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

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ABSTRACT

West Africa faces a rapid growth in population and a subsequent demand for food production. Despite increasing demand, local farmers still follow traditional practices and try to overcome low productivity by continuously expanding cultivated areas. To assess the consequences of this expansion and to describe, based on anticipated population growth rates and land accessibility, the dynamics of agricultural land-use, we developed a spatially explicit agent-based ALADYN model of agricultural land use in the savannah around Kita, Mali. The model is based on remote sensing data on agricultural land use and data from field surveys. 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 practices will result in the cultivation of all available agricultural lands by 2015. Under current practices, every farm will experience a period of 1–3 years every 15–20 years, during which field fertility will be too low to allow cultivation. Thus, to avoid severe food shortage, emigration or alternative sources of food are necessary. Comparison of the model and remote sensing data reveals that already in 2003 the cultivated part of the study area is lower than projected. That is, farmers anticipate over-exploitation and, most probably, emigrate from the area. The model highlights the great need for new agricultural practices in West Africa.

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1. Introduction: Land degradation in West Africa

The West African environment is believed to be undergoing a continuous crisis due to excessive population pressure. According to previous studies of the region (Bah et al., 2003; Benjaminsen, 2001; Shapiro and Sanders, 1998; Vanlauwe and Giller, 2006), degradation, i.e., the loss of soil fertility of the West African croplands is the most extensive in all of Africa. Land degradation leads to decreasing yields and lower food production in the farming systems of sub-Saharan Africa (Drechsel et al., 2001a,b; Kaya et al., 2000; Sanchez, 2002), where agriculture remains the main engine of economic growth (Benjaminsen, 2002; Sanchez, 2002). We investigated these processes in Mali, where the current annual population growth is close to 3% (Benjaminsen, 2001; FAO, 2010) and food sustainability in the near future may be at risk.

Since the late 1950s, the production of cotton has increased immensely in West Africa and specifically in Mali, currently the largest producer of cotton in sub-Saharan Africa (Benjaminsen, 2001). 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 one or two years of cereal or groundnut (Kidron et al., 2010). Whereas cereal is cultivated for domestic use, cotton is planted to provide cash, while the groundnut serves for both cash and domestic use. During cultivation, manure and chemical fertilizers are added to the fields, but not consistently. They are added primarily for cotton cultivation, providing the major nutrients of nitrogen (N), phosphorus (P), and potassium (K) (Kidron et al., 2010).

Cotton production in Mali is controlled by the Compagnie Malienne pour le Developpement de Textiles (CMDT), established in 1960s. CMDT assists farmers in cotton cultivation and trading, providing seeds, fertilizers and pesticides during the growing period. Seeds, fertilizers and pesticides are lent to the farmer at the beginning of the rainy season on the premise that the cotton will be sold to CMDT and the cultivation expenses provided by CMDT will be deducted from the farmer's revenue. Fertilizers were subsidized by the CMDT until 1982. When the subsidizing ceased, clearing new

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fields became attractive. As a result, substantial increase in the area of cultivated and fallow fields was observed (van der Pol and Traore, 1993).

Extensive agriculture, aimed at meeting the needs of the constantly growing population, leads to low productivity of soils (Africare, 2000; Butt and McCarl, 2005). The soil, in most parts of Mali, is sandy- or loamy-textured, characterized by a lack of organic matter. Following wind erosion, soils may intermingle with basement rocks or indurate iron stone (Laryea et al., 1991). Agricultural use of these soils, given their excessive permeability and low nutrient content, requires careful management (Shapiro and Sanders, 1998).

In order to avoid exhaustion of the soil, farmers in Mali used to divide their land into 2–3 fields: while one field is cultivated, the others are left fallow until they regain fertility. Recent observations have revealed that Malian farmers are intensifying their land use by reducing the period of time that fields are left fallow between cultivation periods, thus decreasing the overall amount of land left fallow. In parallel, the use of chemical fertilizers is still low (Butt and McCarl, 2005; Kidron et al., 2010). More and more lands are approaching the threshold fertility level, below which agricultural production becomes vulnerable (Kidron et al., 2010). The only way farmers can ensure food production in this situation is to cultivate marginal land (Benjaminsen et al., 2010) and land that is further away from their settlement and is not yet included in the agricultural cycle.

To investigate the limits of current agricultural practice, we developed the Agricultural LAnd DYNamics (ALADYN) model and employed it to assess the consequences of extensive traditional-style agriculture, given the current rate of population growth. ALADYN belongs to a class of spatially explicit agent-based (AB) models that explore relationships between the changes in socio-economic parameters and the changes in landscape pattern (Lambin and 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 the field research data of soil degradation in the Kita area from 2004 to 2006, and on space-borne data of the Kita area during the period 1976–2004 (Kidron et al., 2010).

2. Conceptual model of land degradation in Mali

The conceptual model of soil degradation in Mali was introduced by Kidron et al. (2010), who studied the relations between the soil organic matter (SOM), the major nutrients (N, P, K), and cotton yield, and evaluated the rate of soil degradation. They demonstrated that SOM, composed, as it is, of macro- and micro-nutrients and trace elements, can serve as an indicator of soil fertility. Their findings implied that soil fertility could not have been fully rehabilitated by the current use of chemical fertilizers.

Since the 1960s, the CMDT Company not only controlled cotton production in Mali but also supplied chemical fertilizers to farmers. In 1981, the Malian government signed an agreement with the International Monetary Fund and the World Bank to join a structural adjustment program that led to a dramatic reduction in subsidies for chemical fertilizers and an immediate reduction in their use (Benjaminsen, 2001; Benjaminsen et al., 2010). This drop was followed by the expansion of cultivated areas to new fields and accelerated soil degradation.

According to Kidron et al. (2010), soil fertility is defined by the amount of soil organic matter (SOM), and the threshold below which a field becomes unproductive for cotton yield is ca 18 t/ha. Kidron et al. (2010) have estimated the rate of SOM degradation in the cultivated fields and the rate of SOM restoration in the fallow fields of the Kita area: the rate of SOM restoration is lower than that of the degradation during cultivation. With the help of a simulation model, Kidron et al. (2010) demonstrated that if farmers are not able to extend their cultivated lands, then their fields eventually enters the land-use cycle characterized by 10–12 years of cultivation, followed by 12–16 fallow years, in order to restore the SOM in the fields. However, the period of 12–16 years is insufficient for the full restoration of a field's fertility, and as a result, *all* of a household's fields simultaneously become unproductive after 25–30 years of land use. The farmer is forced to leave all his fields fallow for at least 1–3 years, until one of them regains its fertility. This paper develops a spatially explicit model of agricultural land-use dynamics in Kita, a typical West African area, and employs the model to investigate the future of traditional agriculture in the region. To this end, we combine remote sensing data and data on soil degradation within the framework of an agent-based spatially explicit model of agricultural land use.

3. Land-use dynamics in the Kita area during the last 30 years

3.1. Site description

Our research site is located to the northeast of Kita (Fig. 1), the town of ca 50,000 population (Resultats Provisoires RGPH, 2009).

Its area is characterized by an inter-tropical climate with two distinct seasons: dry and rainy. Precipitation in the area is about 800 mm, falling mostly between May–June and October–November (the rainy season). A flat plateau is dissected by narrow valleys that form low hills. The soils are Ferric Lixisols with loamy and silt-loamy texture. The natural landscape is described as savannah type, with grassland, bushes, and scattered individual trees (Butt et al., 2011). Within this region, the area of 28 $\times$ 28 km was chosen for detailed study.

