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Spatial modelling of agro-ecosystem dynamics across scales: A case in the cotton region of West-Burkina Faso

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ABSTRACT

Models are increasingly being used to investigate agro-ecosystems dynamics, although processes interacting at different scales remain difficult to consider. When upscaled or downscaled based on aggregation or disaggregation methods, information is generally distorted. This study explores agro-ecosystem modelling using an interaction graph-based modelling approach that explicitly link elements at different scales without up or downscaling. The study area/time frame is the cotton region of West Burkina Faso over the last fifteen years. Field, plot, farm and climate entities are linked in graphs that evolve according to functions computed along different time steps. Three main processes and their interrelations are simulated, occurring at different spatial and temporal scales: crop area expansion, crop rotation and crop production. Three simulation examples are presented to illustrate the analytical possibilities allowed by the approach. These examples test i) the geographical distribution of plots as a means to face climatic risks, ii) the effect of fallowing practice in a spatially constrained cotton dominated landscape and iii) the consequences of reduced access to credit for farmers to buy fertilizers. Model outputs enable quantifying and mapping the respective effects of processes at different scales. Results show that modelling across scales is achievable without resorting to methods of aggregation or disaggregation, which opens new perspectives in multi-scalar analyses of agro-ecosystems that link land production and land use and land cover.

1. Introduction

Recent studies have stressed on the importance of identifying driving factors of agro-ecosystems dynamics in order to support decision-making (National Research Council, 2013; Verburg et al., 2013). By postulating that landscape dynamics result from interrelations between natural resources, farming practices and landscape patterns, the landscape agronomy approach provides an appropriate framework for studies focusing on agro-ecosystem dynamics (Benoît et al., 2012). However, understanding farming activities within their agricultural landscape setting implies that processes at multiple scales must be considered. Gibson et al. (1999) refer to scales as "the spatial, temporal, quantitative or analytical dimensions used for measuring or studying phenomena", whereas the term "level" refers to organisational aspects with no clear extent and resolution. Each process takes place at a specific level in the agro-ecosystem (Dovers, 1995; Meentemeyer, 1989; Veldkamp et al., 2001; Verburg et al., 2004) and can include elements at other levels. The processes and actors involved at different levels are linked through interactions or retroactions (O'Neill et al., 1989) that define the cross-scale organisation of the system (Peterson and Parker, 1998). For example, cropping practices induce processes that occur at plot level, but result from farmer strategies deployed at farm level. The strategies themselves take into account a variety of factors that pertain to the regional level, such as public policy, the evolution of food prices or recommendations from farmer organization. Thus, a multi-scalar approach is often necessary for understanding and monitoring agro-ecosystem dynamics.

Modelling is increasingly being employed for investigating such dynamics at regional level (e.g. Agarwal et al., 2002; National Research Council, 2013; Veldkamp et al., 2001) and also faces important scale issues that have to be addressed (Houet et al., 2010). These are primarily due to the complexity of inter-scalar relations, like for instance when observations made at a given level are due to interactions at different

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levels (Overmars and Verburg, 2006). These relations are often non-linear and may be valid at a given level but not at another. They are thus difficult to describe in a model. Moreover, modellers can be led to adopt a specific scale of analysis that often depends on the research question, or under the constraint of the extent and spatial resolution of the data used.

Aggregation and disaggregation between levels which are the current methods used when working at different scales generally cause information distortion. Indeed, relations taking place at a fine level cannot be transposed to another level, and vice versa (King et al., 1989; Overmars and Verburg, 2006; Rastetter et al., 1992; Verburg et al., 2004). Aggregation methods often simplify information (Leenhardt et al., 2010), most of the time averaging the outputs in order to upscale them, and information aggregated into a coarser level often does not fairly reproduce phenomena occurring at this level. These raise the question of how to model processes in agro-ecosystems across spatial and temporal scales without distorting information through upscaling or downscaling.

Several approaches are available for modelling a system in space and time (e.g. cellular automata, systems dynamics, agent-based or graph-based systems) (Degenne et al., 2010; Fall et al., 2007; Ferber, 1995; Forrester, 1968; Gasser et al., 1987; Hewitt, 1976; Von Neumann, 1966). Among them, the Ocelet approach (Degenne and Lo Seen, in press; Degenne et al., 2009), that had been developed for modelling spatial dynamics, uses interaction graphs to describe a system (like here, an agricultural landscape) in terms of entities distributed in space that are in interaction with each other. The capabilities of graphs to link entities that are defined at different scales make an interaction graph-based approach a good candidate for studying scale issues.

The objective of the present study is to explore the possibility of modelling agro-ecosystem dynamics with processes that explicitly reach across scales, and to use such modelling for investigating problems that link the agricultural landscape, the farm and the plot levels.

