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A system dynamics approach to land use changes in agro-pastoral systems on the desert margins of Sahel

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ABSTRACT

Land use changes in the Sahel are influenced by multiple socio-economic and bio-physical driving forces that result in a complex and dynamic land use system. This paper outlines to what extent a system dynamics approach may serve to nuance the understanding of Sahelian agro-pastoral systems. Firstly, by using the Sahelian part of Northern Burkina Faso as a case study, we build a simple model that includes the most influential drivers of land use changes and their impacts in the land use system. As the developed model is proven to successfully simulate the main directions of change in the land use system, we employ the model to explore the impacts of important and realistic alterations in those factors driving land use change. This is done by generating 'what if' scenarios. The results show that 'what if' scenarios based on sudden events, such as a drop in millet prices or a total stop in circular migration, have a more pronounced impact on the system than other more long term alterations such as increased rainfall variability. As the developed model allows testing simple hypotheses about the dynamics of land use systems, the approach serves as a useful complementary tool to more established approaches in advancing land change science.

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1. Introduction, background and objectives

Insight into the generic nature of land change processes in the Sahel has been difficult to establish as land use changes are poorly documented and their causes are not fully understood (Reynolds et al., 2007; Lambin et al., 2003; Geist and Lambin, 2004). Much explorative research has focussed on single-factor causation and various primary causes have been suggested such as population pressure (Boserup, 1965; Malthus, 1970) and climate variability (Olsson et al., 2005). More recently, empirical studies of land use changes have documented the co-existence of a broad range of driving forces (Brooks et al., 2005; Brooks, 2006; Desanker and Magadza, 2001; Hesse and Cotula, 2006; Kandji et al., 2006; Liechenko and O'Brian, 2010; Reenberg, 2009; Liu et al., 2007; Dietz et al., 2004) and attributed land use changes to complex interactions between multiple causes. Although land use changes are increasingly recognized as resulting from a multitude of feedback mechanisms involving various socio-economic and bio-physical components, an explicit inclusion of these non-linear feedback mechanisms remains one of the major challenges in land use system analysis (Turner et al., 2007; Verburg, 2006).

The challenge in dealing with complex systems, such as Sahelian land use systems, stems from the fact that typically the cause and effects may be separated across different spatial and temporal scales (Guneralp and Seto, 2008). Often the complexities of the systems are beyond the grasp of our mental models. Hence, integrative and quantitative approaches that take a systems-oriented stance are suggested as a means of untangling these complexities of the biophysical and socio-economic systems (Dougill et al., 2010; Forrester, 2007; Sterman, 2002; Guneralp and Seto, 2008; Saqalli et al., 2011). A system dynamics approach may thus serve as a tool to enhance the understanding of complex system interactions. System dynamics places special emphasis on explicit representation and simulation of non-linear feedback mechanisms when addressing complex problems (Richardson, 1999). Hence, it may be a valuable approach that allows us to explore how the systems work, and more critically, to assess the sensitivity and vulnerability of the systems.

A limited number of dynamic models have been developed for simulating land use changes in the Sahel (Bah et al., 2010, 2006; Stephenne and Lambin, 2001; Picardi, 1976). The models range in scale from the Sudano-Sahelian region (Picardi's models and the SALU model developed by Stephenne and Lambin) to land use around a deep well in Senegal (Bah's model). Picardi's system dynamics model describes the self amplifying cycle of deterioration of rangelands, whilst the SALU model simulates rates of land use changes in five different land cover types. The model developed by Bah et al. is an agent-based model dealing with factors driving land use change around a deep well. These models rely heavily on dominant narratives of the functioning and direction

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of change in Sahelian land use system, assuming a vicious circle of land degradation and field expansion prompted by population pressure and low rainfall. This may not suffice to capture more recently acknowledged features of complex dynamics in the land use systems, such as impacts of climate variability and price fluctuations (Reenberg, 2009; Nielsen and Reenberg, 2010; Batterbury and Warren, 2001). With this background, the main objective of the paper is to explore what a system dynamics approach can reveal further about these recently acknowledged features that influence the dynamics in Sahelian agro-pastoral systems. Firstly, a system dynamics model of the Sahelian agro-pastoral land use systems is constructed. Secondly, the potential use of the model is demonstrated with a case study in Northern Burkina Faso. Thirdly, the developed model is employed to explore the behaviour of the system under a variety of conditions. This is done by generating 'what if' scenarios that captures important and realistic alterations that may be expected to affect human-environmental interactions in the Sahelian land use system, such as changes in agricultural commodity prices, migration or rainfall variability.

2. Materials and methods

2.1. Case study: the Sahel region, Northern Burkina Faso

Of the 13 regions in Burkina Faso, we target our analysis to the most northern, the Sahel region. The Sahel region in Burkina Faso is part of the Sahelian zone south of the Sahara desert extending more than 2000 km from Senegal through Mali, Burkina Faso, Niger and Chad.