Farmers constitute most of the population in the Kita region. Kita, with its ca 50,000 inhabitants, is the urban center of the region (Koening, 2006). The villages in the area are mostly small with 5–6 to 50–60 small mud houses. Dirt road, create 4–8 km grids, provide access to the villages and fields and the villages are located close to the roads. Farmers' families are relatively large with 4–7 children. All villagers are engaged in traditional agriculture, using oxen for cultivation and carts for mobilization of goods. The fields are divided in accordance with family links, with each extended family having its own territory (Koening, 2006). Renting of land is not common. No irrigation facilities are available.

During the period of 1960–1980s, the farmer's lands consisted, typically, of three fields, one cultivated and two left as fallow, constituting a total area of 3 ha. Since 1990s, the typical farmer's possessions decreased to two fields constituting a total area of 2 ha, one cultivated and the other left as fallow. Cultivated fields are located in the flat area that is characterized by relatively deep (60–80 cm and deeper) soil profiles. Hilly areas in Kita are mostly unsuitable for agriculture due to excessive stoniness and shallow soils.

Cotton in the area is sown following the first substantial rain (20 mm or more) (De Bock et al., 2010), which typically happens between the end of May – mid of July, and is harvested in December or January. During cultivation, manure and chemical fertilizers are added, although not consistently. The manure is always limited, and is usually collected during several years. Commonly, both manure and chemical fertilizers are added in the year of cotton cultivation.

3.2. Remote sensing analysis of agricultural land use in the Kita area

To investigate the dynamics of agricultural land use in the Kita area, we relied on remote sensing data. As mentioned above, the

Fig. 1. Research site in Kita region, Mali.

cultivation period of cotton begins with the onset of the rainy season. It is thus difficult to detect cropland by remote sensing techniques during the cultivation period because of cloudy skies and sparse vegetation cover. Therefore, we identified cultivated fields with images taken after the harvest when the fields appear as bare soil. Fallow fields were identified as those that were cultivated in the past, according to the previous image, but are covered according to the current image, by savannah vegetation.

Two sets of multispectral satellite images were used in the analysis (Table 1). The first consists of Landsat MSS, TM, and ETM + images taken in the middle of the dry season (February and March) in 1976, 1985, and 2003. The second set, consisting of one QuickBird image taken in 2004 (February), was employed for verifying the Landsat-based classification. The Landsat images were L1G geometrically corrected product. Additional pre-processing included one-step radiometric correction with the latest calibration coefficients (Chander et al., 2009) and atmospheric corrections using the dark-object subtraction method (Chavez, 1996; Song et al., 2001).

Table 1
Characteristics of Landsat and QuickBird multi-spectral sensors. NIR stands for near-infrared, SWIR for short-wave infrared, and x2 indicates two sensors of the same spectral region on the same spacecraft.

Bands	Spatial resolution	Date	Satellite system
4 (green, red, NIRx2,)	80 m	February 28, 1976	Landsat-2 MSS
6 (blue, green, red, NIR, SWIRx2)	30 m	February 3, 1985	Landsat-5 TM
6 (blue, green, red, NIR, SWIRx2)	30 m	March 17, 2003	Landsat-7 ETM+
4 (blue, green, red, NIR)	2.4 m	December 4, 2004	QuickBird

A high-resolution QuickBird image of 2004 that covered 2×2 km^2 of the study area, 15 km north-east from Kita, was used for the visual classification of lands that it covers into three types, two of agricultural area – cultivated fields and visible fallow fields, and the rest of the area. It is important to note that fallow area can be visually recognized on the Landsat images during few first years only, until it is fully covered by savannah vegetation. We do not have data for estimating the period of time during which the fallow fields can be distinguished from the savannah. Ignoring 1-year difference between the Landsat-7 and QuickBird images, signatures of the agricultural and non-agricultural areas were established based on the part of the Landsat ETM + image of 2003 that is covered by the QuickBird image. Based on the obtained signatures, maximum likelihood classification was performed for separating agricultural (cultivated and fallow together) and non-agricultural areas over the entire Landsat ETM + image of 2003 and for the Landsat images of 1976 and 1985.

In order to distinguish between cultivated and fallow areas, we employed the Normalized Difference Vegetation Index (NDVI) (Tucker, 1979):

$$\text{NDVI} = (\rho_{\text{NIR}} - \rho_{\text{red}})/(\rho_{\text{NIR}} + \rho_{\text{red}}) \quad (1)$$

where ρ is the reflectance value in the respective spectral region. The values of NDVI vary between -1 and $+1$. Generally, negative NDVI values characterize water, NDVI values of less than 0.15 characterize bare soil, and values greater than 0.16 represent vegetation, depending on its density (Jackson and Huete, 1991).

To differentiate between cultivated and fallow fields in the Landsat images, we started with the part of the ETM + image that is covered by the QuickBird image in which cultivated and fallow areas were visually recognized. In the ETM + image, the areas that were cultivated during the most recent year appear as bare soil. The maximal NDVI value for this area was 0.176; thus, we accepted this value as a threshold for the areas that had recently been harvested. The fallow fields in the same image that are covered by vegetation have NDVI values above 0.176.

Before applying this value for separating between cultivated and fallow areas of the entire 2003 and of the 1976 and 1985 Landsat images, it is important to note that different sensors are sensitive to different wavelengths, and thus, the systematic bias of the NDVI values derived from the Landsat images of different years has to be corrected. According to the calibration study of Steven et al. (2003), the NDVI from the Landsat sensors employed in 1976 (MSS), 1985 (TM) and 2003 (ETM+) can be standardized as follows:

$$NDVI_{MSS} = 0.924*NDVI_{ETM+} + 0.025 \quad (2)$$

$$NDVI_{TM} = 0.979*NDVI_{ETM+} + 0.002 \quad (3)$$

Applying this correction to the NDVI threshold value established for the ETM + images, we obtained the NDVI thresholds for distinguishing between cultivated and fallow fields: in 1976 – 0.187 and 1985 – 0.174; we then constructed maps depicting three land uses: cultivated, visible fallow and the rest of the area for 1976, 1985 and 2003 (Fig. 2).

Comparison between the areas classified as agricultural (cultivated or fallow) in 1976, 1985 and 2003 reveals that some of the areas classified as agricultural in 1976 were abandoned in 1985 and some of the areas classified as agricultural in 1976 and 1985 were abandoned in 2003 (Fig. 3). To remind, we hypothesize that some areas classified as abandoned in 1985 and 2003 were actually areas left for fallow for the long period of time. That is, some of the abandoned areas may be, actually, areas of fallow. Note also that abandoned agricultural fields can be identified in the Landsat images of 1985 and 2003 only.

Combining information obtained from three available Landsat images, a 30 × 30 area (represented by the pixel of the Landsat image) is considered as suitable for agriculture if it was classified as a fallow or cultivated area in at least one of these maps The total size of land suitable for agriculture in the Kita area is 25,462 ha, which is 32.8% of the total research area of 78,400 ha.

Fig. 4 shows the dynamics of the cultivated, cultivated plus visible fallow, and cultivated plus visible fallow plus recognized abandoned area in each of the years 1976, 1985 and 2003 from the start of research period in the study area of Kita.