The study area chosen for the present study is the cotton region of West Burkina Faso. During the last fifteen years, agro-systems in this area have been undergoing rapid and profound changes, due mainly to intense demographic pressure and development policies in favour of export crops (Gafsi et al., 2007). These changes were clearly observable at landscape level, with the wide adoption of cotton as export crop resulted in a drastic shift from a former system based mainly on cereals, to the present maize-cotton crop rotation system (Bainville and Dufumier, 2009; Vall et al., 2006). Those new crop systems gradually extended at the expense of savannahs (Augusseau, 2007; Caillault et al., 2012; Leroux et al., 2014; Serpantié, 2003; Tallet, 2007). The increasing pressure on agricultural lands, mainly due to population natural growth, migrations and increase in cropped areas, forced farmers to gradually reduce fallows and to develop more intensive production systems (Caillault, 2011; Gafsi et al., 2007; Guyer and Lambin, 1993; Serpantié, 2003). Today, these systems are subject to soil-depletion, and land pressure has given rise to conflicts over access to resources (Vall et al., 2006). These conflicts occur mainly between farmers and livestock farmers during the crop season. The livestock farmers having their systems based on herding often have to adapt their herd management to the new saturated landscape. This situation is further worsened by the strong inter and intra-annual climate variability to which farmers are exposed due to a severe lack of basic facilities (Gafsi et al., 2007).

The main agro-ecosystem processes in the cotton region of West Burkina Faso were thus modelled using the Ocelet approach to simulate crop production and land use and land cover changes over the last fifteen years. After a description of the known processes in the study area and how they have been modelled, the paper focuses on the use of the model to test the effects of: a) the distribution of plots within the landscape in a strategy to limit climatic risks, b) fallowing in landscapes short of available space, and c) the use of fertilizers on food crops by farmers contracted to cotton companies. These issues have been chosen both to illustrate the potential use of such models when analysing an agro-ecosystem at different scales, and to give examples of what types of processes, entities and interactions need to be taken into account. We then discuss the results obtained in terms of opportunities and limits of the use of agro-ecosystem models to address scale issues, before concluding on the methodological and thematic contributions of the study.

2. Material and method

The time frame for modelling agro-ecosystem dynamics of the study area is between 2000 and 2015. Three processes linking elements at different scales and/or organisation level are considered as the main factors of change: i) the expansion of the cropland, ii) the crop rotation, and iii) the crop production. The study area, the data used, the model and the scenario are described in this section.

2.1. Study area

The study area of approximately 6000 km² is the Tuy Province, located in the cotton region of West-Burkina Faso. The landscape is a plateau of about 300 m above sea level, with a few isolated hills of 570 m maximum height, separated by plains. The most common soil type is ferruginous tropical (Leprun and Moreau, 1969). The climate type is Sudanian with a rainfall of 800 to 1100 mm per year (Aubréville, 1949). Inter-annual rainfall variability is high, which strongly affects yields in a predominantly rainfed agriculture. The rainfall spatial variability is also important, with an average annual difference of 240 mm between the extreme values. The maximal difference (437 mm) was recorded in 2012 between Koumbia and Bereba (Fig. 1b).

The land cover is composed of cultivated plots and some degraded savannahs, with about 20% of the area in reserve forests. The main crops are maize, cotton, sorghum and millet. Marre-Cast and Vall (2013) gave a typology of the farms in the region, with farmers (around 10 ha, some draft animals), agro-pastoralists (6.5–30 ha and a cattle herd), and livestock farmers (less than 6.5 ha, a herd of 10–50 heads) (Fig. 2a). Farmers make up 80% of the farms in the region, agro-pastoralists 15%, and livestock farmers, 5%.

Since 2000, the region has undergone important transformations due to multiple factors. One of them is demography, with a growth rate of 42% between the 1996 and 2006 censuses. This higher than expected growth rate is the result of migration mainly from the north of Burkina Faso, or the return of migrants from neighbouring countries (e.g. Ivory Coast), amplifying the natural growth of an already large population. The number of farms thus increased from about 22,000 in 1996 to 27,000 in 2006 (RGPH, 1996 and RGA, 2007). In parallel, studies have shown an increasing trend in farm size (Marre-Cast and Vall, 2013), with the spread of animal traction and chemical herbicides, and the introduction of the first tractors.

All these innovations have accompanied the development of cotton, which has become increasingly important (Fig. 2b). The cotton sector is indeed extremely well organized around a semi-private company that sells seedlings and inputs on credit to farmers at prices determined before the beginning of the seasons. Farmers are organized in groups to deal with the company. Each village has several Cotton Producers Groups (GPC) all of them belonging to the National Cotton Producers Union Burkina (UNPCB). But although well organized, the cotton sector could not avoid a decrease in the cultivated area in 2006 due to various factors (e.g. decreasing cotton prices, raising inputs prices, decreasing soil fertility) (Fig. 2b) (Augusseau, 2007; Bainville and Dufumier, 2009; Caillault et al., 2012; Diallo and Vall, 2010; Serpantié, 2003; Vall et al., 2006).

2.2. Material

The initial landscape, in 2000, was obtained by combining a simplified land cover map and a vector plot structure (Fig. 3). The simplified