In Northern Burkina Faso, agricultural and pastoral production are the main sources of sustenance for the population and the land use system can briefly be characterized as a combination of cultivated fields and pastures. The livelihood conditions are thus strongly linked to the ability of the natural resources to support human population and livestock (Reenberg, 2009). Cropping activities and pastoralism are traditionally integrated, the most important links being income, feed and manure. The use of livestock manure enhances soil fertility, and crop residues provide feed for livestock during the dry season (Powell et al., 1995). Trees, notably *Faidherbia albida*, contribute to soil fertility by nitrogen fixation and provide extra fodder for livestock in the dry season (Reij et al., 2009). Manure may be obtained either from farmers own herds, from the livestock of other farmers or through exchange relationships with transhumance pastoralists. The main crops are pearl millet and sorghum, whilst cowpeas, groundnuts, and cotton are grown to a lesser extent. Furthermore vegetables and rice are grown where irrigation is feasible.

The use of land is influenced by a wide range of driving forces operating at different spatial scales, with population pressure and high annual as well as decadal variability in precipitation being known as two of the main challenges for local livelihoods (Dietz et al., 2004). Generally, it applies for the Sahelian zone that under conditions of increased demographic pressure, farmers face a reality of increased demand for staple food. The potential response options can largely be divided into two: Either on-farm responses aiming at increasing the crop production, or off-farm responses providing money for food purchase.

The on-farm response options include expanding the field acreage (change land use pattern) and intensifying cultivation of existing fields (change land use practice) (Reenberg and Paarup-Laursen, 1997). The changing of land use pattern is the most widespread strategy as the possibilities of intensification are very limited due to large labour inputs in application of manure and insufficient economic responses if applying mineral fertilizers. Due to these limited economic incentives for applying mineral fertilizers, a key production strategy becomes supply of manure from either local herders or herders from other villages. As fallow is not conceived as a regular element of the agricultural strategy, there is scope for soil improvement (Krogh, 1993).

The engagement in circular migration constitutes one of the most important off-farm strategies, whilst working for development projects and searching for gold are other off-farm strategies of importance. Abidjan, Côte d'Ivoire, surpassed Ghana and Saudi Arabia as the major migration destination in the 1970s and has remained so ever since, despite unrest in Côte d'Ivorie since 2002 (Reenberg, 2009; Nielsen and Reenberg, 2010). After the crop harvest in November, a large proportion of the men depart on migration to have salary work or to engage in small commerce. As they most often are away for at least 9 months, migration collides in time with the labour-intensive weeding in July and August. As well as influencing the weeding, migration may prevent villagers from participating in the key intensification strategy; application of manure, as these strategies also collide in time. The level of migration thus tends to affect the size of the cultivated area as the available agricultural labour force may be limited by migration. In cases of labour shortage villagers concentrate the weeding and application of manure in small parcels within the fields, and the remaining parts of the field are left uncultivated. In fact, migration has been identified to be the dominant demographic factor influencing land use (Lambin et al., 2001; Warren et al., 2001a). The migration level, depending on the possibilities of earning enough money in Abidjan or elsewhere to cover the food requirements, can thus be seen as a third major challenge/driving force for local livelihoods in addition to the variability in precipitation and population pressure.

Finally, changing millet and livestock prices are also known as major determinants for livelihoods. Although agricultural activities are mainly for subsistence, farmers are highly concerned with fluctuating prices as the selling and buying of millet and livestock represents an important part of the livelihood portfolio both for cultural reasons and in order to cover the food requirements, as the millet production seldom suffices. The intensity with which cash is sought is also reflected in the way local villagers cooperate with development projects in order to bring more cash flow into the system (Nielsen and Reenberg, 2010).

2.2. A system dynamics model

As our effort aims to synthesize information about the major factors driving land change processes and to analyze the dynamics over time, the conceptual model must include drivers at different spatial scales. The identification of the most influential drivers is based on two rounds of fieldwork in Northern Burkina Faso carried out in February and March 2010 and between October and December 2010 as well as a systematic screening of published case studies of land use dynamics in the Sahel. The exogenous drivers of the land use changes are suggested to be human population increase, variability in annual precipitation, opportunities to earn income in Côte d'Ivorie, which may be represented by GDP (Gross Domestic Product) and world market prices of millet and livestock. Data on these exogenous variables are available on an annual basis from the FAOStat database (Food and Agricultural Organisation, 2010) and the Meteorological Office in Ouagadougou, which provides precipitation data from a station near Gorom-Gorom. For clarity, the derived data on these exogenous variables are shown in Fig. 1.

The model is a multiperiod and regional model representing the most northern region in Burkina Faso. The model includes two land use types: Cultivated land generating food for the population and grazing areas supporting feed for livestock. The model consists of two submodels; a cultivation submodel and a pastoral submodel. Main assumptions of the overall model are presented in Table 1. The cultivation submodel simulates changes in the cultivated area,