Following Prudencio (1993), we assume that the farmers prefer to exploit the land closest to the settlement areas. To verify this assumption we considered separately the lands in three rings circling a settlement – at distances of up to 1 km, between 1 and 2 km, and between 2 and 3 km (Fig. 5).

The area suitable for agriculture within each of rings, estimated in the same way as it was done for the entire area is 6404 ha for Ring 1, 8582 ha for Ring 2, and 6199 ha for Ring 3. Fig. 6 shows the dynamics of the cultivated area from the start of research period in the study area of Kita by 1-km rings. The area that is suitable for cultivation at a distance of more than 3 km from the settlement is 4277 ha – 16.8% of the total area suitable for agriculture.

During the observation period, the total area that is recognized as used for agriculture tripled, from 8673 ha in 1976–25,462 ha in 2003, while cultivated area grow between 1976 and 1985 and then remain at the same level (Fig. 4). Considering the rings (Fig. 6), during the period 1976–1985 the cultivated area in the middle and outer rings expanded by 6.9% and 11.4% respectively, while in the inner ring, it decreased by 4.8%. Between 1985 and 2003, the cultivated area expanded in the outer ring only, by 2.4%, while within the inner and middle rings, the cultivated area decreased by 3.06% and 1.3%, respectively. This expansion of agriculture further away from settlements is a strong sign of land over-exploitation and a loss of fertility in the nearby lands.

Interpretation of two important non-agriculture land uses – settlements and roads can be also validated versus available GIS layer of roads and settlements both dates to the year 2000. Comparing between the GIS layers and the Landsat images, we succeeded in recognizing 33 of 56 settlements presented at the 2000 layer of settlements in the Landsat image of 1976 and all of them in the Landsat image of 2003. The 33 settlements that existed in the year 1976 will serve us below for establishing initial conditions for the simulation model. The resolution of the Landsat images was insufficient to recognize which of the roads of the GIS

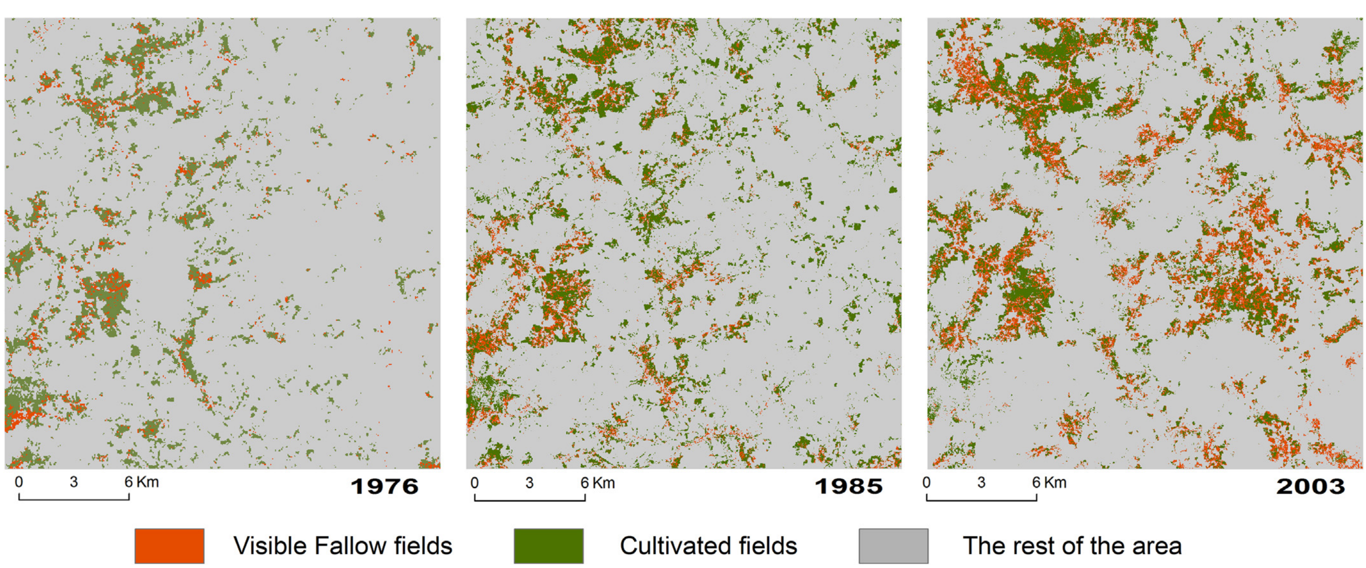

Fig. 2. Classified land-use maps of the study site in Kita region, by years.

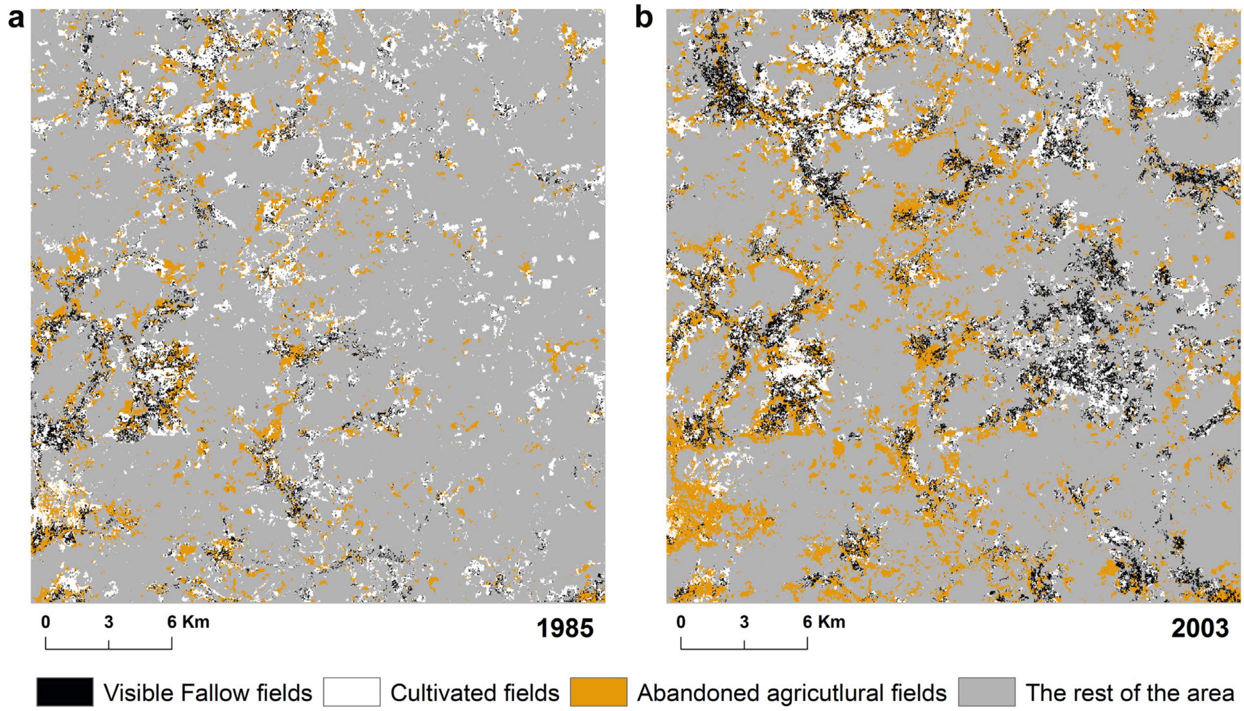

Fig. 3. 2003 Maps of agricultural lands in 1985 (a) and 2003 (b) in the research area of the Kita region.

layer of 2000 were present in 1985 and 1976. We thus employ the entire layer in the model.

