Simulating land-use degradation in West Africa with the ALADYN model

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1. Introduction

West Africa faces a rapid growth in population and in the subsequent demand for food production. Despite increasing demand, local farmers still follow traditional practice and overcome low productivity by continuously expanding cultivated areas. To estimate the consequences of this process, we have developed the Agricultural LAnd DYNamics (ALADYN) model and employed it to assess soil degradation given the current rate of population growth and agricultural practice.

ALADYN belongs to a class of spatially explicit agent-based (AB) models that explore relationships between the changes in socioeconomic parameters and the changes in landscape pattern (Lambin & Geits, 2001; Parker et al., 2001), and are increasingly used to simulate land use/cover changes (Balmann, 1997; Berger, 2001; Kamusoko et al., 2009). ALADYN is based on remote sensing analysis of agricultural land-use dynamics during last 30 years, and field research data of soil degradation in Kita area from 2004 and 2006, and on space-borne data of the Kita area during 1976–2004 (Kidron et al., 2010).

2. ALADYN model of the agriculture land-use dynamics in Kita, Mali

2.1. ALADYN's Overview

Since the late 1950s, production of cotton has increased immensely in West Africa and specifically in Mali. Cotton cultivation in Mali takes place in rotation with cereal and groundnut. The typical cycle begins with a year of cotton cultivation followed by a year of cereal (sorghum, millet or corn), and then an additional year of cereal or groundnut (Kidron et al., 2010).

ALADYN simulates agricultural land dynamics as an outcome of farmers' decisions regarding land use and crop choice, and interacts within settlements. Kita area is represented by a set of cells, that are characterized by one of land use types and soil fertility. A settlement's population consists of farmers and grows at a rate defined by the model scenario. Below we consider two scenarios – a constant 3% annual growth rate, and a growth rate that linearly declines over 60 years at a rate of 3% to 1% per year, in accordance to the UN prognosis (Zougmoré et al., 2002).

2.2. Objects and agents in ALADYN

A settlement is characterized by the location of its center (as a cell), its initial number of farmers and its population growth rate.

Fields are spatially continuous sets of land cells, characterized by the distance to the nearest settlement and the amount of SOM.

Each farmer belongs to a settlement and possesses fields that are cultivated with cotton or crop. At the beginning of the agricultural season, the farmer decides on the future land use of each of his fields: whether it will be cultivated, and with which crop. The farmer decides to cultivate the field if the amount of SOM is above the threshold level, otherwise the field will be left fallow.

2.3. ALADYN structure

The ALADYN model consists of four main modules: Initialization, Agriculture, Prognosis and Demography (Figure 1). After the Initialization is performed, the major loop is repeated until the end of the modeled period (during 1975 - 2035 years in this paper). The model's time step is one year.

