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A dynamic simulation model of land-use changes in Sudano-sahelian countries of Africa (SALU)

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Abstract

This paper presents a simulation model to project land-cover changes at a national scale for Sudano-sahelian countries. The aim of this study is to better understand the driving forces of land-use change and to reconstruct past changes. The structure of our model is heavily determined by its spatially aggregated level. This model represents, in a dynamic way, a simplified version of our current understanding of the processes of land-use change in the Sudano-sahelian region of Africa. For any given year, the land demand is calculated under the assumption that there should be an equilibrium between the production and consumption of basic resources derived from different land-uses. The exogenous variables of the model are human population (rural and urban), livestock, rainfall and cereals imports. The output are the areas allocated to fuelwood extraction, crops, fallow and pasture for every year. Pressure indicators are also generated endogenously by the model (rate of overgrazing and land degradation, labour productivity, average household "budget"). The parameters of the model were derived on the basis of a comprehensive review of the literature, mostly of local scale case studies of land-use changes in the Sahel. In agreement with farming system research, the model simulates two processes of land-use change: agricultural expansion at the most extensive technological level, followed by agricultural intensification once some land threshold is reached. The model was first tested at a national scale using data from Burkina Faso. Results simulate land-use changes at two time frequencies: high frequency, as driven by climatic variability, and low frequency, as driven by demographic trends. The rates of cropland expansion predicted by the model are consistent with rates measured for several case studies, based on fine spatial resolution remote sensing data.

Keywords: Land-use change; Land-cover change; Sahel; Desertification; Modelling

1. Introduction

Understanding the role of land-use in global environmental change requires historical reconstruction of past land-cover conversions and/or projection of likely future changes. While, at a local scale, part of these historical data can be generated from direct or indirect field evidence (e.g. old vegetation maps, aerial photographs, high temporal resolution pollen studies), at a regional scale, the reconstruction of past land-cover changes has to rely on backward projections using land-use change models (Klein Goldewijk and Battjes, 1997). Such models rely on an understanding and simulation of the interactions between drivers of land-use change.

The objective of this paper is to present a dynamic simulation model of land-use changes in the Sudano-sahelian countries of Africa (SALU). The specific purpose of this model is to generate backward and forward projections of land-use change over several decades at a national scale. The Sudano-sahelian

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region has undergone changes in land-cover over the last decades (Little et al., 1987; Bolwig, 1995). It is still very much debated, however, whether these changes are related to short-term climate fluctuations or longer-term anthropogenic impacts (Nicholson, 1989; Hellden, 1991; Hulme, 1996). Several authors have suggested that "desertification" in the Sahel has caused a change in regional climate (Xue and Shukla, 1993). One possible application of the output of our model, if generated over a large region, is to investigate the impact of land surface changes on regional climate. This can be achieved by conducting experiments with general circulation models (GCMs) at a coarse spatial resolution. The structure of our model is heavily determined by this coarse resolution. The model represents, in a dynamic way, a simplified version of the current understanding of the processes of land-use change in the Sudano-sahelian region.

2. Background

The backward or forward projection of land-use changes can be performed using two main categories of models (Lambin, 1997): (i) empirical models based on an extrapolation of the patterns of change observed over the recent past, with a limited representation of the driving forces of these changes, and (ii) dynamic simulation models based on a thorough understanding of the processes of land-use change. Empirical models integrate landscape variables and proximate causes of change in a data-rich spatial context. However, they can only provide short-range projections (5–10 years at most) due to the dynamic character of land-use change processes.

Longer range projections require, first, a good understanding of the major human causes of land-use changes in different geographical and historical contexts. It also requires an understanding of how climate variability affects both land-use and land-cover. Such understanding is gained through a collection of local scale case studies on land-use dynamics, which highlight how people make land-use decisions in a specific situation. A generalised understanding of the drivers of land-use change, that can be linked to regional scale patterns of change, is gained through a comparative analysis of these case studies.

The knowledge gained through these case studies supports the development of simulation models of land-use changes that represent the dynamics of driving forces operating at regional to global scales. These models include a representation of the processes linking driving forces to changes in land-use allocation. They have to cope with issues such as technological changes, policy and institutional changes and changes in economic system. On this basis, regional scenarios can be generated to simulate possible future land-use changes or for identifying land-use patterns with certain optimality characteristics satisfying simultaneously various economic, social and environmental goals.

In this study, we reviewed a large number of published case studies of land-use dynamics in the Sudano-sahelian region, compared and generalised these case studies to identify the dominant driving forces, processes and parameters values of land-use change in the region, and represented these processes in a simulation model using a combination of simple, equilibrium equations and knowledge rules. The regional focus of the study on the Sudano-sahelian region means that we could represent region-specific processes of land-use change.

3. Model structure

The exogenous variables of the model are human population (rural and urban), livestock population, rainfall and cereals imports. New values of these exogenous variables are defined every year from the Faostat database (FAO, 1995) and the global monthly precipitation dataset gridded at 2.5° latitude by 3.75° longitude resolution (Doherty et al., 1999). These exogenous variables are driving yearly changes in land-use allocation. These land-uses generate different resources for the population: fuelwood in natural vegetation areas, food for subsistence and market needs in cropland and fallow, livestock in pastoral land. These different land-uses compete for land. Note that these *land-use* categories do not strictly coincide with *land-cover* types. In this model, the land-use classes "fuelwood extraction areas" and "pastoral lands" refer to a variety of vegetation cover types such as woodlands, savannahs or steppes.

