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Retrospective and prospective dynamics of soil carbon sequestration in Sahelian agrosystems in Senegal

M. Loum [a,c,*], V. Viaud [b], Y. Fouad [a], H. Nicolas [a], C. Walter [a]

[a] Agrocampus Ouest, UMR 1069, Soil Agro- and hydrosystem Spatialization, 65 rue de Saint-Brieuc, F-35000 Rennes, France
[b] INRA, UMR 1069, Soil Agro- and hydrosystem Spatialization, 65 rue de Saint-Brieuc, F-35000 Rennes, France
[c] Gaston Berger University, Geography Department, BP 234, Saint-Louis, Senegal

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ABSTRACT

Changes in organic carbon after deforestation in Sahelian soils in Senegal were simulated both retrospectively and prospectively with the RothC model. Retrospective simulation modeling allowed us to recreate organic carbon dynamics during the exploitation period of a cropping system from 1991 to 2009. Beginning with an initial carbon stock equal to that measured in the undisturbed forest (14.8t C ha^{-1}), predicted carbon stocks after 18 years of different crop rotations were of the same order as the mean stock measured in the cropped zone in 2009 (8.1 t C ha^{-1}). The sustainability of the cropping systems that may be established in the future was evaluated with prospective simulation from 2009 to 2080, taking climate change scenarios into account. Rotations of continuous crops, even with fallow periods, led to loss carbon stock of about 5 and 6 t C ha^{-1}, which may involve decrease in land productivity in the long term. Agroforestry systems generated relatively large gains in soil organic carbon, which could render local cropping systems sustainable. The effect of climate change on changes in soil organic carbon appeared of secondary importance compared to inputs of carbon from spontaneous or sown vegetation associated with crop rotations.

1. Introduction

The agricultural use of soils and its impact on the environment depends on the spatial variability of the soil cover and the means to adapt to it or take it into account (Walter, 1990). In the Senegalese Sahel, the dynamics of deforestation and agricultural use of soil of non-cultivated areas (forests or wooded savannahs) is an issue of production and sustainability. Production of the annual crops peanut (*Arachis hypogaea*) and pearl millet (*Pennisetum typhoides*) often affects the quality of these soils (Charreau, 1972). Organic carbon plays a major role in soil quality: it influences plant production as well as physical and biological properties of soils. In the Sahel, organic carbon of surface horizons has been recognized as a potential indicator of cropping system sustainability (Feller, 1995), giving an estimation of the potential for maintaining soil productivity and the state of the soil resource. Feller and Beare (1997) proposed a threshold value of soil organic carbon content in the 0-to-10-cm horizon derived from clay (CL) and fine loam (FL) contents below which cropping systems are considered not sustainable in the Sahel: $C‰ = 0.32*(\%CL + FL) + 0.87$. Despite having low carbon contents (0.1–1.5%), Sahelian soils can make an important contribution to global carbon sequestration (FAO, 2002; FAO, 2004). Improved agricultural-management methods can contribute to stocking 0.2–1.5 t C ha^{-1} yr^{-1} in sub-Saharan Africa (Vagen et al., 2005). These carbon stocks, however, are vulnerable. Annual crops, continuous or with short fallow periods, often lead to soil-carbon losses and diminish soil physical and chemical properties (Elberling et al., 2003; Manlay et al., 2002a; Woomer et al., 2004). In this context, the objective of this work was to quantify via retrospective and prospective simulation modeling the potential of soils in the Senegalese Sahel to stock carbon. The retrospective simulation quantified changes in organic carbon from 1991 to 2009, corresponding to the exploitation period of a cropping system. In the prospective approach, organic carbon was simulated from 2009 to 2080 under different cropping systems and climate-change scenarios. The model represents the area to the agrosystem of Kelcom (Senegal), which once was an IUCN (International Union for Conservation of Nature) protected zone of 100,000 ha known as the Mbégué Sylvo-Pastoral Reserve. Since 1992, the

* Corresponding author. Agrocampus Ouest, UMR 1069, Soil Agro- and hydrosystem Spatialization, 65 rue de Saint-Brieuc, F-35000 Rennes, France. Tel.: +33 (0) 2 23 48 70 40; fax: +33 (0) 2 23 48 54 30.

E-mail addresses: macoumbaloum@yahoo.fr (M. Loum), valerie.viaud@rennes.inra.fr (V. Viaud), youssef.fouad@agrocampus-ouest.fr (Y. Fouad), herve.nicolas@agrocampus-ouest.fr (H. Nicolas), chistian.walter@agrocampus-ouest.fr (C. Walter).

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Muslim community of Mourides has transformed 55,000 ha of the reserve into cropland. The goal of modeling was to evaluate the sustainability of agricultural systems that may be adopted there in the future.

2. Material and methods

2.1. Study zone

The study zone is the current agrosystem of Kelcom, located in the Peanut Basin of Senegal at the junction of the administrative regions of Diourbel, Kaolack, and Fatick (14°35′43.6″N, 15°24′12.64″O) (Fig. 1). It corresponds to the 55,000 ha managed by the Mourides. The area has a hot arid climate (Kottek et al., 2006). Rainfall occurs mainly from June to September and varies from 300 to 1000 mm per year (Colobane and Malem-Hodar rain gauges). Mean monthly temperatures are 29.2 °C in April and 24 °C in January. The Alfisol soils (FAO, 2006), also called *Dior*, are weakly-leached ferruginous tropical soils from sandstone of the Continental Terminal that contain approximately 90% sand.