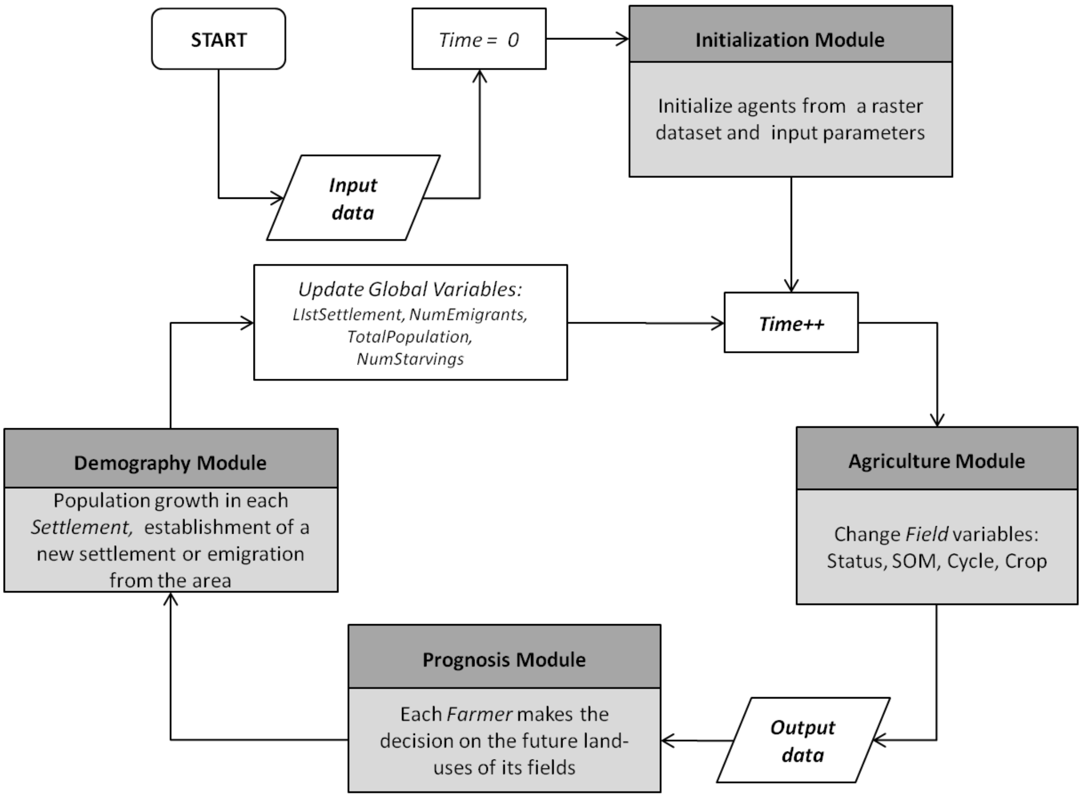


Figure 1. Basic blocks and processes of the ALADYN model.

Initialization module: Settlements are populated by farmers. The initial number of farmers in a settlement is established as 70% of their number in 2003. Each farmer in the model possesses two fields, each 1 ha in size, within a distance of 3 km from the settlement. According to satellite images analysis, in 1976 the fraction of the fallow area is about 20% of the cultivated area. Based on this, we assume that 20% of the farmers' population in 1976 cultivate one field and possess a fallow field. For the rest of the farmers we assume that the second field is virgin and not yet involved in cultivation.

The initial amount of SOM in each of the cultivated and fallow fields depends on the year within its cultivation cycle or fallow period. We assume that the amount of SOM at the beginning of the cultivation period is the maximally possible 43 t/ha (Kidron et al, 2010), while the amount of SOM in the fallow field at the beginning of the fallow period is 18 t/ha. We then apply formulae (1) – (3) of the Agriculture module below in respect to the initially randomly assigned year of cultivation or fallow to estimate amount of SOM in farmers' fields.

Agriculture module: The model simulates cotton and cereal production, by fields. Based on Kidron et al. (2010), the decrease of SOM during cultivation and its increase during the years of fallow are described by linear equations:

SOM decline during a year of cotton cultivation

$$SOM_{T+1}(t/ha) = SOM_{T}(t/ha) - 2.38 \quad (1)$$

SOM decline during a year of non-cotton crop cultivation

$$SOM_{T+1}(t/ha) = SOM_{T}(t/ha) - 1.19 \quad (2)$$

SOM restoration during a year of fallow

$$SOM_{T+1}(t/ha) = SOM_{T}(t/ha) + 0.963 \quad (3)$$

where T denotes time in years.

Prognosis module: Based on the amount of SOM in the soil, the farmer decides whether the field will be cultivated the next year. If the amount of SOM decreases below 18 t/ha, the farmer leaves it fallow. If not, the farmer decides on the future crop. A field can be exploited again once the SOM exceeds 25 t/ha.

Demography module: The rate of a settlement's population growth depends on the model scenario. If the population exceeds the settlement’s capacity for agriculture, new farmers migrate to the other or establish new settlements.

Parameter	Default value
Length of cultivation cycle	3 yr
Amount of SOM in a virgin field is above	43 t/ha
Cultivation starts when SOM is above	25 t/ha
Cultivation stops when SOM is below	18 t/ha
Overall area of each farmer’s fields	2 ha
Population of a settlement in 1976 (as a percentage of the settlement’s capacity in 2003)	70%
Fraction of fallow fields in 1976	20%

Table 1. Parameters of the ALADYN model.

ALADYN model parameters are represented in Table 1.Figure 2 represents the model interface that is developed within the NetLogo modeling environment (Wilensky, 1999).