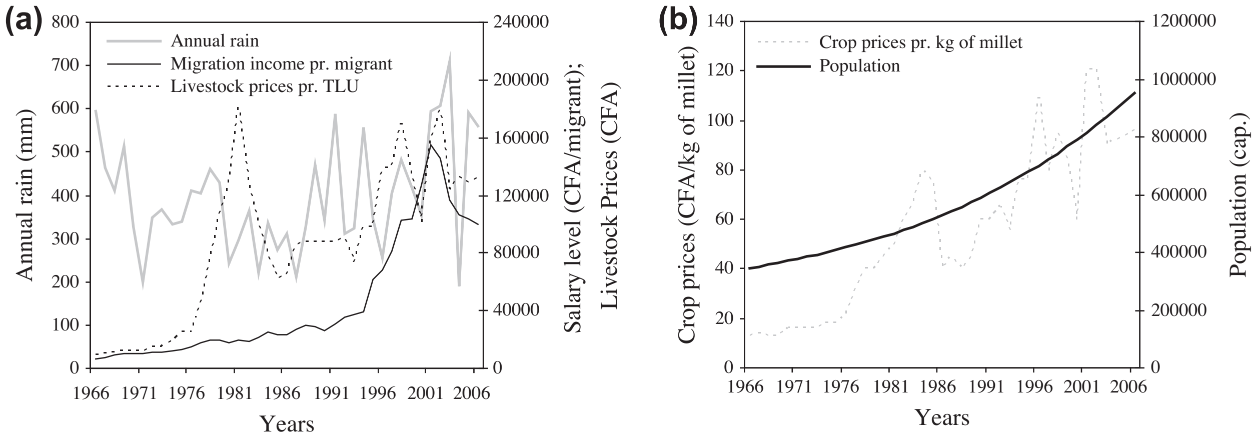

Fig. 1. Data on the 5 exogenous variables of the model. (a) Annual precipitation, livestock prices pr. TLU and migration income pr. migrant when going to Côte d'Ivorie, and (b) Crop prices pr. kg of millet and population. Crop prices, livestock prices and income levels are given in the local currency West African CFA franc. Data are derived from the FAOStat database (Food and Agricultural Organisation, 2010) and the Meteorological Office in Ouagadougou.

Table 1
Primary assumptions of the model.

(a) Continuous cultivation does not lead to land degradation and lower yields
(b) Spatial differences in land management and soil attributes do not influence biomass productivity and yields
(c) The population is only selling the harvested millet if the food requirements are fulfilled
(d) The migration level is determined on purely economic grounds

whilst the pastoral submodel simulates changes in the livestock number in the Sahel region. The two submodels interact through the calculated pasture area and the estimated agro-pastoral income (Fig. 2). The structure of the overall model differs from previous Sahelian land use models in three significant ways: (1) The model places the Sahelian land use system in a larger system that includes drivers at other spatial scales, e.g. world market prices (this has only been done to some extent by Picardi (1976)); (2) The basic assumption of an equilibrium between the production and consumption of food for humans is disregarded by incorporating off-farm strategies such as migration; (3) the model does not assume a simple causation path from agricultural expansion to land degradation, instead it acknowledges the findings by Niemeijer and Mazzucato (2002) and Warren et al. (2001b) suggesting that continuous cultivation does not necessarily imply land degradation. It should, however, be noted that this requires continuous supply of dung, which can be obtained from the herds of local farmers or by keeping good relations with other herders.

In each submodel, the mathematical relations are based on a combination of an existing land use model, SALU (Stephenne and Lambin, 2001), the literature and our knowledge of the study area.

In the pastoral submodel, we assume that biomass productivity (Bio_{Py}) in Sahelian grasslands only depends on rainfall (Le Houérou and Hoste, 1977) as in Stephenne and Lambin (2001). This is described by the following statistical relationship between dry matter biomass, Bio_{Py} (tonnes/ha), and annual rainfall, R (mm), taken from ground measurements by Breman and Dewit (1983):

$$Bio_{Py} = 0.15 + 0.00375 \times R \quad (1)$$

The total biomass production, Bio_{Po} (tonnes), in the Sahel region is thus:

$$Bio_{Po} = Bio_{Py} \times Area_{Graz} \quad (2)$$

where $Area_{Graz}$ is the grazing area in ha. As in Stephenne and Lambin (2001), the proper consumption of biomass measured per

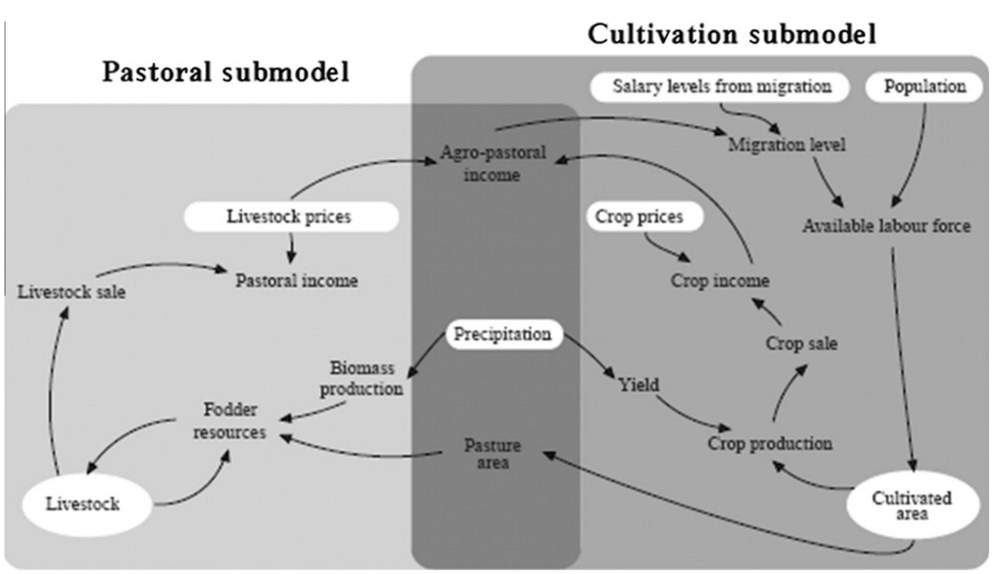

Fig. 2. Conceptual representation of the model structure. The white boxes are model input, while the white circles represent model output.

