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Agent-based modelling as a time machine to assess nutrient cycling reorganization during past agrarian transitions in West Africa

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A B S T R A C T

Although in agronomy most model-based simulations explore future agro-ecosystems, we used a simulation model to explore past agro-ecosystems, which was particularly useful in a context where historical quantitative data on nutrient flows are lacking. The aim of this study was to assess the impact of an agrarian transition on the reorganization of nutrient cycles in agro-sylvo-pastoral systems (ASPS) in West Africa. The model was an agent-based model called TERROIR (TERRoir level Organic matter Interactions and Recycling model) that analyzes nutrient cycles at three levels of organization: plot, household, and landscape. Simulated scenarios were defined based on the agrarian transition that occurred in the 1920–2010 period in the groundnut basin of Senegal, a rapid transition caused by strong population growth, high climate variability and fluctuating cash crop markets. The main trends of the simulated agrarian transition are expansion of croplands onto rangelands and a shift from subsistence to market oriented farming systems, resulting in a shift from a livestock feeding system based on free grazing to a system based on the increasing use of feed concentrates and crop residues after harvest. The transition led to intensification of nitrogen flows and to reduced nitrogen use efficiency, due to the accumulation of nutrients in the area near the homestead and incomplete return of nutrients to cultivated plots. Two major properties appear to be outlasting the transition: (i) independence towards external inputs, based on crop-livestock integration, i.e. high biomass and nutrient recycling within the system; (ii) spatial heterogeneity due to nutrient transfers from peripheral land units to core land units, mainly through livestock. We argue that the persistence of these two emerging properties is a key pattern of past trajectories that can be used to make assumptions on and explore future ASPS trajectories.

1. Introduction

Traditional agro-sylvo-pastoral systems (ASPS) in the rural Sahelo-Sudanian zones of West Africa are widely described in the literature (Dugué, 1998; Powell et al., 2004). Soils are inherently poor and farming systems are low input systems. The limiting factors to the productivity of these systems are biomass and nutrients (Affholder et al., 2013). ASPS are based on crop and livestock integration; crop residues and fodder from non-cultivated areas are used to feed animals; animal excreta produced during free grazing and night corralling are used to fertilize crops. Livestock are consequently key drivers of nutrient recycling and of the spatial transfers that are essential to maintain soil fertility (Dugué, 1998). Under resource scarcity, the main household strategy is to concentrate organic matter in fields located near the homestead, in order to ensure food security. The spatial heterogeneity of nutrient inputs and nutrient availability for crops is consequently high between home fields and bush fields (Manlay et al., 2004).

The population growth rate in West Africa reached 2.7% between 2010 and 2015, which is particularly high compared to the world growth rate (+1.2%) (United Nations, 2015). The resulting increase in the demand for food led to the rapid expansion of croplands onto rangelands (Achard and Banoin, 2003; Dugué, 1998), which reduced the land available for livestock and consequently, livestock mobility within the village landscape, particularly during the cropping season (Dugué, 1998). In addition, farming systems were impacted by crop market variability, such as the groundnut crisis in Senegal in the 1980s (Lericollais, 1999) and the cotton crisis in Mali and Burkina Faso in the 2000s (Falconnier et al., 2015). In this context, ASPS were subject to

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constant change, and their productive resources were reorganized in space and time. For instance, today in response to attractive animal product markets, more intensive livestock systems, i.e. that mobilize more resources per animal, are developing; for instance livestock fattening in Senegal (Sow et al., 2004) or dairy production in Mali (de Ridder et al., 2015). In these systems, livestock are kept in barns and their excreta is managed by humans in the form of manure, rather than directly deposited on the field by the herds. Consequently, the functioning and maintenance of soil fertility in traditional ASPS based on crop-livestock integration and livestock-driven spatial nutrient transfers are called into question (Lericollais and Faye, 1994; Vayssières et al., 2015).

Many studies have been conducted to understand how the farming systems function in terms of biomass and nutrient cycling. These studies had different objectives and used different methods, for example, ecological network analysis was used to assess recycling intensity and crop-livestock integration (Bénagabou et al., 2017; Rufino et al., 2009; Stark et al., 2016), spatial heterogeneity and soil fertility dynamics were evaluated using system gate balances (Manlay et al., 2004; Schlecht and Hiernaux, 2004), and biomass recycling was quantified using a stock-flow model (Diarisso et al., 2015). However, these studies focus on current systems and disregard past dynamics of nutrient cycles caused by changes in landscape and in farming systems.

In contrast, agrarian transition approaches aim to assess changes in land use, changes in farming systems and their drivers in order to foresee possible future agricultural dynamics (Matthews et al., 2007; Ryschawy et al., 2013). These studies focus on the range of successive farming systems that appear in a given region and period in response to a changing environment (Mazoyer and Roudart, 1997). These studies generally analyze land use policies (Castella et al., 2005; Le et al., 2010) in Vietnam), decision making that affects land use (Jahel et al. (2016) in Burkina Faso), or describe farming system trajectories (Falconnier et al., 2015; Saqalli et al., 2013; Vall et al., 2017). However these studies generally show little or no interest in biomass and nutrient recycling. Knowledge is thus lacking on the consequences of changes in land use and of changes in farming systems on nutrient cycles, particularly in West Africa.