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

ALADYN, a spatially explicit AB model (Benenson, Torrens, 2004; Berger, 2001; Berger et al., 2006; Bishop et al., 2009; Grimm and Railsback, 2012), simulates agricultural land dynamics as an outcome of farmers' decisions regarding land use and crop choice. The model was developed within the NetLogo modeling environment (Wilensky, 1999).

4.1. *ALADYN Overview*

The ALADYN model is based on field data collected in the Kita area in 2003 and 2005 (Kidron et al., 2010). The Kita area (28 × 28 km) is represented in the model by a 30 × 30 m grid. Each grid cell is described by its land use. The model accounts for six types of land use that were recognized on the Landsat images and available GIS layers of the roads and settlements. Three of the lad use types are non-agricultural (settlements, roads, and lands unsuitable for agriculture), and three suitable for agriculture (virgin areas that are suitable for agriculture, cultivated fields and fallow fields).

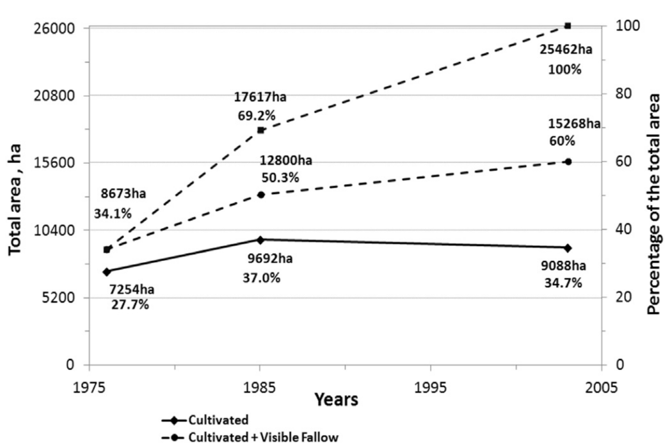

Fig. 4. Dynamics of cultivated, cultivated plus visible fallow, and cultivated plus visible fallow plus recognized abandoned areas in the research area of the Kita region during 1976–2003, in hectares, and as a percentage of the total agricultural area (25,462 ha).

A settlement's population consists of farmers and grows at a rate defined by the model scenario. Each farmer is considered separately in the model. Agricultural areas are considered at resolution of a single field. In the model, we assume that the fields of each farmer extend as far as 3 km from the settlement. If the population exceeds the settlement's capacity for agriculture within the 3 km distance from the settlement, new farmers migrate to the other settlements. If all settlements are full, new farmers can establish a new settlement at a point located 3 km or more away from all of the existing settlements. The fertility of the agricultural lands is characterized in the model by the amount of SOM that changes in time depending on the history of area's cultivation.

4.2. *ALADYN model objects*

In the ALADYN model we introduce three types of objects: settlements, agriculture fields, and farmers. Farmers are the only ALADYN objects that make decision and, according following the ideas the agent-based modeling (Benenson, Torrens, 2004; Grimm and Railsback, 2012), we call them *agents*.

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

Farm fields are spatially continuous sets of land cells, each with a total area of ca 1 ha (11 or 12 Landsat 30 × 30 m pixels), characterized by the distance to the nearest settlement and the amount of SOM. Fields can be of different shape – in this way, the area suitable for agriculture can be fully partitioned into fields. The shape of the field does not change after the field is established.

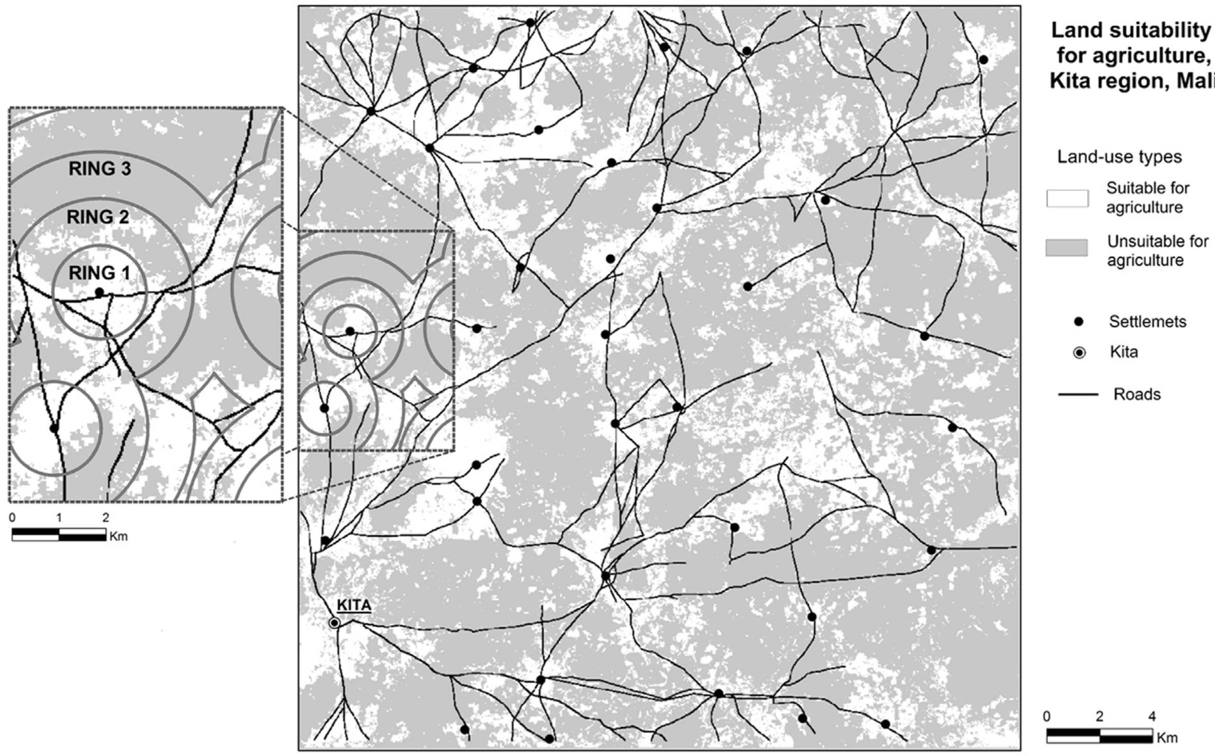

Fig. 5. Lands recognized as suitable for agriculture in the Kita area in at least one of the Landsat images, overlapped with layers of settlements and roads. In the inset, three 1-km rings are shown.

Each model farmer possesses two fields that are cultivated with cotton or another 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. The dynamics of the SOM in the field's soil during the periods of cultivation and fallow follows Kidron et al. (2010) (see below).

4.3. ALADYN structure

The ALADYN model consists of four main modules: Initialization, Agriculture, Prognosis and Demography (Fig. 7). After the Initialization is performed, the major loop of Agriculture, Prognosis and Demography modules is repeated in time, until the end of the modeled period (60 years in this paper). The model's time step is one year.