cattle equivalent (TLU) is estimated at an average value of 4.6 tonnes/year (Table 2) and accounts for the following: the consumable forage of grasses is only one-third of the aboveground biomass and crop residues are also part of the biomass consumption in addition to the production from shrubs and trees (Le Houérou and Hoste, 1977). The actual available fodder resources per TLU, Bio_{TLU} (tonnes/TLU), in the study area are given by the following equation:

$$Bio_{TLU} = Bio_{Po}/TLU \quad (3)$$

As in Hein (2006), the total number of livestock is assumed to follow a logistic growth process depending on the available fodder resources per TLU (see Fig. 3). If the available fodder resources per livestock unit are lower than the suggested 4.6 tonnes/ha, the stocking rate is assumed to decrease to a minimum of −20% per year. It may seem peculiar that the minimum is not −100% in times with depleted fodder resources, but as low availability of fodder resources evokes a southward migration with the animals, the livestock population is not likely to be totally decimated (Powell et al., 1996; Mortimore and Turner, 2005). The opportunity of migrating southwards becomes, however, limited, when droughts are widespread, which is not included in the model. The growth rate increases with values of Bio_{TLU} higher than 4.6 tonnes/ha, and Boudet (1975) and Mortimore and Adams (2001) estimate a maximum of natural growth of herd size of 20% per year for the Western Sahel. Using these estimates, the growth process of livestock is given in the following equation:

$$\Delta TLU = 40/(1 + (0.000131 \times 0.2) \wedge (Bio_{TLU} - 10)) - 20 \quad (4)$$

In the cultivation submodel the crop yield ($Crop_Y$) is defined as a linear function of rainfall (Larsson, 1996; Ellis and Galvin, 1994; Vossen, 1988; Sicot, 1989). Stephenne and Lambin (2001) and Groten (1991) define the relationship between millet production, $Crop_Y$ (kg/ha), and annual rainfall as

$$Crop_Y = 0.91 \times R \quad (5)$$

It is worth noting that for example Agnew (1990) highlights that it may be highly contestable to ignore the temporal patterns of precipitation during the growing season. Furthermore, it must be noted that low availability of soil nutrients may be a more serious constraint on yields than rainfall, which we are not taking into account due to the substantial data requirements. The total crop production in the area, $Crop_{Po}$ (kg), is thus:

$$Crop_{Po} = Crop_Y \times Area_{Cult} \quad (6)$$

where $Area_{cult}$ is the cultivated area in ha. As in Stephenne and Lambin (2001) human consumption is estimated to average value of 300 kg grain per capita, including losses at different stages of grain processing (Table 2). If the population's food requirements are fulfilled by the total crop production, the surplus is being commercialized.

The size of the cultivated area is assumed to be more influenced by the available labour force than the food requirements, and is thus given in the following equation:

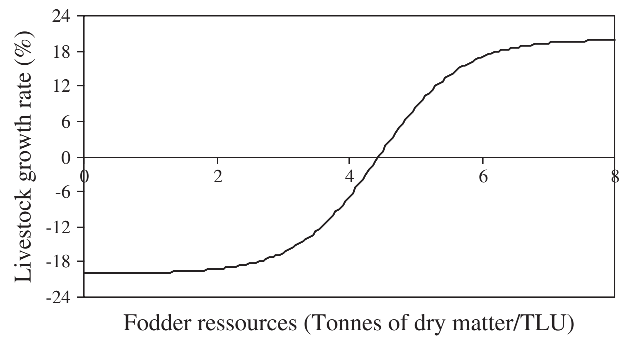

Fig. 3. Logistic function of the livestock growth process depending on fodder resources (tonnes of dry matter) pr. TLU (Tropical Livestock Unit).

$$Area_{cult} = Lab_{agri} \times Cult_{Ca} \quad (7)$$

where Lab_{agri} is the available labour force and $Cult_{Ca}$ is the acreage each person is able to cultivate. Based on observations in the study area, the acreage is assumed to be 2 ha, whilst the available labour force is related to population and migration. The model differentiates between the potential and the actual labour force as the potential labour force for agricultural work is assumed to be reduced by the level of migration. The potential labour force is comprised primarily of men in the 15–64 year age group, and we determine this fraction of the total population from regional statistics in Burkina Faso (Ministere de l'Economie et des Finances, 2009). Field surveys in the case area show, however, that a fraction of women and elderly men also participate in the agricultural work but are not likely to migrate. By counting the women and elderly men who participated in agricultural work, this fraction is determined to be 10% of the total population and is added to the labour force consisting of men aged 15–64. Note that ethnic differences in terms of participation in agricultural work and migration are not taken into account, which is contestable, but as the intention of the model is to capture trends of land use change at a regional scale, this simplification is believed to be acceptable. The actual labour force, Lab_{agri} (capitas), is thus given in the following equation:

$$Lab_{agri} = Pop \times Pop_{Men15-64} - Mig + Pop \times Pop_{AdLa} \quad (8)$$

where Pop, $Pop_{Men15-64}$, Mig and Pop_{AdLa} are population, fraction of the population aged 15–64 and males, number of migrants and fraction of the population assumed to be an additional labour force. The number of migrant workers is determined on purely economic grounds. The potential salary income in Côte d'Ivorie is used as a proxy for the economic pull-effect of Abidjan and, based on field surveys and literature, the current average amount a migrant returns to the household after all expenses have been paid is around US$200–300 (Nielsen and Reenberg, 2010). We then use the historic rate of GDP in Côte d'Ivorie as a proxy for income levels throughout the period. The appeal of migration is assumed to be influenced by the economic pull of Côte d'Ivorie compared with the probable income generated by agro-pastoral activities (crop and livestock sale).