This paper is based on the concept of agrarian transition used to study the agricultural transformations in a region as a succession of distinct systems constituting as many steps of an historical period (Mazoyer and Roudart, 1997). The objective is to show how a modelling approach can be used to assess the impact of an agrarian transition on the reorganization of nutrient cycles in ASPS. Similarly to other agrarian transition studies, the ultimate goal is to identify drivers that can be used to make assumptions about alternative farming systems and on the agrarian transitions that are most likely to occur in the future. This paper presents a typical application of a dynamic “functioning model”, the TERROIR agent-based model, which is described and evaluated in detail in Grillot et al. (forthcoming). The model represents and spatializes the daily interactions between farming activities in terms of biomass and nitrogen flows. It calculates indicators for ASPS structure, functioning and performances. It does not simulate the transition itself but is used to simulate scenarios representing the main steps of the agrarian transition in a case study of the groundnut basin of Senegal.

Seven scenarios were built to assess three trajectories of village terroirs and the corresponding agrarian transition typically encountered in the groundnut basin of Senegal. Each simulated scenario represents the state of an ASPS between 1920 and 2010 for the three trajectories studied. Scenarios were based on data collected in the last century by researchers of the Niakhar Population and Health Observatory, which is one of the oldest in Africa (Delaunay et al., 2013).

2. Materials and methods

2.1. The TERROIR agent-based model

The TERROIR model (TERRoir level Organic matter Interactions and Recycling model) was built to simulate the organization of biomass and nutrient flows in a village during a given year.

The model distinguishes **households** as the main agent for decision-making, **livestock** as independent herds moving within the village landscape, **land plot** as the main spatial unit, assumed to be the smallest area managed by households as an entity (0.25 ha) and biomass **stock** dynamics. Livestock herds can be managed extensively, i.e. in free-grazing with low inputs or intensively, i.e. kept in-barn for fattening purposes with high requirements as regards forage quality and quantities of feed concentrate.

A full description and evaluation of the model is provided in Grillot et al. (forthcoming) and a summary of model key characteristics is provided in Appendix A. The purpose of the model is to focus on activities that produce biomass flows that enhance farming activities, these being the main activities in the ASPS studied (Lericollais, 1999; Powell et al., 2004). The model uses general guide rules, such as priority fertilization of home fields, livestock paddocking on the owner's plot, etc. Quantities are determined according to adjustable thresholds, e.g. family needs for the amount of land under millet, livestock needs for forage storage. The rules and thresholds are based on previous studies (Audouin et al., 2015; Lericollais, 1999). Although the model does not capture all the household strategies (off-farm activities, human migration, etc.), indirect effects are included. For instance, economic constraints are represented by inputs and workforce availability.

The main input data concern (i) landscape structure, i.e. the share of each land unit, (ii) farming system diversity, i.e. the share of each household type and type-specific variables, based on actual data collected on the field (see example in Appendix B), and (iii) annual rainfall (see Appendix A for more details on the biophysical model). The time step is a day, although some processes are updated every week (every 7th step), e.g. changing in the coral, and annually (every 360st step), e.g. yield computation, which is based on a simple empirical sub-model. Each simulation runs for five years, after which the output indicators are stabilized. Each simulation is repeated eight times due to the stochasticity of the model. Simulation outputs describe the structure, functioning and performance of the system for one year, i.e. the last year of the simulation run.

Biomass and nutrient flows are transfers that occur in space and over time between two types of functional compartments (Appendix C): (i) compartments related to **farming activities**, i.e. soil and plants, livestock, humans, manure heap and granary; (ii) compartments related to **land units**, i.e. homestead area, home fields, bush fields and rangelands. The main functioning and performance output indicators are based on nitrogen flows circulating between these compartments (Table 1). These indicators were fully described and implemented by Rufino et al. (2009), Stark et al. (2016) and Vayssières et al. (2011). They are calculated by the model at the three organizational levels, landscape, household and plot. All the indicators are based on apparent flows, i.e. those resulting from household activities. The only exception is for the calculation of the full balance, which includes invisible flows corresponding to atmospheric deposition, fixation by legumes and losses to the environment (leaching, run-off and gaseous emissions).

The model is spatially explicit, i.e. each N flow is spatialized. This makes it possible to account for the households' fertilization practices, which consists in concentrating the organic matter in specific fields, and to account for livestock mobility. This mobility generates indirect exchanges of biomass between households. During the day, herds may graze on any land plots located nearby where biomass is available, but at night are corralled in their owner's land plots where they excrete.

Livestock versus human-driven flows are distinguished; livestock-