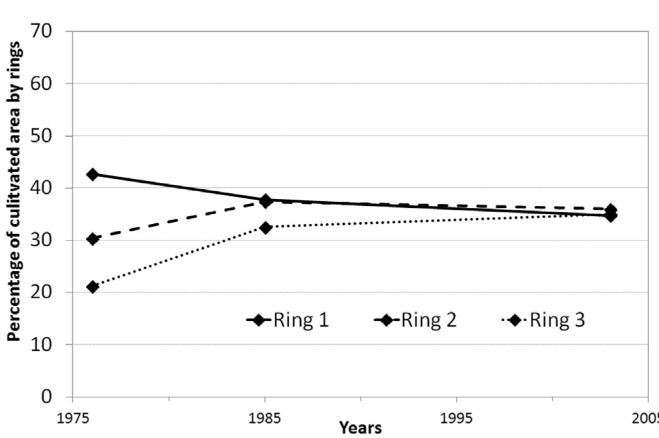

Fig. 6. Dynamics of cultivated part of the study Kita area during 1976–2003, by rings of 1 km width around the settlements, as a percentage of the total agriculture area within the ring.

4.3.1. Initialization module

Model initialization is based on additional analysis of the Landsat image from 1976 and the GIS layers of roads and settlements. All settlements and roads of the GIS layers are recognized at the 1976 Landsat image and, thus, model settlements are established at the locations of the actual settlements in the research (Fig. 3). The model settlements are populated by farmers and the initial number of farmers in a settlement is established as 70% of their number in 2003 that is provided by Kidron et al. (2010). This estimate is based on the Landsat image of 1976, according to which about 70% of the 2003 agricultural area was cultivated in 1976. As already mentioned above, each farmer in the model possesses two fields, each of an area close to 1 ha in size, within a distance of 3 km from the settlement. According to the 1976 Landsat image, the fraction of the fallow area was about 20% of the cultivated area. Based on this, we assumed that 20% of the farmers' population in 1976 cultivated one field and possessed a fallow field. For the rest of the farmers, we assumed that their second field in 1976 was virgin and not yet involved in cultivation.

As we do not possess data on the start of the last cultivation or fallow period at a field resolution, we assume that the distribution of these start years is uniform and the length of the cultivation period before 1976 was not longer than 12 years, while the length of the fallow period not longer than 18 years. To simulate the uniform distribution, each cultivated field was randomly assigned the number of years from the start of the period of cultivation, between 0 and 11, and each fallow field was randomly assigned the number of years from the start of the fallow period, between 0 and 17. The

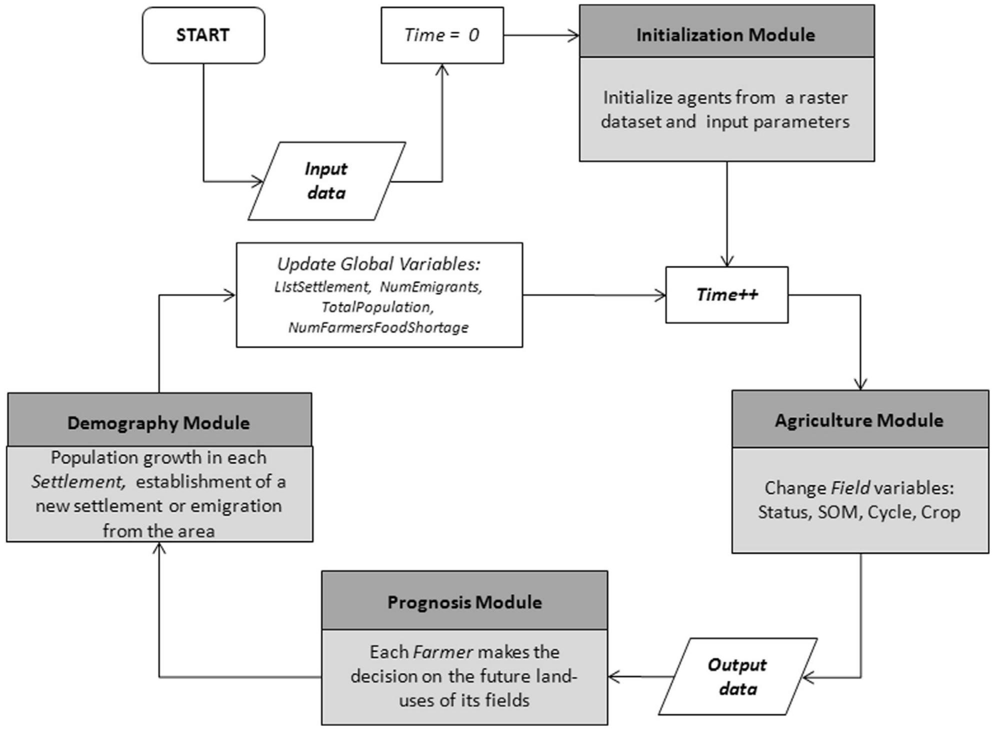

Fig. 7. Basic modules and processes of the ALADYN model.

initial amount of SOM in each of the cultivated and fallow fields depended on the year within its cultivation cycle or fallow period. We assumed that the amount of SOM at the beginning of the cultivation period was the maximally possible 43 t/ha, while the amount of SOM in the fallow field at the beginning of the fallow period was 18 t/ha (Kidron et al., 2010). We then applied formulas (4)–(6) of the Agriculture module below with respect to the initially assigned year of cultivation or fallow.

4.3.2. Agriculture module

The model simulates cotton and cereal production, by fields. The fields' status (cultivated/non-cultivated) and the amount of SOM in the soil of the model field are updated every year during the years of cultivation, with respect to the crop choice of the model farmer. Based on Kidron et al. (2010), the decrease of SOM during the cultivation of the model field and its increase during the fallow years, are described by linear equations:

SOM decline during a year of cotton cultivation

$$SOM_{T+1}(t/ha) = SOM_T(t/ha) - 2.38 \quad (4)$$

SOM decline during a year of non-cotton crop cultivation

$$SOM_{T+1}(t/ha) = SOM_T(t/ha) - 1.19 \quad (5)$$

SOM restoration during a fallow year

$$SOM_{T+1}(t/ha) = SOM_T(t/ha) + 0.963 \quad (6)$$

where T denotes time in years.

4.3.3. Prognosis module

Based on the amount of SOM in the soil after the harvest (Equation (4) or 5, depending on the current crop), the farmer decides whether the field will be cultivated next year. As mentioned above, we follow here Kidron et al. (2010): if the amount of SOM in the soil drops below 18 t/ha, the farmer leaves the model field for fallow. If the amount of SOM in the field is above 18 t/ha, the farmer decides on the future crop. If the field is fallow, the amount of SOM in the soil is restored according to Equation (6). The fallow model field can be exploited again once the SOM exceeds 25 t/ha.

4.3.4. Demography module

The rate of a settlement's population growth depends on the model scenario. While the current annual population growth rate in Mali is about 3% (Benjaminsen, 2001; FAO, 2010), the UN prognosis is that in 3–5 generations, the growth rate in developing countries, like Mali, will decrease to 1% (Zougmoré et al., 2002). Based on these estimates, we considered below two scenarios – a constant 3% annual growth rate, and a growth rate that linearly declines over 60 years at a rate of 3%–1% per year.

Over the course of time, the population of a model settlement may exceed its capacity. In this case, new model farmers attempt to migrate to another existing settlement. If all existing settlements are full, new farmers attempt to establish a new settlement. According to a visual inspection of the QuickBird image, the minimal number of households in Kita's settlements is six. We thus assumed that a new settlement can be established if the area within a distance of 3 km around suffices for at least six farmers.