Table 2
Values for the constant parameters in the model and literature sources from which these values were derived.

Parameter	Value	References
Food consumption	300 kg of grains/capita/year	Bolwig (1995), Claude et al. (1991), Netting et al. (1993), Reardon et al. (1988)
Livestock forage consumption	4.6 tonnes of dry matter/TLU/year	Behnke and Scoones (1993), Boudet (1975), Claude et al. (1991), Groten (1991)
Cultivation capacity	2 ha/capita included in the available labour force	Field work observations in 2010
Additional labour force (elderly men, women and children)	10% of the total population	Field work observations in 2010
Potential livestock sale	5% of the livestock herd	Field work observations in 2010

This relationship represents the migration index and is presented in the following equation:

$$\text{MigIndex} = \text{In}_{mig}/(\text{In}_{crop} + \text{In}_{liv} + \text{In}_{mig}) \quad (9)$$

where In_{mig}, In_{crop} and In_{liv} are the potential income from migration per capita after all expenses have been paid, the potential income generated from crop and livestock sale per capita. The potential value of livestock sale is based upon an estimated fraction of 5% of the livestock herd likely to be sold in any given year. This rough estimate was based on the field surveys. It should be noted that the fraction most likely is higher in dry years, but as the motivation behind selling animals in dry years is anchored in necessity and villagers regard it as a loss, it is not included as an income generating activity in the model. After calculating the migration index, the migration level is then assumed to be a logistic function of this. The field surveys revealed that a migration index of 1, meaning that no income can be generated from agro-pastoral activities, translates to a fraction of 90% of the men aged 15–64 migrating. The migration level is assumed to decrease to a minimum of 0% with a migration index of 0, which reflects that the probable income generated in Côte d'Ivorie is 0. Thus, the migration level as a logistic function of the migration index is given in the following equation:

$$\text{MigLevel} = 90/(1 + \text{EXP}(-(-4.369448 + 9.222918 \times \text{MigIndex})) \quad (10)$$

Note that the migration level is subsequently affecting the de facto population in the case area and thus the total food requirements.

2.3. Set up of the calculations

The model was run for a period of 41 years, from 1966 to 2006. We started by running a baseline analysis for the Sahel region using the aforementioned set of assumptions, fixed parameter values and annual values derived for the external variables. The rationale behind providing a baseline analysis was to test the ability of the model to capture main observed and well-known directions of change and mega trends in the Sahelian land use systems.

To validate the model, simulated changes in the livestock population were firstly compared with a time series (1981–2006) of the annual Normalized Difference Vegetation Index (NDVI) employed as a proxy for vegetation productivity as is common amongst ecologists (Kerr and Ostrovsky, 2003). The NDVI values representing grazing areas in the Sahel region were extracted from the GIMMS global dataset (Tucker et al., 2011). The rationale behind using NDVI values for validation was the assumption that the number of livestock was highly dependent on biomass production in the area. Secondly, the simulated changes in livestock population were evaluated against national data sets of long term changes in livestock population for Burkina Faso and Niger available on an annual basis from the FAO-Stat database (Food and Agricultural Organisation, 2010). No historical data records existed at the regional scale. As a third validation method, simulated trends in cultivation percentage were compared to a quantification of land use changes at the village level in the Sahel region. The quantification rested on the use of aerial photos from 1955 and 1956, SPOT satellite images from 1988 and 1991 and GPS measurements carried out in 1995, 2009 and 2010. A more detailed description of the analysis of aerial photos and satellite images is given in Reenberg et al. (1998). This validation method was chosen due to very limited data availability on long term changes in land use in the region. Measurements of the cultivated area were, however, only carried out in isolated years allowing for a highly limited comparison.

After validation, the baserun simulation that approximated mega trends in Sahelian land use systems was then used as a reference when generating 'what if' scenarios to explore the impact of change in system parameters capturing realistic alterations. Four 'what if' scenarios were generated in order to evaluate the sensitivity of the system to important and realistic alterations in the assumed major factors affecting land use (Table 3). The formulation of each 'what if' scenario was based upon fieldwork in three small villages in the Northern Burkina Faso. The first two runs assessed the potential impacts of specific events, whilst run 3 and 4 considered the influence of generic alterations throughout the whole simulation period.

It is worth noting that even though the model provided quantitative estimates of land use changes, the baseline as well as the scenarios should not be read in an absolute sense. The intention was not to simulate system behaviour in a quantitatively precise way; instead we focussed upon main directions of change and mega trends in the system behaviour.

3. Results and discussion

3.1. Baseline simulation

When simulating changes in the cultivated area and the livestock population during the period 1966–2006 for the Sahel region,

Table 3
Summary of 'what if' scenarios developed to quantify the relative effect of different drivers of land use changes in the Sahel region.