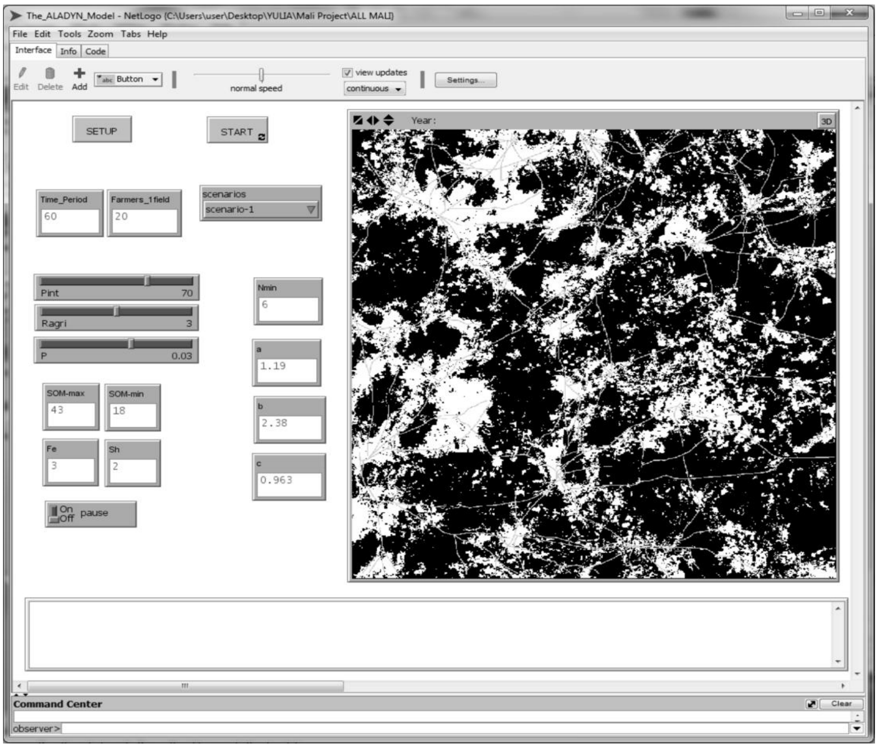


Figure 2. Interface of ALADYN model.

2.4. Results

The dynamics of SOM in the fields of a single farmer are presented in Figure 3. As can be seen, after the first 40 years the amount of SOM in the farmer's fields stabilizes and varies between 15-25 t/ha. During 60 years, three periods of infertility of a 1-3 year length are observed.

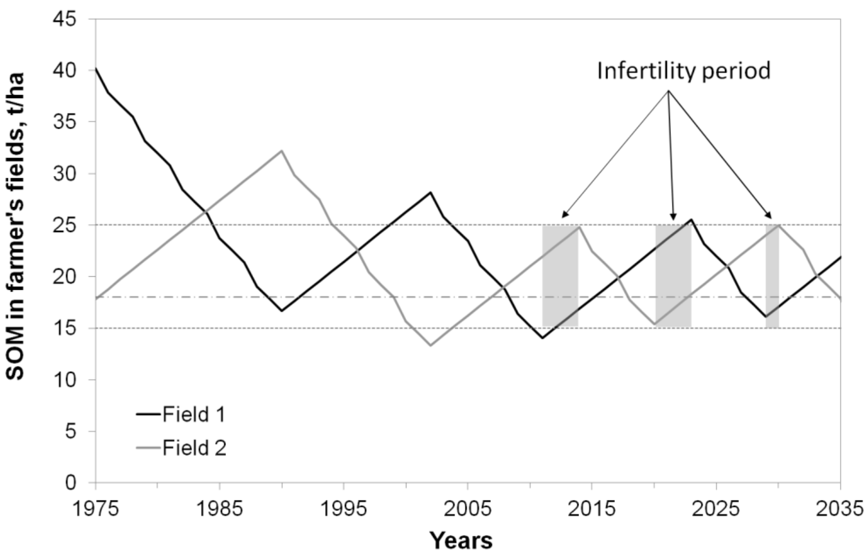


Figure 3. Amount of SOM in one farmer's fields, basic scenario of 3% rate of population growth

Figure 4 presents the model dynamics of the agricultural and cultivated areas over the entire Kita area as percentages of the total agricultural area, and three experimental points estimated according to the satellite images. As it can be seen, the cultivated area reaches its maximum towards 2010 and then slightly declines. Starting from that, more than half of the exploited agricultural land is left fallow. ALADYN adequately represents the dynamics of agricultural land use in Kita, Mali.

