperature and rainfall), plant growth, livestock and SOC. The coupling with the Century model is based on client/server simulation making it possible to distribute the simulation of soil dynamics over several computers. The third module, the spatial module, is based on coupling with QGIS (QGIS Development Team, 2009) using PostGis (The PostgreGIS Global Development Group, 2009). The fourth module, the data module, manages the inputs and outputs for the simulation and data exchange between the MAS, Century and the GIS through PostgreSQL (The PostgreSQL Global Development Group, 2008) and PostGis.

2.2. Data collection

The model was tested using three climate scenarios for a virtual village. The model was calibrated with a dataset derived from the literature (Table 1) and from Century libraries. The input data includes demography, cropping systems, farm economy, biophysical properties (e.g. soil types and climate data), animal characteristics (e.g. herd structure and pastoral data) and spatial data for the GIS.

2.2.1. Cropping systems and crops

Cropping system data was based on Touroukoro village in south west, sub-humid Burkina Faso (Youl, 2009). The two cropping systems represented were a semi-continuous system (SCS) and a continuous system (CS). The SCS was based on a 5-year yam-maize-sorghum-sorghum-sorghum crop succession rotated

Table 1
The sources of data used in CaTMAS.

Types of data	Sources from literature
Cropping systems and crops	Youl (2009) Matlon and Fafchamps (1988)
Demographic data	UNDP (1999) UNPP (2006, 2007) FAO (2001)
Crop and soil data	Manlay et al. (2002, 2004a,b) Youl (2009)
Animal	Landais and Guérin (1992) Landais and Lhoste (1993) Botoni (2003) Schlecht et al. (2006, 2007)

Table 2

Some major parameters used for four crops in the CaTMAS simulations.

Crop	Labor (day year ⁻¹ ha ⁻¹)	Energy content (kcal 100 g ⁻¹)	Purchase price (€ t ⁻¹)	Selling price (€ t ⁻¹)
Maize	102	327	110	110
Sorghum	65	371	133	133
Yam	265	112	154	154
Cotton	139			236

Sources: Matlon and Fafchamps (1988), Youl (2009).

Table 3

Initial parameterization of families for the CaTMAS simulations.

Type of farm	Number of farms	Family members per farm (ind. farm ⁻¹)	Farm area (ha farm ⁻¹)	Livestock (TLU farm ⁻¹)	External manpower (ind. farm ⁻¹)	Cropping system
SCS farm	10	17	31	26	5	Semi-continuous
CS farm	10	17	15	38	5	Continuous

Source: Youl (2009)

TLU: tropical livestock unit.

with fallow and fertilized organically. The CS was based on a 5-year maize-cotton-maize-sorghum-sorghum succession with possible fallow. Several literature sources were used to define crop properties (Table 2) such as the energy value, labor (Matlon and Fafchamps, 1988), purchase price and selling price (Youl, 2009).

2.2.2. Demography

The village comprised two types of family, corresponding to the two types of farming system in Touroukoro (Table 3): (1) native, relying on the SCS cropping system (SCS family) and (2) migrant using the CS cropping system (CS family). Some of the properties for the families had to be estimated from sources other than field surveys for the simulations. For instance, some demographic data (such as family population structure, natality and mortality) was based on the national average for Burkina Faso (UNPP, 2006, 2007), while data from the Food and Agricultural Organization (FAO) (FAO, 2001) was used to define the human energy requirement for the age classes which defined the structure of the family types (Belem, 2009). The crop use (consumption or sale) depended on the cropping system used by a family (Table 4).

The initial population comprised 20 families: 10 SCS families and 10 CS families. The simulations described in this article did not include immigration and emigration.

2.2.3. Soil and crop data

Some biological and physical (soil texture, SOM, land cover, etc.) properties were based on various studies carried out in West Africa (Lufafa et al., 2008; Manlay et al., 2002, 2004a, 2004b; Youl, 2009). In these simulations, all the plots were assumed to have the same initial intrinsic properties (land cover, soil type). Although

Table 4

Contribution of crops to meeting the family's cash and consumption requirements for SCS and CS type farms.

Farm	Crop	Cash (%)	Consumption (%)
SCS farm	Maize	10	60
	Sorghum	10	20
	Yam	80	20
	Total	100	100
	CS farm	Maize	20
	Cotton	70	0
	Sorghum	10	20
	Total	100	100

Source: Youl (2009).

unrealistic, this simplified the comparison of the effects of different organic matter management strategies and different cropping systems. The vegetation comprised both tree and herbaceous layers with the biomass density of each layer depending on the balance between uptake and regrowth. The biological and physical data (land cover, the soil texture, SOM and soil mineral content, water content) were defined using the Century samples and default data.

2.2.4. Animal data

The animal data described the structure (age and sex distribution) of the herds' population and pastoral activities (moving, grazing and excretion). Only cattle were simulated. The herd structure used for the simulations was adapted from Breman and Ridder (1991). Data for pastoral activities (intake, excretion, grazing distance and duration) were based on various sources (Botoni, 2003; Landais and Guérin, 1992; Landais and Lhoste, 1993; Schlecht et al., 2006, 2007).

2.2.5. Climate

Rainfall and temperature regimes were assumed to be those of Bobo-Dioulasso (Burkina Faso) for 2006, provided by the Burkina Faso Department of Meteorology (Table 5).

2.2.6. The GIS data

The GIS data for Touroukoro was used for the spatial representation of the C dynamics. Only 530 plots (530 ha) were simulated. Two GIS layers were defined: the land use layer and the C layer.

Table 5Climate parameters used for the C₀ simulation (Bobo-Dioulasso, year 2006).