The tree layer of the forest was originally dominated by species of the Combretaceae and Mimosoideae families, while perennial and annual grasses and legumes populated the grass layer (Loum, 2007). Currently, plant cover corresponds to a wooded savannah, with dense vegetation cover locally.

Monitoring of the clearing of the Kelcom agrosystem by digitizing and interpreting Landsat and SPOT satellite images (1992–2010) has shown the first plot of crops cleared in 1992 by the Mourides (Loum, 2012).

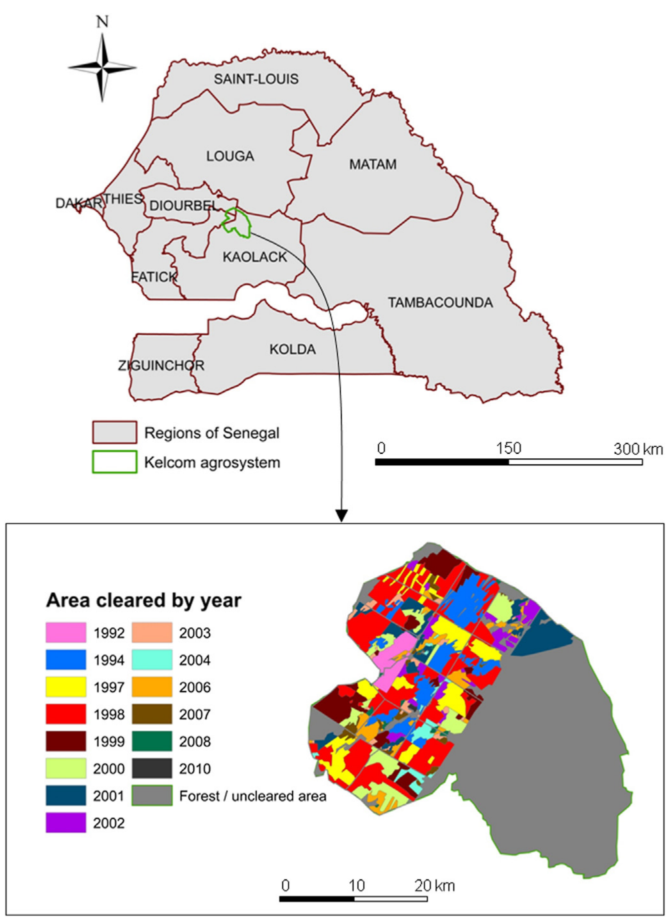

Fig. 1. Location of the Kelcom agrosystem in Senegal.

2.2. Estimating soil C stocks

In 2009, soils were sampled to estimate carbon stocks in both the cropped and undisturbed zones. We performed stratified random sampling according to the clearing dates of Mouride villages (*daaras*) in the zone. A total of 115 sampling points were selected, of which 26 were located in the undisturbed sector. In the cropped zone, 49 points were selected from plots cleared between 1992 and 1998, and 40 points were taken from plots cleared between 1999 and 2009. At each sampling point, two composite samples (at 0–10 and 10–25 cm in depth) were created by mixing 5 individual samples taken within a 100 m^2 area.

Soil C content of the 230 samples was estimated by spectroscopy, using an estimation model calibrated with a partial least squares regression of local data (Mevik and Wherens, 2007). Explanatory variables of the model were spectral reflectances of the samples determined by spectroscopy after sieving to 2 mm and drying at 45 °C. Spectra were obtained with a spectroradiometer (Analytical Spectral Devices, Inc., Boulder, Colorado, USA) at 350–2500 nm. Organic carbon from 100 soil samples analyzed according to ISO 10694 (1995) served as calibration data. They were selected by principal component analysis as a function of their altitudinal distribution, determined from a digital elevation model built from elevation data collected by the Senegalese Geographic and Mapping Agency (DTGC). Spatial analysis of the variability of soil organic carbon from the estimated contents was performed and enabled to describe the distribution of soil C content in 2009.

Carbon stocks were calculated for 64 soil samples. Particle-size analysis was performed by laser diffraction (CILAS 1180, Orleans, France). Soil bulk density was estimated with the pedotransfer function of Kaur et al. (2002). Estimated C stocks in cropped and undisturbed zones were used as initial values in the prospective and retrospective simulations, respectively, described in the following sections.

2.3. Dynamic soil-carbon model

Simulation of C dynamics was performed with the RothC model 26.3 (Coleman and Jenkinson, 2005). RothC simulates the turnover of soil organic C on a monthly time step, assuming five conceptual carbon pools with different decomposition rates: DPM (Decomposable Plant Material), RPM (Resistant Plant Material), BIO (Microbial Biomass), HUM (Humus), and IOM (Inert Organic Matter). Input variables of the model include the initial C stock, climate parameters (monthly rainfall, temperature and evapotranspiration), amount of plant cover, soil clay content, and organic C inputs (e.g. plant residues, organic fertilization). At the beginning of the simulation, initial C content in each conceptual compartment is computed from the soil organic carbon stock measured in the field using RothC in a reverse mode (Coleman and Jenkinson, 2005). RothC has been used and tested extensively, including the modeling of soil organic carbon in semi-arid environments (Jenkinson et al., 1999; Kintche et al., 2010).

2.4. Simulation experiments

Two types of simulation were performed:

- retrospective (1991–2009) – to simulate the change in C stocks from the initial clearing to their current state and to compare current predictions to the stocks observed in the field;
- prospective (2009–2080) – to evaluate the potential of these soils to sequester C under different cropping systems and in the context of climate change.