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

Mahamadou Belem[a,b,c,d,*], Raphaël J. Manlay[a,b], Jean-Pierre Müller[c], Jean-Luc Chotte[a]

[a] IRD, UMR Eco&Sols, F-34060 Montpellier, France
[b] AgroParisTech, UMR Eco&Sols, F-34060 Montpellier, France
[c] CIRAD, UPR GREEN, F-34398 Montpellier, France
[d] Fondation 2ie, 1 rue de la science 01 BP 594 Ouagadougou 01, Burkina Faso

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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.

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.

* Corresponding author at: Fondation 2ie, 1 rue de la science 01 BP 594 Ouagadougou 01, Burkina Faso. Tel.: +226 74 77 99 87; fax: +226 50 49 28 01.
E-mail addresses: mahamadou.belem@2ie-edu.org, mahamadou.belem@gmail.com (M. Belem).

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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)