Month	Rainfall (mm)	Temperature (°C)	
		Min	Max
1	0	19.8	34.2
2	0	22.4	36.2
3	0	24.8	38.4
4	24	25.7	37.5
5	140	23.7	34.9
6	154	23.7	34.9
7	116	22.0	34.4
8	250	21.5	30.5
9	276	20.9	30.7
10	145	20.9	30.7
11	0	20.9	34.1
12	0	18.5	32.5

3. Description of CaTMAS model

3.1. Main assumptions

The following main assumptions were made in order to simplify the modeling of carbon dynamics at village scale:

1. Individual human decisions are aggregated at family level, which means that “individual” refers to a family, which is considered as a unified human community behaving as a single “organism”. A family belongs to a type of family.
2. The type of family is characterized by the cropping system, farm size, number of persons, family structure (sex and age distribution), resources (material, financial and external manpower) and use of crops (own consumption and cash).
3. The family structure is dynamic, as it evolves with the birth and death of family members.
4. The labor power depends on the external manpower, the sex ratio and ages of family members. The manpower is defined as the contribution of an individual to the labor power. The use of external manpower influences the family's financial requirements: a family produces goods both to satisfy its own financial requirements and pay external manpower.
5. The use of equipment is represented by the level of equipment which reduces the labor power required for agricultural production. It evolves depending on the investment capacity of the family and wear.
6. A family uses only one cropping system. It cannot change it even if it is unsuitable for the environmental context. A cropping system defines the crop sequence and the crop management sequence associated with each crop. The crop management sequence associated with a crop is defined in the model as a crop-specific farming calendar. It specifies the operations (sowing, fertilization, weeding) to be carried each month.
7. Emigration covers permanent migration only. Seasonal migration is not considered.
8. Animal behavior is represented at herd level. A herd is a group of one species of animal belonging to one family. A herd is considered as a unified animal group behaving as a single “organism”.
9. The composition of a herd is defined by age class distribution. An age class defines the animals of the same age and sex ratio. Animals in same age class have the same mass.
10. The daily grazing and walking speeds of animals depend on the season.

These assumptions were used to define a conceptual model using the OREA framework. This paper presents a simplified description of the conceptual model (see Belem, 2009; Belem and Müller, 2009, for more details on the conceptual model).

3.2. Entities

The structure of the model has two main entities: *Family* and *Herd*. A *Family* entity belongs to one type of family as described above. The allocation of initial resources (including farm, grain stock, cash, livestock and equipment), cropping system and family composition, etc., depend on the type of family and its characteristics can change over the simulation time. The main activity of a *Family* is crop production although it may also raise livestock depending on its type.

Herd entity is the second type of entity in the model. Initially, the sex and age ratios are the same for all herds, but the initial size differs. A *Herd* is characterized by the monthly quantity of biomass consumed, the composition of the herd (individuals), the monthly quantity of faeces produced and the grazing duration and distance.

The model structure includes other entity types manipulated by *Family* and *Herd* entities: *Plant* (tree, crop or grass), *Plot* and *Climate*. A *Plot* represents an elementary spatial unity. It is characterized by its occupancy (field, houses, forest, etc.), the type of soil and type of vegetation (tree, crop, grass, mixed tree/grass or tree/crop), its area and bio-physical structure (see Century description for more details). *Climate* defines the monthly temperature and rainfall.

3.3. Organization of the environment

The environment is represented by cellular automata (Vanbergue et al., 2000). The environment is not designed for a specific site. Each cell represents a plot. To configure the environment, the user must specify the spatial data for each plot (position, area, land cover, type of soil). Cells are aggregated to form farms that spatially delimit the production activities of the families. The area of a farm varies as it depends on the definition in the type of family. Farms are defined according to the number of families. The environment is represented by the GIS using PostGIS (The PostgreGIS Global Development Group, 2009). The coupling of CaTMAS to the GIS allows dynamic observation of land use and spatial distribution of carbon, nitrogen and phosphorus stocks.

3.4. Time management

Based on the flexibility of Mimoso to manage entities that evolve at different timescales, CaTMAS can handle daily or monthly increments depending on the objectives of the simulation, the size of the simulated site (number of plots) and the available computer resources. A simulation with a daily increment requires considerable computer time. Entities in the model do not all evolve with the same increment of time: *Herd* entities can evolve on daily or monthly bases, *Family* entities follow a monthly pattern only.

3.5. Model dynamics

The model dynamics are mainly based on the dynamics of *Family* and *Herd* entities, plant growth and soil carbon dynamics.

3.5.1. Family entity dynamics

The Family entity dynamics include crop production (crops and land management), economic behavior (buying and purchasing of food, animals and equipment) and social behavior (ageing, natality, mortality, immigration and emigration).

3.5.1.1. Natality and ageing. The *Family* is structured as a collection of groups according to age classes. The age of the each class is incremented yearly. Natality is a function of the sex ratio and varies between age classes and is partly stochastic. Natality decreases when food production does not meet the food requirements of the population, otherwise it increases.

3.5.1.2. Mortality. The mortality of the human population of a farm is a function of the mortality rate of each age class. Each year, a random value determines the mortality within a class. The mortality rate evolves according to the population size and the food production. The mortality rate increases if production does not meet the food requirements of the population, otherwise it decreases.

3.5.1.3. Emigration and immigration. The population growth is not strictly endogenous. The model includes emigration and immigration. Emigration is a function of the emigration rate of each age class. Each period (year), depending on the structure of the *Family*, a random function determines the departure of an individual in an age class. The emigration rate evolves in the same way as the mortality rate, inversely with food production.