Name of the scenarios	Description	Parameterization based on field work observations
Millet prices (Scenario 1)	This run simulates the effects of a potential project intervention creating highly subsidized millet prices in the Sahel regions	The millet prices in the villages with project intervention are currently 18% lower than in villages without projects. As many projects began around 1990, this run reflects: • What if a sudden price drop of 18% happened across the entire region in 1990?
Cote d'Ivorie (Scenario 2)	This run shows how a sudden change in migration trends may affect the land use	Despite the unrest in Cote d'Ivorie since 2002, Abidjan has been the preferred migration destination. But in the light of the current escalated situation in Cote d'Ivorie, this run simulates • What if the migration had stopped in 2002?
Rainfall variability (Scenario 3)	This run shows the outcome of an increased rainfall variability and is based on IPCC rainfall projections (Christensen et al., 2007)	As a 40% increase in the rainfall variability is projected, this run shows: • What if rainfall variability had increased by 40% during the whole period?
Livestock valuation (Scenario 4)	This run simulates the effects of a change in the value of livestock likely to be sold. By contrast to the other 3 runs, this one is related to changes in the parameter values.	When estimating the value of livestock, farmers expressed that they would normally sell 1 out of 20 livestock. However, there was some disagreement concerning years with drought (rain is >20% below the mean) as the amount sold is likely to increase to 4 out of 20 due to necessity. This run simulates: • What if 20% of the livestock is sold in years following droughts?

the results revealed both annual variations and long term trends (Fig. 4). Based on the observed change patterns, the analysis period was divided into three phases.

The first phase was dominated by expansion of cultivated land and a growing livestock population. However, the model also captured the well-known decrease in the Sahelian livestock population in the beginning of the 1970s triggered by droughts. This first phase characterized by expansion and growth continued until the beginning of the 1980s. At this time, a second phase occurred with another severe drought causing a significant decline in the livestock population. During this second phase, expansion of the cultivated area was stopped. By the beginning of the 1990s, substantial annual variations were observed in the size of the cultivated area as well as in the livestock population, which created a more blurred pattern of behaviour characterizing a third phase. The most pronounced decreases in the cultivated area were found from 1999 to 2001 and 2004 to 2005. As regards the livestock population, the simulation revealed an increasing trend despite the annual variations.

The expansion of cultivated land in the first phase may be partially explained as a consequence of an increasing agricultural labour force fuelled by population growth and low migration levels, whilst the growing livestock population was spurred by sufficient fodder resources. In the second phase, the increasing economic appeal of migration was chiefly responsible for slowing down land expansion. The significant annual variations observed in the third phase were most likely a consequence of greater annual variations in precipitation during the last decades of the simulation (detrended standard deviations of 110.6 mm in the 1990s and 180.5 mm in the 2000s) compared to the earlier decades (detrended standard deviations of 86.7 mm, 76.9 mm and 71.1 mm in the 1960s, 1970s and 1980s) (calculations of detrended standard deviations were based on the Gorom-Gorom precipitation dataset from the Meteorological Office in Ouagadougou). Furthermore, fluctuating income levels and crop and livestock prices during this phase caused substantial variations in the migration level and consequently implied a variable cultivated area. Rising income levels in Côte d'Ivorie between 1998 and 2001 and consequently a decreasing agricultural labour force may explain the first drop in the cultivated area. More interestingly, the second drop (2004–2005) was characterized by declining income levels accompanied by diminishing crop and livestock prices. Hence, the substantial decrease in the cultivated area was a consequence of very dry conditions in 2004 – indicating that the impacts of an extremely dry year may overrule changing income levels, crop prices and livestock prices. As the simulation revealed an increasing trend in the livestock population despite significant annual variations, it indicated that fodder resources were only severely limiting in few years.

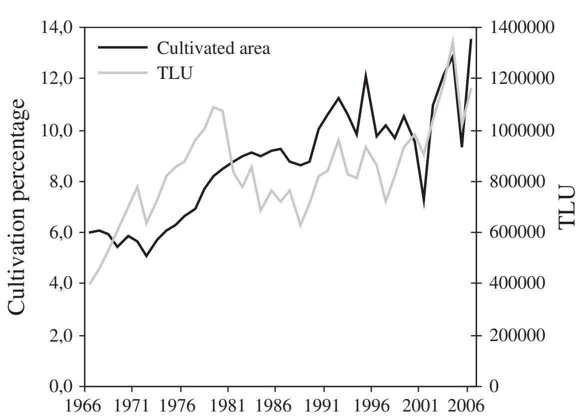

Fig. 4. Base run of changes in the cultivated area and TLU (Tropical Livestock Units) in the Sahel Region.

3.2. Validation of long term model behaviour against observations

When simulated changes in livestock were compared to observed trends in NDVI (Fig. 5a), both annual variations and long term trends corresponded well to observed trends in NDVI (correlation of 0.73, $n = 26$).