A new settlement should satisfy the following conditions: (1) be located at a distance of more than 3 km from any existing settlements; (2) be adjacent to the existing road; (3) contain 12 ha of the virgin lands (i.e., be sufficient for six farmer families at least) within a distance of 3 km from it. To establish the new settlement, the 3-km buffers are constructed around the existing settlements and then erased from the modeled area. Then, a size of a virgin area within the 3-km buffer of every 30 × 30 cell is estimated. The cell for which this area is the largest (and higher than 12 ha) is chosen to establish a new settlement. Each farmer residing in the new settlement is assigned two 1 ha fields, adjacent to each other, within the 3-km distance from the settlement, as close as possible to it.

When all the available agriculture land is occupied, and a new settlement cannot be established, new farmers emigrate out of the system.

We considered land-use dynamics at an annual resolution and investigated scenarios for a 60-year period from 1975 to 2035. ALADYN model parameters are represented in Table 2.

Model GUI is presented in Fig. 8.

The map at the right presents non-agriculture, cultivated and fallow lands with the roads and settlements overlapped. Model parameters presented in Table 2 and parameters of the formulas (4)–(6) are presented in the text boxes at the right and can be changed by the user. The model dynamics is calculated for the period of 60 years, starting from 1975 and up to 2035. Model scenarios differ in the rate of population growth during this period.

In the following, we employ ALADYN to investigate the dynamics of agricultural land use in Kita under two different scenarios of population growth.

5. Analysis of ALADYN results

5.1. Basic scenario of agricultural land-use dynamics in Kita

The basic ALADYN scenario employs the parameters presented in Table 2 and, according to (Benjaminsen, 2001; FAO, 2010) assumes a constant 3% rate of population growth. Fig. 9 presents the model dynamics of the cultivated and agricultural (cultivated plus fallow) areas over the entire Kita area as percentages of the total agricultural area, together with the experimental data that were already presented in Fig. 4. The cultivated area reached its maximum towards 2010 and then slightly declined. Beginning then, more than half of the exploited agricultural land has been left fallow. The number of settlements grew, between 1976 and 2003, from 36 to 53, according to the ALADYN simulations. As mentioned above, the number of settlements in 2003 is 56.

As can be seen in Fig. 9, the model prediction and the Landsat-based estimate of the total cultivated area are very close in 1985, but essentially diverge in 2003. The percentage of the cultivated area according to the 2003 Landsat image is 34.7% while according to the model projection this percentage is 46.9%.

We consider estimates of the cultivated areas as most reliable and compare, by rings, model projections and Landsat estimates for the cultivated areas only. Fig. 10 present model dynamics of the cultivated lands at different distances from a settlement, together with the Landsat-based estimates that were already presented in Fig. 6.

Considered by rings (Fig. 10), model predictions and Landsat estimates are qualitatively similar in respect to the Rings 2 and 3 – both in the model and in reality the fractions of the cultivated lands in these rings increase between 1976 and 1985. The model percentages reach, in 1985, the values of ca. 42% in both Ring 2 and Ring 3, while the fractions estimated by the Landsat imaginary remain at the level of 36%. The model repeats Landsat estimate in regards to the Ring 3, where the percentage of the cultivated area is low (ca 20% in the model and ca 10% according to the Landsat estimates) in 1976 and increases to ca 32% in 1985. The percentages of the cultivated area continue to grow, slowly, between 1985 and 2003 and reach in 2003 the level close to 50% in both Ring 2 and Ring 3, while the Landsat-based fractions remain as it was in 1985 and even slightly declines. The model dynamics of the cultivated lands within the Ring 1 differ, however, from the dynamics of the Landsat estimates. Model percentage of cultivated lands within the Ring 1 remains at a level of 42–43% between 1976 and 1985 and then grows to 49% towards 2003, while the Landsat estimates decline between 1976 and 1985 and then remain at the level of 35%, just as the percentage of the cultivated lands within the two other rings.

Agent-based model considered every farmer separately. This makes possible to present dynamics of SOM in two farmer's fields. Fig. 11a presents the dynamics of SOM in the fields of a typical farmer that starts in 1975 with one cultivated and one virgin field. It takes between 30 and 40 years of cultivation to fully exploit the initial amount of the SOM in a virgin field. During this period each of two farmer's fields will be cultivated twice and twice left for the fallow. Only then, about 2010, the SOM dynamics reaches the stabile regime and varies between 15 and 25 t/ha. This stable regime is characterized by a short 1–3 year length period of infertility of both fields that occurs each 10–12 years.

The aggregate dynamics of the percentage of farmers over the entire study area whose both fields are infertile due to soil degradation are presented, for the basic scenario, in Fig. 11b. As can be seen, this percentage remains low until the year of 2010, but increases to the level of 20–25% towards the period of 2025–2035.

5.2. Sensitivity to the population growth rate

As mentioned above, the current annual population growth rate in Mali is about 3% (Benjaminsen, 2001; FAO, 2010), while according to the UN prognosis, in 3–5 generations, the growth rate in developing countries, such as Mali, will decrease to 1% (Zougmoré et al., 2002). We thus compare the basic scenario with the scenario, in which the population growth rate decreases linearly, from 3% to 1%, during 2010–2035 (0.0333% decrease per year).

Fig. 12 presents overall land-use dynamics in Kita for these two scenarios, and as can be seen, the differences between the scenarios' outcomes are insignificant. That is, the capacity of the study area in the Kita region is already essentially exploited and the fraction of the population of farmers that should emigrate from the area will remain very high even in case of essential reduction in the population growth rate.

The model dynamics of the fraction of cultivated and fallow areas, and cultivated and fallow areas within each of the three 1 km rings around the settlements, and of the fraction of the farmers who are not able to cultivate their lands are also very close in the two scenarios.

Table 2
Parameters of the ALADYN model.

Default value	Parameter
3 yr	Length of cultivation cycle
43 t/ha	Amount of SOM in a virgin field
25 t/ha	Cultivation starts when SOM is above this level
18 t/ha	Cultivation stops when SOM is below this level
2 ha	Overall area of each farmer's fields
70%	Population of each of the existing settlements in 1976 (as a percentage of the settlement's capacity in 2003)
20%	Fraction of farmers that have a fallow second field in 1976. The rest of farmers have a virgin second field.

6. Discussion

Agriculture in sub-Sahara Africa remains the main engine for economic growth (Benjaminsen, 2002). High rates of soil degradation may therefore cause high risk to the farmer's wellbeing. Soil degradation in West Africa is a known phenomenon, resulting in a substantial decrease of crop yield per hectare in the second half of the 20th century (Bationo and Mokwunye, 1991). In Niger for instance, sorghum and pearl millet yields per hectare decreased by