Immigration depends on the family type. For each family type, a variable defines the probability of the arrival of a family. Immigration also depends on the village food production. Immigration stops when production is insufficient to meet the population's food requirements and restarts when there is adequate food.

3.5.1.4. Land management. Land management concerns the land use for crop production and fallow management. The land use evolves depending on the crop sequence and the families' needs. Every year and at the beginning of the cropping season, the *Family* determines, for each plot, the next use depending on the previous use and the crop sequence. That allows to define the available plots for each crop. If there are insufficient plots available for a crop in the crop sequence, the *Family* clears new land or plots in fallow from its farm.

If a plot is at the end the crop sequence, the *Family* puts it in fallow. The plots in fallow are used for crop production if there are not enough plots to meet the production targets. The fallow period evolves depending on the farmers' needs. If more land is required, the fallow period decreases.

3.5.1.5. Soil management. The carbon dynamics depend on how the *Family* manages the soils. In the model, soil management depends on the cropping system. For each plot, depending on the crop and the farming calendar for that crop, the *Family* schedules the labor and determines the amount of organic matter and mineral fertilizers to be added. Cropping affects the soil physical properties, the carbon and mineral budget and the crop production.

3.5.1.6. Crop production. The purpose of the *Family* is to satisfy its food and cash needs which depend on its size and the external manpower. At the beginning of the rainy season, it sets up a production plan defining, for each crop, the area to be cultivated depending on (1) the *Family's* needs, (2) the crop use in the needs and previous yields and (3) the resources (labor, land and fertilizer) (Fig. 1).

The *Family* then (1) determines the availability of plots as described below and (2) manages cultivation and production by following the crop-specific calendar until harvest.

Meeting food and financial needs depends on grain production. Grain production is calculated by Century and depends on cropping intensification and climate. The *Family* defines the sales plan based on the production and needs. The sales plan defines, for each crop, the quantity to be sold depending on production, the selling price and its own consumption of the crop. When cash and food needs have been satisfied, the *Family* can invest in animals or equipment (to improve or renew its equipment).

3.5.1.7. Food consumption. The food consumption is monthly based. Each month, the *Family* determines its food requirement depending on its food energy requirement. The energy requirement is a function of the *Family* structure as it depends on the age classes of the individuals. The crops are consumed depending on their share in the *Family's* "basket". If there is insufficient food, the *Family* buys it. However, if the *Family* has no money, it must sell animals to buy food.

3.5.2. Herd entity dynamics

Ingestion and excretion are seasonal. At each step of the simulation (daily or monthly), the animals graze the village land, moving from the current position to the most attractive plot. The attractiveness of a plot depends on its biomass availability. In the model, animals consume crop residues in the field only out of the production season. Ingestion stops when their food requirement is met or when the maximum duration of grazing is reached.

On each plot, forage intake and excretion of faeces and urine are calculated according to the season, the available biomass, plot area,

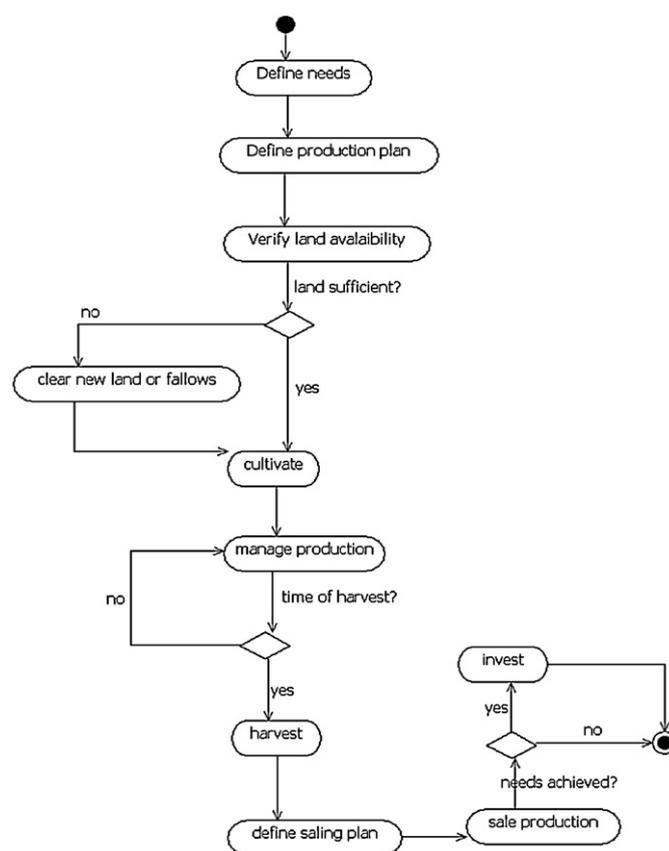


Fig. 1. UML description of the decision process for crop production.

duration of stay, hourly intake and excretion (faeces and urine). The plot area depends on the spatial configuration of the environment.

The animal natality and mortality processes are represented in the same way as for the *Family* entity. They change with biomass availability.

3.5.3. Plant growth, grain production and soil dynamics

The plant growth and the impact of grazing and climate on plant production and soils are simulated using Century which simulates plant growth and soil carbon dynamics, taking into account the effects of the climate (rainfall and temperature), the cropping system (crop sequence and cropping intensity) and animal grazing and excretion.

Depending on the cropping intensification (cultivation, harvesting, fertilization, clearance and fire) and the animal activity (including biomass uptake and faecal excretion) for the plots and climate from the CaTMAS model, Century simulates, for each plot, the plant growth, the carbon dynamics and change in the physical properties of the soil. In CaTMAS, the intensification is defined by the cropping system.