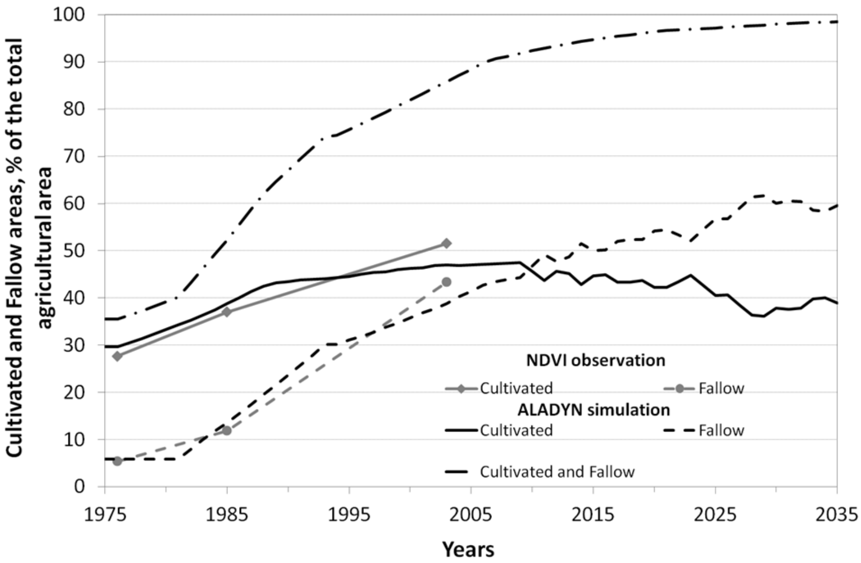
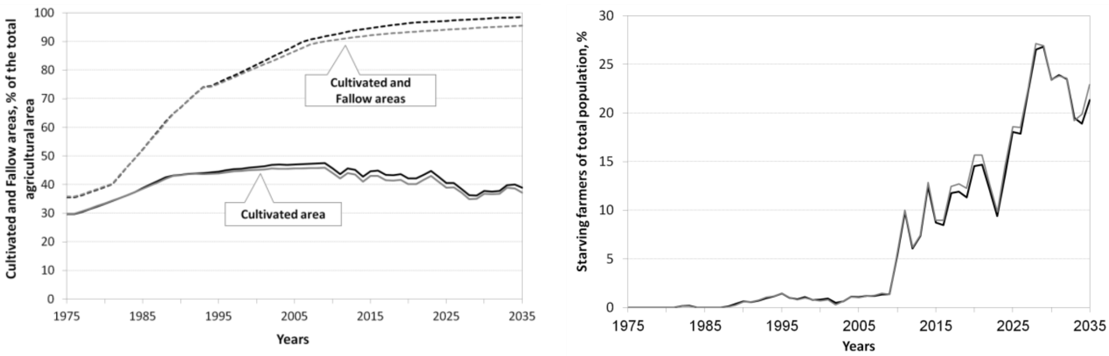


Figure 4: ALADYN dynamics of cultivated and fallow areas in Kita during 1975-2035, for basic scenario of 3% rate of population growth, as percentages of total agricultural area with the experimental data superimposed.

Assuming that the current agricultural practice will continue, ALADYN predicts a substantial increase in fallow areas and a reduction in cultivated areas, no matter if the population growth rate will remain at a current level or decrease (Figure 5a). While the growth in overall agricultural land is slowing, the area of cultivated land and subsequent agricultural production remains at the same level. As a result, the percentage of farmers not able to cultivate their fields every year remains about 20% starting from 2025 (Figure 5b).



a b

Figure 5: a) ALADYN dynamics of the agricultural and cultivated areas in Kita during 1975- 2035 as percentages of the total agricultural area, and b) the fraction of

potentially starving farmers, for two scenarios of population growth rate: 3% (black line) and 3-1% (gray line).

3. Conclusions

The ALADYN simulations clearly demonstrate that traditional agriculture is not sustainable. Even under the optimistic scenario of a declining rate of population growth, the current agricultural practice will result in the cultivation of all available agricultural lands towards 2010, when less than 50% of available agricultural land is cultivated, and production is 20-25% lower than maximally observed. Traditional agriculture essentially demands a higher ratio of fallow to cultivated lands than modern agriculture. Under current practices, every farm, every 15-20 years, will experience a period of 1-3 years during which field fertility will be too low to allow cultivation. Emigration will be the only way to avoid starvation in these circumstances. The model highlights the great need for new agricultural practices in West Africa.

4. Acknowledgement

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