The second validation method of simulated changes in livestock population against the national datasets of long term changes in livestock for Burkina Faso and Niger only gave a reasonable characterization of mega trends. In this vein, it should be noted that our confidence in the national datasets was weak, which may explain the limited correspondence. This is also supported by the fact that the well-known decrease in livestock population during the droughts in the early 1970s and 1980s was only displayed in the Niger dataset, not in the Burkina Faso dataset. This indicated that long term trends in the size of the livestock population in Northern Burkina Faso were likely to be most comparable with the Niger dataset. A reasonable correspondence throughout the simulation period was observed (Fig. 5b), but the Niger dataset presented, however, no substantial annual variations like the model simulation.

The third validation method, which consisted of a comparison of simulated changes in the cultivated area with observed mega trends, revealed that the first phase of land expansion as simulated by the model corresponded well to the observations (Fig. 5c). The simulated second phase characterized by a less rapid expansion was also observable in the observations from 1988 and 1991, likewise the third phase with substantial annual variations may partly be recognized in the observations from 1992 to 2010.

3.3. Exploring the dynamic features of agro-pastoral systems

The first scenario run assessed the influence of a sudden event (drop in millet prices caused by projects offering highly subsidized prices) in 1990. As expected, the price drop would lead to a lower cultivation percentage (Fig. 6a) as the appeal of migration increased due to the diminished value of millet production. Consequently, the cultivated area would remain almost stable from the mid 1980s until the end of the simulation, except for a significant increase in 1995 followed by a rapid decrease in 1996 and subsequently a returning to previous cultivation levels. This pronounced increase was likely to be triggered by an especially rainy year in 1994 suggesting that a hypothesized constantly low millet price could not eliminate the effects of significant annual variability in precipitation. The more smoothed trajectory of changes in the cultivated area compared to the baserun also indicated that fluctuating millet prices were highly responsible for the annual variations presented in the baserun. Hence, annual variations could not be attributed to climate variability only. This first scenario run revealed negligible impacts on the simulated number of livestock (Fig. 6b).

As was done in scenario run 1, the second scenario run considered the possible impacts of a sudden event: 'what if' migration had stopped in 2002 due to the unrest in Cote d'Ivorie. Our rationale was to test the sensitivity of the agro-pastoral system to large changes in migration patterns. The abandonment of migration would lead to almost a doubling of the cultivated area from 2002 to 2003. Importantly, the increase would continue after 2003 and, despite a highly varying precipitation in the period 2002–2006, this continued increase was steady, i.e. without annual variations, suggesting that a potential abandonment of migration could efface the effects of annual rainfall variations on the size of the cultivated area. As with scenario run 1, the impacts on the livestock population would be negligible.

The third scenario run evaluated 'what if' climate variability had been increased by 40% throughout the simulation. As for this

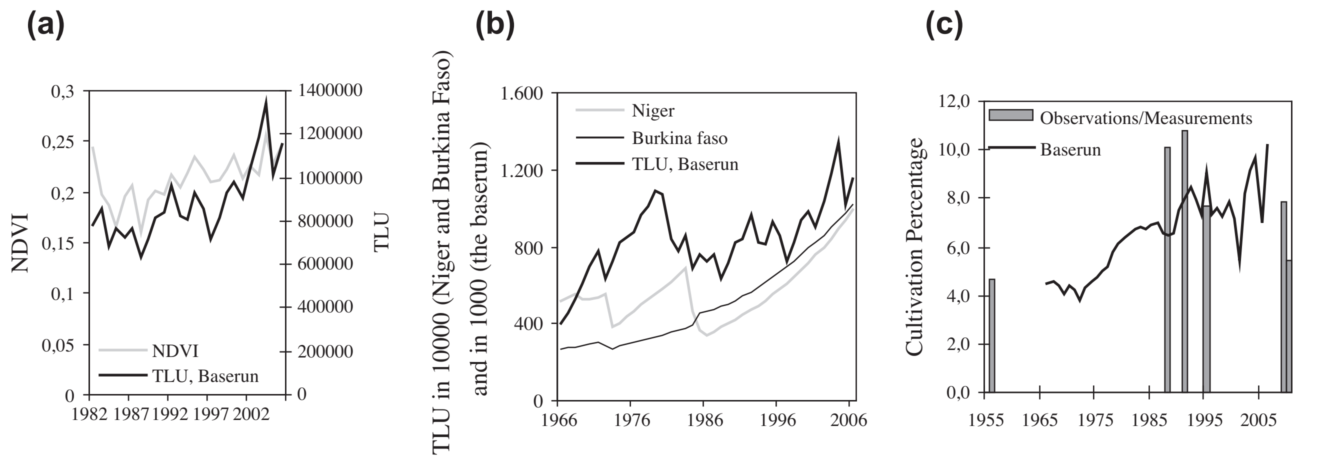

Fig. 5. (a) Time series of observed annual Normalized Difference Vegetation Index (NDVI) for pasture areas in Northern Burkina Faso based on the GIMMS global dataset, (b) National data sets (Burkina Faso and Niger) of long term changes in livestock population available from the FAOStat database (Food and Agricultural Organisation, 2010), and (c) Measurements of the cultivated area in Yomboli village in Northern Burkina Faso on the basis of interpretation of aerial photos (1955), SPOT satellite images (1988 and 1991) and GPS measurements (1995, 2009 and 2010).