3.6. Parameters and outputs

CaTMAS has a large number of parameters and outputs for describing and studying a range of village territories from socio-economic and biophysical points of view. The model can be parameterized to fit a specific site. The parameters describe the family typology, the animals, the climate, the biophysical properties of the soil (soil texture, SOM, land cover, etc.) and the spatial representation of the village territory (cf. Section 2.2).

The outputs cover households, livestock, land use and evolution of carbon, nitrogen and phosphorus. The outputs of the model

can be used to study (1) the effects of cropping systems on carbon dynamics and their sustainability given variations in climate and (2) the relationship between demography, agricultural production and livestock.

The model provides yearly outputs relating to the carbon, nitrogen and phosphorus budgets of each plot, yearly outputs relating to household size, cash and food production and monthly outputs relating to the herd size (number of animals), mass, pasture distance, ingestion and excretion. The model also provides spatial output for using a GIS to study changes in land use and the spatial distribution of carbon, nitrogen and phosphorus.

4. CaTMAS simulations

This section describes simulations of the effects of the settlement and development of a human community on the C cycle of a virgin territory of the sub-humid West African savanna belt using three climate scenarios. Two typical farming systems found in the region – traditional extensive and recent intensive – were considered. Assuming the existence of virgin vegetation in West Africa is highly theoretical but simplistic scenarios are needed to assess the robustness of the model and bring the system to a complex, heterogeneous state that may be used as the starting point for further simulations on anthropized territories.

4.1. Climate scenarios

Three climate scenarios were defined and tested with the following mean monthly temperature and annual rainfall curves:

- C_0 represents the current precipitation and temperature regimes (“business as usual”).
- C_+ is a possible future climate scenario derived from Giannini et al. (2008) with a 1.5 °C increase in mean monthly temperature and a 25 mm decline in annual precipitation.
- C_{++} , derived in the same way as C_+ , with a 3 °C increase in mean monthly temperature and a 50 mm decline in annual precipitation.

4.2. Initialization and configuration of the simulations

The model initialization starts with the space initialization. The model creates cellular automata by reading the data from the GIS database. Each cell represents a plot. The properties of the plots (occupancy, vegetation, size, connectivity, etc.) are initialized from their description in the GIS database. In these simulations, the space comprised 530 plots with uniform area (1 ha) and virgin vegetation (forest) and soil.

Next, the families are created and initialized. A farm is created and allocated to each family. A plot is selected randomly in the farm as a compound, that will not be eligible for cropping. If the size of the herd for the family type is more than 0, a herd is created and allocated to the family. In this case, a plot is randomly selected for the pen for the animals. In these simulations, each family has a herd so that the simulations have a population of 40 agents: 20 families and 20 herds.

4.3. Results

4.3.1. Human population dynamics

Population growth was slowest in C_{++} and highest in C_0 , with C_+ close to C_0 (Fig. 2). Climate change affected the overall cash production. Cash income per capita did not differ significantly between the scenarios with C_{++} producing slightly lower cash than the other scenarios (Fig. 3) probably as a result of lower crop production (in

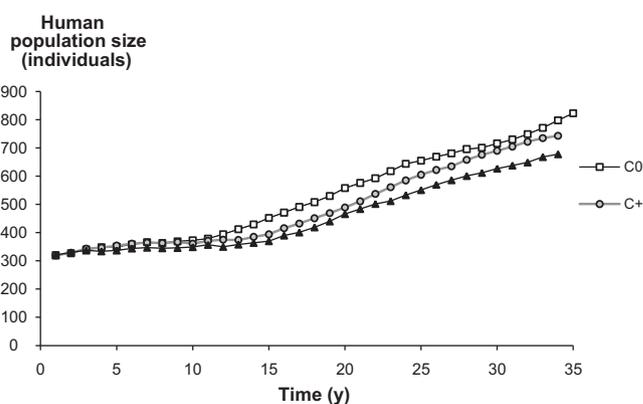


Fig. 2. Simulation of the size of the human population of the village for the three climate scenarios, C_0 , C_+ and C_{++} .

this model, the families' cash production depends strongly on crop production).

4.3.2. Land use dynamics

Throughout the simulation there was a significant change in land use, with an increase in cultivated area and decrease in forest (Fig. 4). In C_0 , the area under fallow increased for 8 years and then decreased. Similar trends were observed for the C_+ and C_{++} scenarios (data not shown).

Land cultivated per capita was higher in C_{++} than in C_+ and C_0 (Fig. 5) (this being clearest after 30 years of simulation). This could be a consequence of a low grain yield pushing families to increase the area cultivated to meet their needs. When the crop yield decreased, families increased the cultivated area the following year to meet their goals. In the C_0 scenario, the yields were highest which explained that this scenario had the smallest area cultivated per capita and probably also the highest population growth.

In the three climate scenarios, the fallow duration in the SCS farms ranged from 1 to 15 years whereas it ranged from 1 to 5 years in the CS farms (Fig. 6). Therefore, the cropping intensity (sensu Manlay et al., 2004b) in the CS is higher than in the SCS system.

4.3.3. Animal dynamics

Climate affects pastoral activities. The average daily walking distance of the animals was higher in C_{++} than in C_0 after seven years of simulation (Fig. 7).