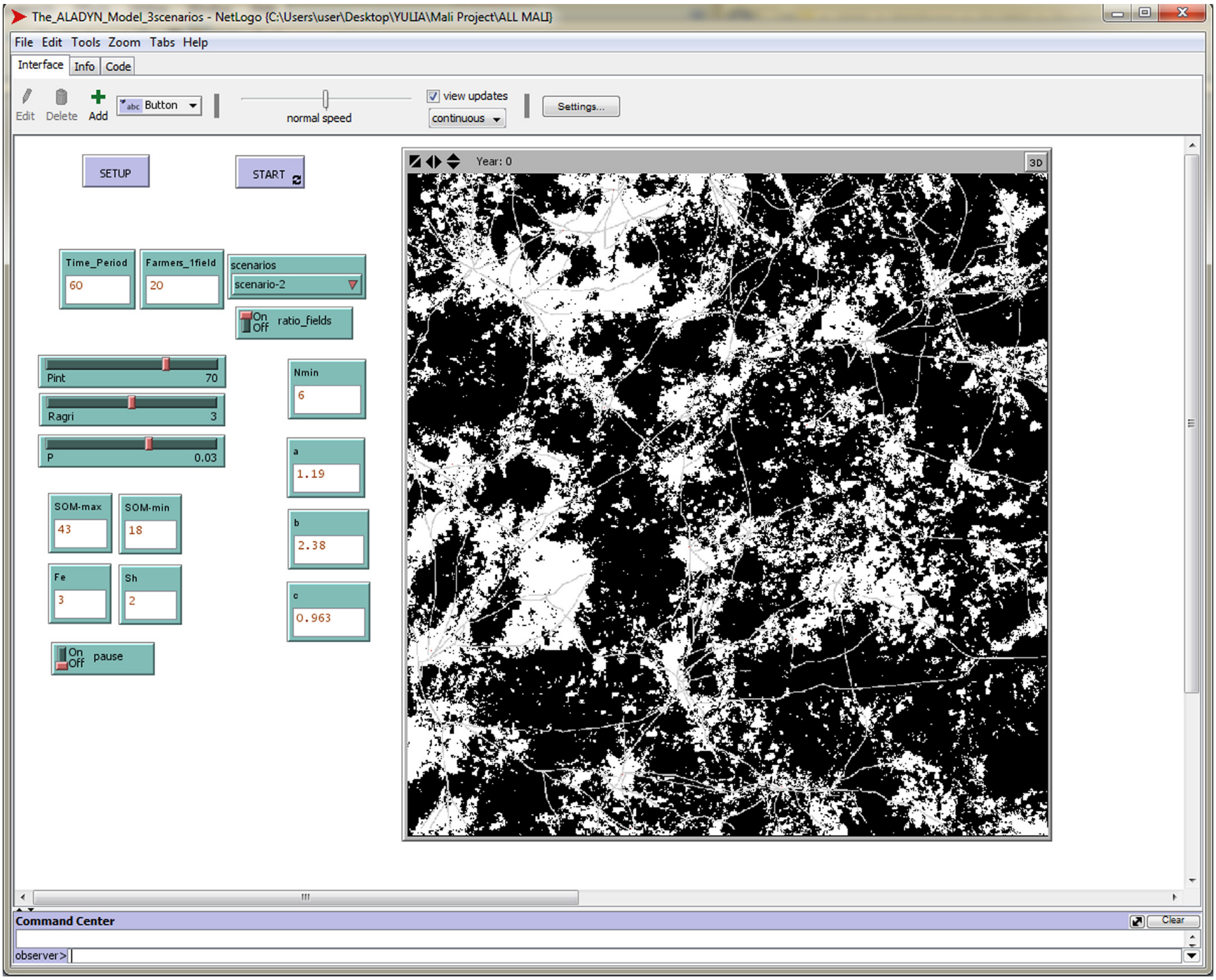

Fig. 8. Interface of ALADYN model.

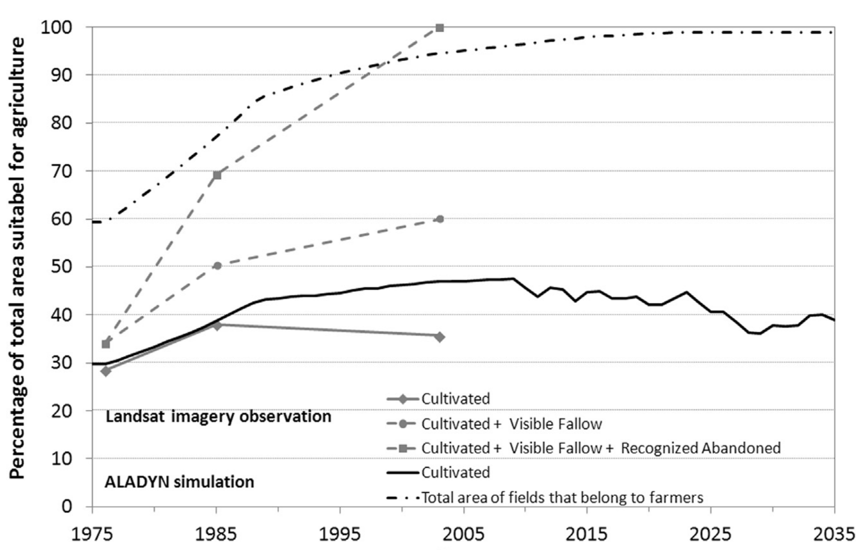

Fig. 9. ALADYN dynamics of cultivated areas and areas in farmers' possession in the study area of Kita region during 1975–2035, for basic scenario of 3% rate of population growth, as percentages of total agricultural area, with the experimental data superimposed.

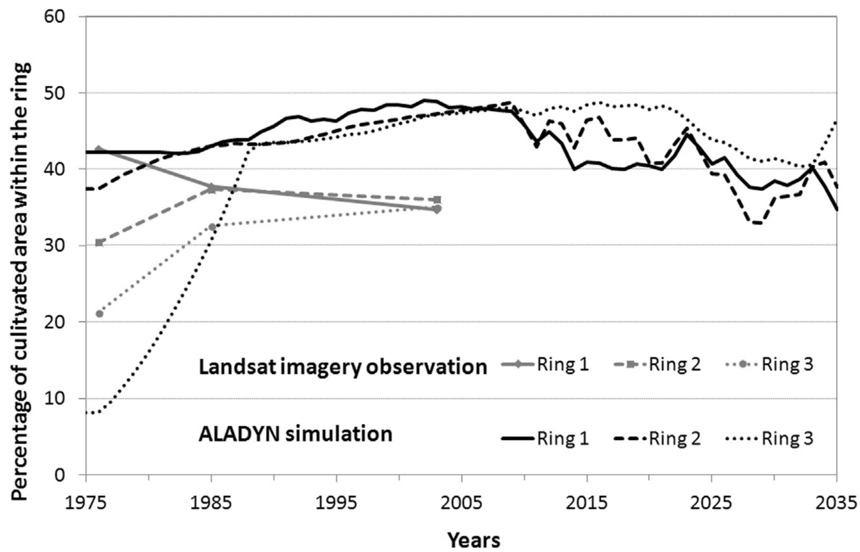

Fig. 10. ALADYN dynamics for the basic scenario of 3% rate of population growth versus the Landsat data: the cultivated area within the ring as a percentage of total agricultural area within ring, by three 1 km rings.

62% and 12% from 1960 to 1999 (Pandey et al., 2002). According to Benjaminsen et al. (2010; Fig. 4), cotton yield per hectare dropped from ~550 kg/ha in the beginning of the 1990s to ~300 kg/ha during 2005–2007. At the same time, all researchers have reported a sharp increase in the area of cultivated land over recent decades. According to Fox and Rockström (2003), only 40% of available land was cultivated in the Yetenga region of northern Burkina Faso in 1973, while by 1996, it had reached 80%. A sharp increase in the total area of cultivated cotton fields from the 1980s to ~2005 is also shown by Benjaminsen et al. (2010).