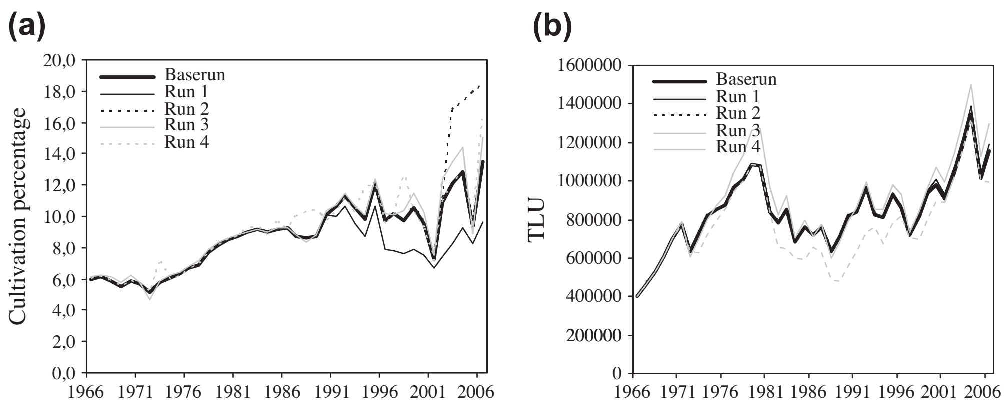

Fig. 6. Comparison of behaviour patterns of (a) cultivation percentage, and (b) TLU (Tropical Livestock Units) under scenario 1, 2, 3, 4 and the base run.

scenario, we would expect the main differences to occur in marginal years (drought years or very rainy years). Accordingly, the simulation demonstrated that increased rainfall variability would not substantially affect the cultivation percentage apart from the period 2002–2004. This indicated that a 40% increased climate variability would simply not seriously change the cultivation percentage in a long term perspective. More interestingly, increased variability would cause a greater livestock population in three periods; 1977–1984, 1995–1996 and 2000–2006. The three periods were all following a very rainy year (1976, 1994 and 1998–1999). This indicated that greater rain in wet years could trigger a rising livestock population. By contrast, lower rain in years or periods already characterized as droughts was not likely to cause an accelerated decline in the livestock population. This was a consequence of the assumed growth process in livestock number, as the droughts occurring in the baserun already triggered the minimum growth rate.

In the fourth scenario run, the impacts of a change in a fixed parameter value, the potential livestock sale, were assessed. 'What if' the amount of livestock to be sold had been assumed to be dependent on the rainfall (change in value from 5% to 20% in years with drought)? This was probably too simplistic an assumption. However, the results served as a first approximation and may be improved upon as more information is incorporated into the model. The cultivated area was found to be highly sensitive to the changing values and increased by 3–30% in the years following droughts due to the greater appeal of agro-pastoral activities. However, as the percentage of livestock likely to be sold was hypothesized to increase to 20% due to necessity, it may seem peculiar that droughts would trigger expansion of the cultivated area. Nevertheless, it corresponded to some extent with observations from the area demonstrating that migration levels may decline as some farmers preferred guarding the livestock they had left rather than leaving for migration after a drought. It is worth noting, that the results must not be interpreted as the simplified narrative that states that low precipitation leads to expansion due to lower yields. As expected, the increasing fraction of livestock to be sold resulted in a decline in the livestock population.

3.4. General discussion

Possible use of the model for future studies include testing of hypotheses with the existing model set-up as well as modifying fundamental relations within the model. Regarding the testing of hypotheses, it has been seen how the model allows for an analysis of simple hypotheses about the links between different driving forces and land use changes in the Sahel. As modelling land use changes based on variation in a single driving force is an oversimplification of reality, results should, however, be treated as hypotheses requiring further testing and as a guide to focus future research design rather than as firm conclusions.

Adjusting fundamental relations in the existing model setup may as well be important in future use of the model. In this vein, attention should be given to the use of exogenous drivers denoting that certain factors supposedly cause land use changes. The term exogenous drivers reflect a static picture of these factors that may actually be dynamic and thus subject to continuous change (Guneralp and Seto, 2008). A key feature of the present model is the five exogenous drivers of land use change. One could experiment with endogenizing for example the population variable in the model, as it may be more apt to treat population as an endogenous variable, which depends on available food from either cultivation or purchase.

4. Conclusion

The simple system dynamics model of land use change presented here has been proven to successfully simulate the main directions of change of land use systems in Northern Burkina Faso (a first phase characterized by field expansion and a growing livestock population; a second phase in which field expansion slowed down and the livestock population declined; and a third phase characterized by substantial annual variations in field area as well as in the livestock population). While there are previous examples of land use models developed for simulating land use changes in the Sahel, this is the first time such a dynamic model is realized without relying heavily on dominant narratives that are insufficient to capture more recently observed features of complex dynamics in the land use system.

As has been seen, the developed model revealed further insight into some of these new features of complex dynamics. This was based on the generation of 'what if' scenarios to evaluate the sensitivity of the system to important and realistic alterations in those factors driving land use change. Among the insights gained, the study showed that sudden events, such as a drop in millet prices or a total stop in circular migration, would have a more pronounced impact on the system than other more long term alterations like increased rainfall variability throughout the simulation period. Consequently, our findings lend credence to the argument that non-climatic factors may play a more crucial role than the annual rainfall, and generalizations about a simple link between climate variability and land use change are, therefore, misleading. Hence, the developed model may complement more established empirical approaches in land change science and it should thus be regarded as a useful tool to enhance the understanding of complex interactions in Sahelian land use systems.

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