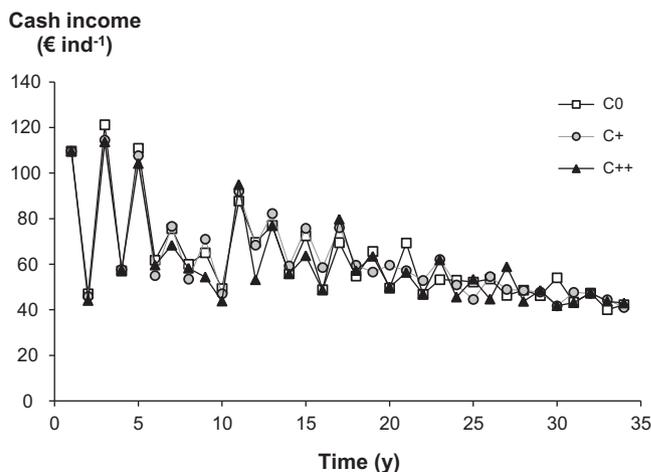


Fig. 3. Simulation of per capita cash production for the three climate scenarios, C_0 , C_+ and C_{++} .

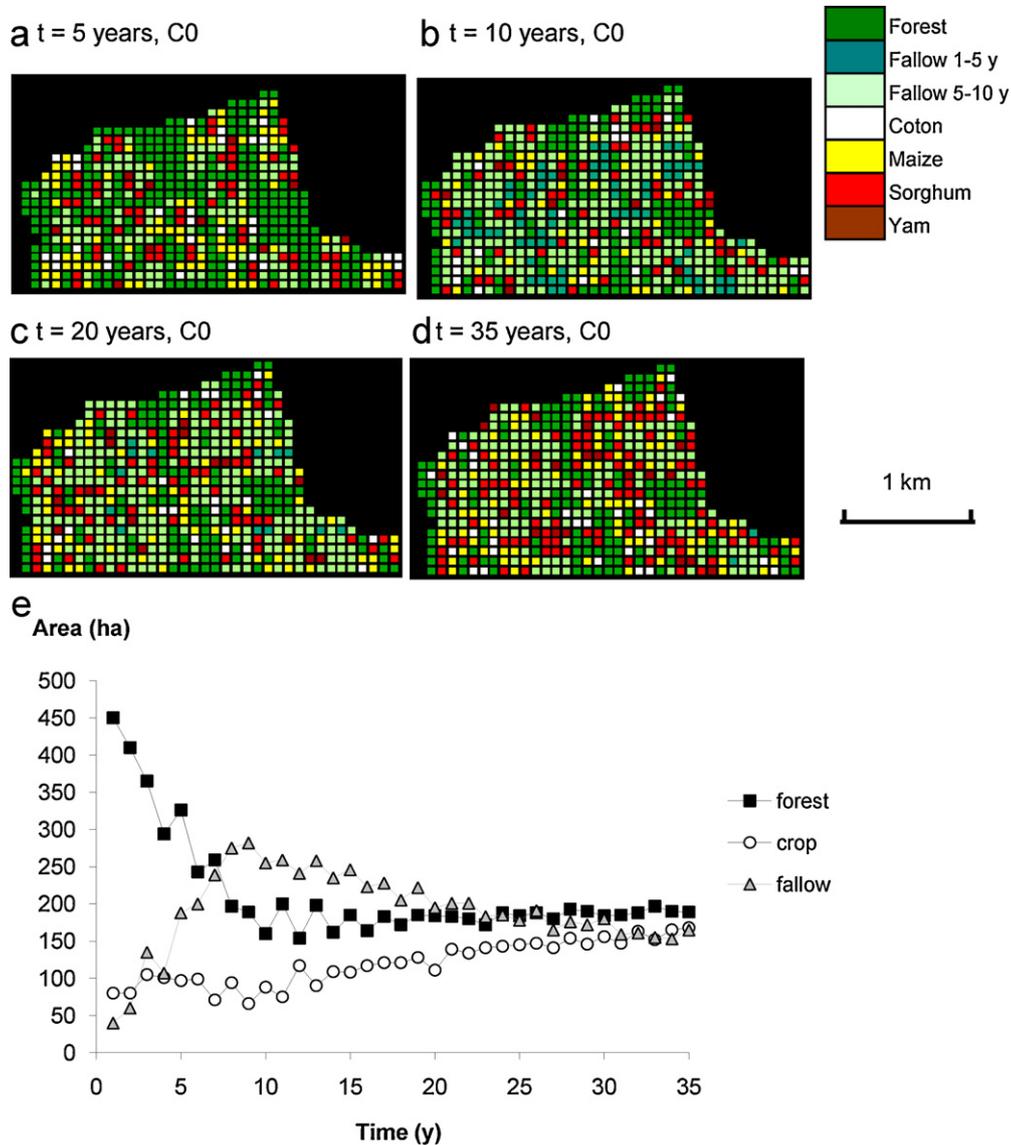


Fig. 4. Simulation of land use for the climate scenario C₀. abcd: spatial distribution. (e) Graph of area per land use type as a function of time.

The increase in the average walking distance of herds in C₊₊ may result from the reduced plant biomass production and availability (see Section 3.5.2). The sensitivity of pastoral activities to climate is shown in Fig. 8. Two periods for the evolution in animal mass

can be distinguished (Fig. 8a). During the first period (1–7 years), the average animal mass increased. It then decreased, the decrease being greater in C₊₊ than in C₀. The decrease in mass after the 15th year could be due to the increase in the area of land cultivated.