A high rate of population growth is the main reason for the sharp increase in area of cultivated land in West Africa (Drechsel et al., 2001a,b). With high population growth rates, soil degradation will result in food shortage which may lead to emigration and social unrest (Henry et al., 2003). However, country-specific factors may also contribute to this phenomenon. The 1982 decision of the Malian government to stop subsidizing chemical fertilizers caused a sharp decrease in their use. Farmers consequently preferred to clear virgin soil for cultivation, which in turn substantially increased the cultivated area (Kouyaté et al., 2000; Pol and Traore, 1993). Additionally, the use of marginal fields (Bationo and Mokwunye, 1991) further enforced increasing soil degradation (Reenberg et al., 1998). Different form Benjaminsen et al. (2010) who attribute the decline in cotton yield solely to the use of marginal soils, our research confirms that this decline is, mainly, the result of the overexploitation of soils (Drechsel et al., 2001a,b; Kidron et al., 2010; Sanchez, 2002). Lack of available agricultural lands resulted in an increase in the cultivation period of fields and a reduction in the fallow period (Chappell et al., 1998; Kouyaté et al., 2000). Researchers also agree that the current practice of agriculture and the high level of soil degradation do not allow for decreasing the size of the field or the duration of the fallow period. This, in turn, limits the options for new farmers.

Taking the Kita area as an example, we explored the dynamics of agricultural land use with the ALADYN model. In agreement with other publications that regard SOM as a key proxy for soil degradation (Bationo et al., 1998; Oenema et al., 2006; Zougmoré et al., 2002), our model was based on SOM decay during field cultivation and restoration during fallow periods. The amount of available land in the Kita area was estimated based on satellite data (from 1976, 1985 and 2003), which show a steady increase in the area of agricultural land from 1976 to 2003, in agreement with reports from other regions in Africa (Fox and Rockström, 2003). This outcome is in agreement with the FAO (2010) report, which states that agricultural areas have expanded since the 1990s while cotton yields have declined. Assuming that the current agricultural practice will continue, ALADYN predicts a substantial increase in fallow areas and a reduction in cultivated areas in the Kita area, no matter if the population growth rate remains at a current level or decreases in accordance with the UN forecast. This is in agreement with

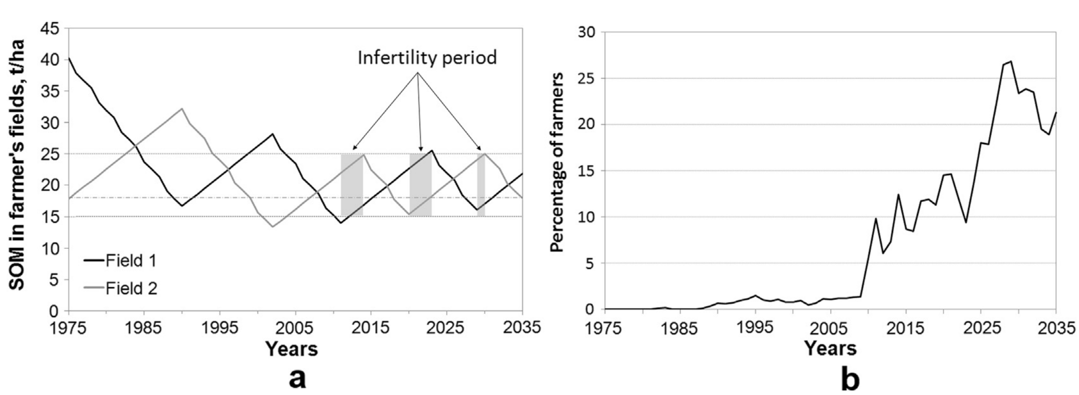

Fig. 11. Amount of SOM in one farmer's fields (a); ALADYN dynamics of the percentage of farmers who cannot cultivate their field due to the soil degradation in the study area of the Kita region for basic scenario of 3% rate of population growth (b).

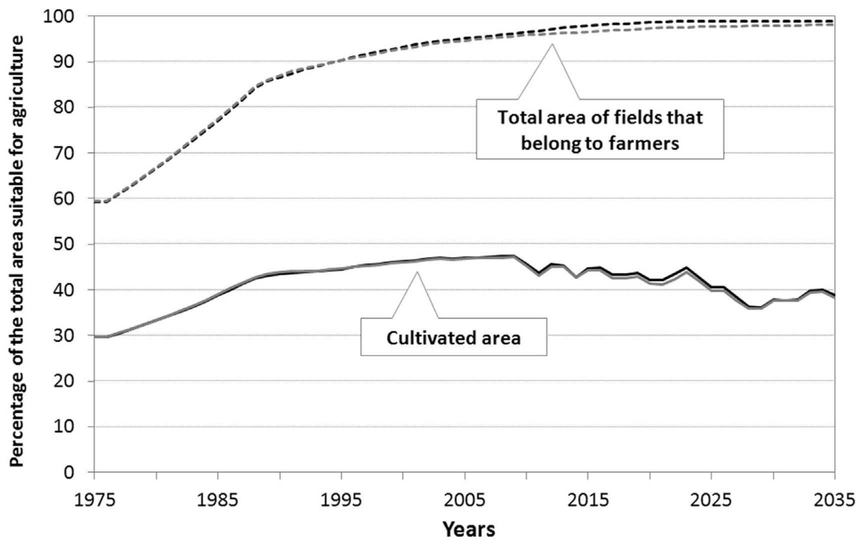

Fig. 12. ALADYN dynamics of the agricultural and cultivated areas in Kita during 1975–2035 as percentages of the total agricultural area, for two scenarios of population growth rate: 3% (black line) and 3–1% (gray line).

reports from other regions in Africa (Fox and Rockström, 2003). In all model scenarios, the system will reach a steady level of production towards 2015, when ca 45% of available agricultural land is cultivated. The closer the cultivated areas to the settlement the faster they reach low level of productivity. In agreement with other reports (Niemeijer and Mazzucato, 2002; Prudenolo, 1993), the model highlights that the boundary of low productivity moves further away from the settlement.

When all agricultural lands that are available to the settlements' farmers reach the state of stable dynamics (in the model, about the year of 2005), each household once every 10–12 years, will experience a 1–3 year period when all its fields are non-productive. A decrease in the rate of population growth does not influence this result – both the area of cultivated land and the subsequent agricultural production will remain at the same level as obtained in the model for a constant 3% population growth rate. As a result, the percentage of farmers not able to cultivate their fields every year will remain about 20%, beginning in 2025. This outcome implies an extra burden on the economic wellbeing of the household and highlights future food insecurity.

The ALADYN model properly predicts the increase in the total area of agriculture land but essentially overestimates the area of the lands that are cultivated in 2003. That is, if the rate of population growth of the population that is involved in the agriculture activities in the study area during 1975–2003 was 3%, as high as it is estimated for that period for the entire country, then the cultivated area in 2003 should be essentially larger than it is in reality. We thus believe that the agriculture population in Kita area *anticipates* future overexploitation and starting after 1985 essential part of the new population does not join agriculture activities. We do not possess population data that are sufficient to verify this hypothesis.

To conclude, in agreement with previous reports (Shapiro and Sanders, 1998), our simulations indicate that current agricultural practices in Mali will not suffice to sustain the population growth. With the Kita area taken as a model for other areas in West Africa, our model highlights the great risk that stems from the high rate of soil degradation. With increasing population pressure, the time duration during which fields are left fallow is shortened. More and more virgin soils and marginal soils are cultivated and more settlements are established. The adoption of new methods of intensive cultivation that, also, preserve soil fertility is called for.

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