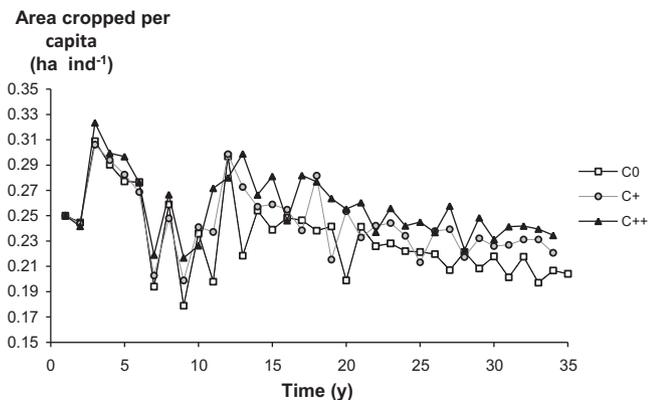


Fig. 5. Simulation of the area of land cultivated per capita for the three climate scenarios, C₀, C₊ and C₊₊ (see text for their description).

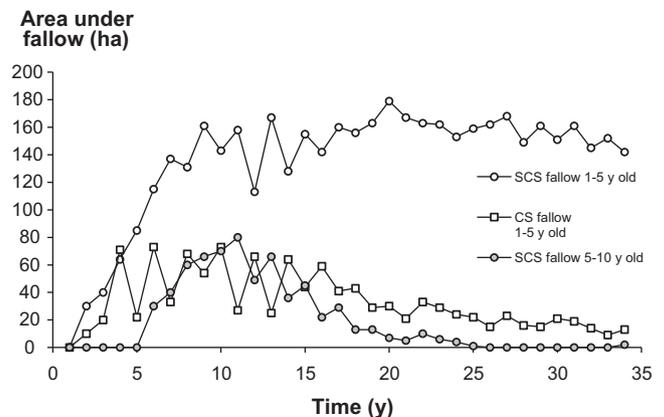


Fig. 6. Simulation of fallow area by duration class and semi-continuous (SCS) and continuous (CS) cropping systems for the climate scenario C₀.

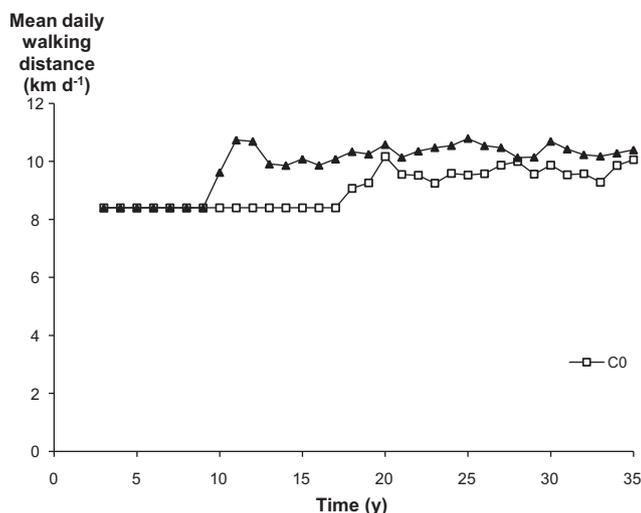


Fig. 7. Simulation of daily walking distance for herds for the two climate scenarios, C₀ and C₊₊.

An increase in cultivated area reduces the pasture and thus the availability of forage. The number of animals increased in C₀ and C₊₊ during the period 0–17 years (Fig. 8b). It then reached a plateau – suggesting that the capacity of the village has been reached – with the number being 8% lower in C₊₊ (0.65 TLU ha⁻¹; 1 tropical livestock unit – TLU – being equal to 250 kg of live weight) than in C₀ (0.70 TLU ha⁻¹). This is slightly outside the range of livestock densities (0.05–0.55 TLU ha⁻¹) reported for West Africa by Landais and Lhoste (1993) and much higher than that found for Touroukoro village by Botoni (2003) (0.09 TLU ha⁻¹) and that calculated from FAO data (FAO, 2010) for West Africa in 2008 (0.14 TLU ha⁻¹).

4.3.4. Carbon dynamics

After 35 years, the SOC density in SCS farms fell by 3, 10 and 17% in C₀, C₊ and C₊₊ respectively, whereas in CS farms it fell by 29, 33 and 36% in C₀, C₊ and C₊₊ respectively (Fig. 9). The decrease in SOC content after conversion to arable farming has been reported from

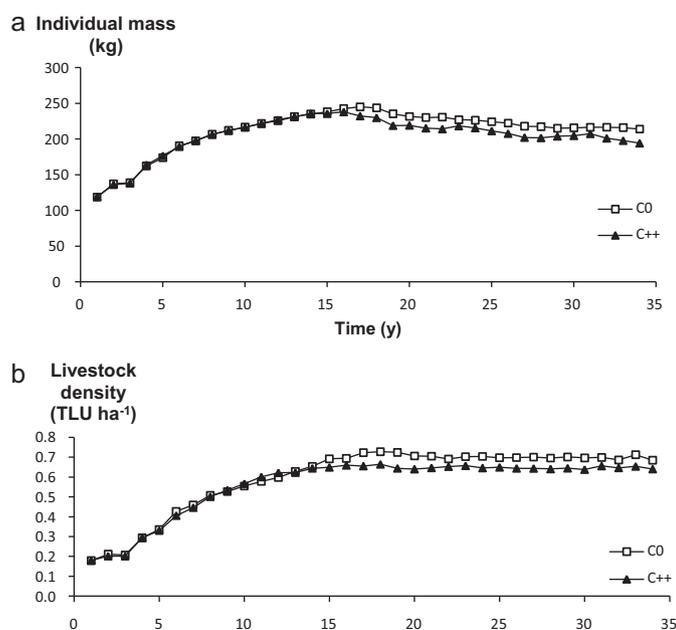


Fig. 8. Simulation of individual animal mass (a) and livestock density (b) for the two climate scenarios, C₀ and C₊₊.

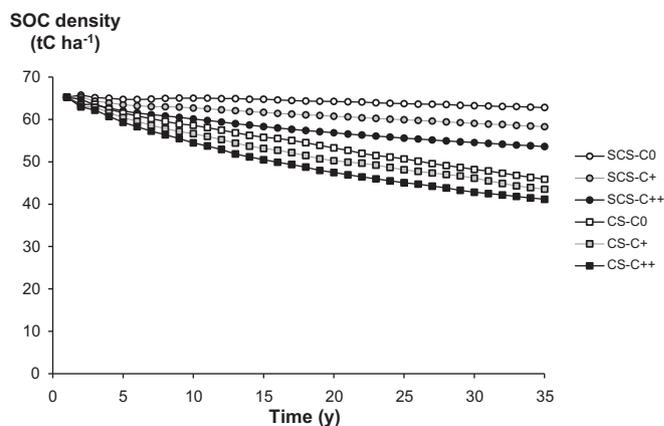


Fig. 9. Simulation of the soil organic carbon (SOC) density of farms under semi-continuous (SCS) and continuous (CS) cropping systems for the three climate scenarios, C₀, C₊ and C₊₊.

field studies (Guo and Gifford, 2002) and is caused by decreased C inputs, increased C exports and modifications in soil physical, chemical and biological conditions.

The simulations showed that the SOC density was higher in SCS farms than CS farms. After 35 years the SOC density in CS was 26, 25 and 23% lower than in SCS, in C₀, C₊ and C₊₊ respectively. This could be due to SCS fertility management being based on higher organic inputs with a longer fallow duration than in CS farms. The effect of climate change on the decrease in SOC density was two times higher in SCS farms than in CS farms, suggesting that fertilization may reduce the impact of climate change on SOC storage, possibly by shifting climate thresholds affecting the carbon cycle.

5. Discussion and conclusion

5.1. Performance of the model

Simulations were used to test the performance of the model. For the simulations presented in this paper, one computer with 2Gb of RAM and a 2 GHz processor was used. The duration of the simulation depends on the performance and the number of computers, the number of the entities (families and cattle), the size of the space and the timescale. Each scenario was simulated over 420 time steps (420 months or 35 years). Each simulation took 8 hours.

5.2. Interactions between population, agricultural production and resources

The results showed that CaTMAS was able simulate the relationships between population and agricultural intensification.

It is now recognized that population is an important driver of agricultural intensification and extensification in developing countries (van Beek et al., 2010). This trend has many effects on land use, fallow management and nutrient balance.

The increase in agricultural production owing to population growth results in an increase in cultivated area (Ramankutty et al., 2002) and land becomes scarcer. Land scarcity leads to agricultural intensification with shorter fallow periods and increased labor and capital inputs (Aune and Bationo, 2008).

The simulations with CaTMAS showed similar trends. The effect of population on agricultural intensification and extensification was illustrated by an increase in cultivated area, a decrease in the area under forest (Fig. 4) and shorter fallow periods (Fig. 6). The cultivated area per capita (Fig. 5) also decreased in the three scenarios as the population grew even though the cultivated area increased.

The simulations also showed that climate change has a major effect on agricultural intensification and extensification. The cultivated area per capita was greater for scenario C₊₊₊ (extreme climate change) than in C₊₊ and C₀. This is due to the effect of climate change on crop production. When the yield decreases, farmers increase the area of cultivated land in order to compensate for the reduced productivity, leading to a land shortage and shorter fallow periods.

The effect of climate change on crop production could be explained by the effect on SOC, which in turn affects the soil fertility and biomass production (Bationo et al., 2007). The effect of climate change on SOC is accentuated by shortening of the fallow periods. Fallow periods which should have restored nutrients and carbon has decreased to lengths which no longer meet this objective, resulting in non-productivity and unsustainability of the system (Nandwa, 2001). There is a rapid decline of SOC levels with continuous cultivation (Bationo et al., 2007). The simulations with CaTMAS showed the effects of climate change and fallow periods on SOC. The SOC level in SCS farms is higher than in CS farms (Fig. 9).

Agricultural intensification and reduction in SOC also affect livestock. They result in decreased biomass availability for feeding, increased duration of grazing and increased animal mortality.

Two major results for studying the C cycle at village level were obtained from this work: (1) evidence of the value of considering multiple feedback paths and interactions for realistic representation of the C cycle at village level, as suggested from simulations with simple scenarios and (2) a generic model.

However, the use of data from the literature prevents the comparison of the outputs with reality. The data used for the simulations was based on independent sources. Using data from independent sources showed that the model was independent of the application context.

5.3. Malthus vs. Boserup model

CaTMAS is a Malthusian model (Malthus, 1817), since the decrease in C resources does not have an effect on the families' strategies. Except for the increase in the cultivated land, families do not change their strategies to improve C management. The Boserup (1965) approach assumes that stakeholders adapt their strategies when resource availability falls below a certain threshold to alleviate the pressure on these resources.

5.4. Further development

The CaTMAS model could be improved in different ways.

5.4.1. Modeling C dynamics at regional or national scales

CaTMAS is applicable at village level only. Important drivers of C dynamics such as (1) movement – population, organic matter and other goods, information – and synergies between villages, (2) existence of marginal lands and (3) national agricultural policies have effects beyond village level. The model could thus be extended to represent C dynamics at larger spatial scales such as regions or countries by taking account of spatial variations in climate and cropping systems. The OREA conceptual model makes this possible. This development would enable studies of (1) C flows between villages and (2) the effect of climate change and national policies on C dynamics and economic wealth.

5.4.2. Adaptive behavior and technology diffusion

To adopt the Boserup (1965) approach, adaptive behavior should be introduced into CaTMAS which would enable the study of how farmers adapt their practices to environmental changes. In addition, it would be necessary to study how farmers react to the

introduction of new technologies and the impact of these technologies on C management.

5.4.3. Economic aspects

CaTMAS could be extended to incorporate the economics of carbon sequestration. Diagana et al. (2007) used a spatially explicit econometric-process simulation model to simulate the impact of carbon-payment schemes on C sequestration in Senegal. Their study shows the potential of econometric modeling for C management, although it does not take account of some social factors such as the effect of population change or interactions between farmers. Coupling CaTMAS to an econometric model would significantly improve the analysis of C dynamics. Greater diversity and flexibility (including adaptation and learning capacities) of farmers strategies would also be needed.

5.4.4. Other developments

The CaTMAS project was not developed solely for cognitive purposes. It should be available as a support for decision-makers including institutions and farmers in developing countries to (1) define strategies that optimize management of C resources for agricultural and environmental purposes while taking account of their socioeconomic impacts and (2) facilitate dialogue between the various parties – whether institutional or not – involved in the management of C resources (Antona et al., 2005). For this, the user interface will need to be improved.

Acknowledgments

This work was supported by the Institute of Research for Development (IRD, mixed research unit Eco&Sols, and the Department “Support and Training”), the Paris Institute of Technology for Life, Food and Environmental Sciences (AgroParisTech), and the Research Unit-Green of Agricultural Research Centre for International Development (CIRAD). The authors thank A. Lufafa, who provided some input data, T. Hilinski for his technical support on the Century model and valuable comments from anonymous reviewers.

Appendix A. The carbon cycle of a village territory in West Africa

The carbon dynamics at village scale are complex as they involve many entities including soil, plant, farmers and livestock that interact over many time and space scales. Carbon resources depend on multiple use and management schemes that are affected by cropping systems and the population's needs.

A.1. The carbon cycle of a farming system

The carbon dynamics of a farming system can be described at plot, farm and village levels. Plot level concerns mainly the biophysical processes whereas the farm and village levels are more related to socioeconomic processes.

At plot level, photosynthesis fixes the atmospheric C in the plant biomass. During plant, microbial and animal respiration and biomass burning, C is transferred back to the atmosphere. Senescent biomass turns into litter, which in turn becomes soil organic carbon. Other SOC sources include root exudates and animal excreta and tissues. SOC and litter return to the atmosphere as CO₂ or CH₄ during heterotrophic respiration and fermentation. The SOC content depends on soil physical, chemical and biological properties and climate as well as past and present land management (e.g. cropping techniques, intensity of wood and crop harvesting, fire management).

At farm level, the rules for the individual management of C resources used to satisfy farm needs are defined and applied. The farmers strive to fulfill food and cash needs by managing production. There are several drivers to farmers' decisions and success: money, labor power and equipment. A farm is characterized by its population size, labor power, land area, herd composition, OM management strategies within cropping systems and the production of own consumption and cash food products. A farm has two main activities: crop production and animal production. Animals account for considerable OM transfer through ingestion and excretion and their management (movement, feeding regime, performance) is determined at farm level.

At village level, there is interaction for land transactions, manure and labor and for collective rules regarding land use. Several ethnic and social groups coexist and the villager's group determines her/his access to resources, the way she/he uses them as well as her/his farming system. A village is also an open system that "exchanges" people, goods and money with the outside. Interactions shape the village organization and may lead to the emergence of new features, such as agricultural practices, social groups or land use patterns.

A.2. Drivers of change

Since sub-Saharan Africa has the highest population growth rate in the world (UNDP, 2010), demography is an important driver of C dynamics in this region. As the population increases, the farmers adapt their cropping strategies to meet the new food and cash requirements. For this, generally, new land is cleared for agriculture while it is available. "Cropping intensity" (sensu Manlay et al., 2004b) increases at the expense of fallow duration. Herd size is usually limited by forage availability which may be temporarily overcome by transhumance. At plot level, the increase in cropping intensity reduces SOM levels and perennial vegetation while stimulating soil erosion. With changing farming conditions, farmers may change their cropping techniques and adopt new technologies.

Carbon resources can be managed individually ("individual" referring to the farm, itself considered as a unified human community behaving like a sole "organism" for the purpose of simplifying the model) or collectively. These two interact at a village level. For example, the individual strategies of land use determine the capacity of the village to support animals and increasing the area of cultivated land affects the growth of animals.

The farmers' practices (land preparation, animal husbandry, number of animals, feeding regime) affect carbon dynamics directly and indirectly. Their decisions are influenced by the socioeconomic context (population size and targeted standard of living, access to market, cash availability, skills, cooking equipment performance) and by the environmental context (soil fertility).

A village is thus a system that is (1) dynamic because of its organization, (2) open because of its interactions with external entities (such as other villages for trade and remote areas for seasonal or definitive migration) and (3) adaptive because the stakeholders can change their behavior according to the local and global environment.

A realistic representation of C dynamics of a village, therefore, requires a multidisciplinary approach. The complexity involved in understanding C dynamics arises both from its multi-level organization and from its multidisciplinary and raises at least two challenges: (1) representation and interaction of the various spatio-functional scales, together with individual and collective management, and (2) representation and integration of disparate points of view into a coherent whole.

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