For any given year, the land demand is calculated under the assumption that there should be an equilibrium between the production and consumption of resources. This assumption drives the land-use allocation for every yearly time step. In other words, the offer of food and energy resources derived from the areas allocated to the different land-uses must satisfy the demand for these resources by the human and animal populations, given the exploitation technologies used at a given time. The second assumption is that the study area, i.e. a country or an eco-climatic region within a country, is geographically homogeneous. As the model is not spatially explicit but only predicts aggregated values of land-use change, spatial heterogeneity is not taken into account. Furthermore, the study area is closed, except for food imports.

The model is programmed with STELLA, a modelling language with a graphic interface which has been widely used for developing simulation models (Costanza et al., 1990; Woodwell, 1998). The name of this model is SALU (SAhelian Land-Use model).

4. Computation of demand for different land-uses

The competition between the different land-uses takes place within the national space, which is finite

$$\mathrm{U} = \mathrm{Veg} + \mathrm{Past} + \mathrm{Crop} \tag{1}$$

where *U* is the used area, *Veg* the fuelwood extraction area, *Past* the pastoral land and *Crop* the cropland, all quantities being in ha. The difference between the national space and the total used area is the unused area

$$\mathrm{UN} = \mathrm{N} - \mathrm{U} \tag{2}$$

where *UN* is the unused area in ha and *N* the national area in ha. The unused area correspond to the same *land-cover* types as pastoral lands and fuelwood extraction areas. It is the area of these land-cover types that would not need to be used for grazing or fuelwood collection given the demand for related resources and given a certain land-use intensity. The total demand for land in a given year is the sum of demands for cropland and pastoral land

$$\mathrm{land_d} = \Delta\mathrm{Crop_d} + \Delta\mathrm{Past_d} \tag{3}$$

where $land_d$ is the land demand, $\Delta Crop_d$ the annual variation in cropland demand and $\Delta Past_d$ the annual variation in pastoral land demand, all quantities being in ha. The demand for land for specific land-uses is computed on the basis of a set of equations described below.

4.1. Pastoral land

In the pastoral land, the equilibrium assumption requires that the consumption of forage is equal to the biomass production. As, in the Sudano-sahelian region, pastoralism is mostly extensive, biomass production relies on the natural productivity of grasslands. Thus

$$\mathrm{BiomPy} * \mathrm{Past_d} = \mathrm{Liv} * \mathrm{BiomC} \tag{4}$$

where *BiomPy* is the biomass productivity in tonnes/ha, *Liv* the livestock population in equivalent tropical livestock unit (TLU) and *BiomC* the consumption in biomass per head in tonnes/equivalent TLU. TLU is a conventional stock unit of a mature zebu weighting 250 kg (Boudet, 1975). One TLU corresponds to one cattle, one horse, five asses, 10 sheeps or 10 goats (Pieri, 1989). We assume that biomass productivity in Sudano-sahelian grasslands only depends on rainfall (Le Houérou and Hoste, 1977). This is described by the following statistical relationship between dry matter (DM) biomass and rainfall, taken from ground measurements by Breman and de Wit (1983)

$$\mathrm{BiomPy} = 0.15 + 0.00375\mathrm{R} \tag{5}$$

where *R* is the annual average of rainfall in mm.

Given its natural biomass productivity, a sufficient area is allocated to pastoral land to produce the biomass required to feed the livestock population, which is determined exogenously (FAO, 1995). The consumption of biomass measured per cattle equivalent (TLU) is estimated at an average value of 4.6 tonnes/year based on the following reasoning. The average dietary requirements of a TLU are 6.25 kg of DM per day (Le Houérou and Hoste, 1977; Behnke and Scoones, 1993; de Leeuw and Tothill, 1993). The consumable forage of grasses is only one-third of the above-ground biomass (Penning de Vries and Djitèye, 1982; de Leeuw and Tothill, 1993). But production from shrubs and trees, and crops residues also take part in the biomass consumption of the livestock (Le Houérou and Hoste, 1977). Pieri (1989) evaluates this part to one-third of the total consumption. However, this fraction does increase with scarcity of pastoral land and intensification. Initially, the model estimated the total DM biomass required to satisfy the average biomass consumption of livestock as $6.25\,\text{kg} * 365 * 3 * \frac{2}{3} = 4.6\,\text{tonnes/year}$. TLU. The factor 3 accounts for the consumable fraction of above-ground biomass and the factor $\frac{2}{3}$ for the contribution of grasses to the consumption. In the intensification phase (see below), the later factor becomes $\frac{1}{3}$ (i.e. $\frac{2}{3}$ of the consumption is based on crop residues). The demand for pastoral land is thus computed endogenously per Eq. (4). Whether this demand will actually be satisfied will depend on the competition with the other land-uses.

4.2. Cropland

In cultivated land, food crops for the subsistence needs of the rural population, are separated from crops which are commercialised. The subsistence demand for food crops depends on the rural population and its basic consumption requirements. The crops which are commercialised consist mainly of food crops for the subsistence needs of the urban population, but may include some cash crops (e.g. cotton). The part of the production which is commercialised on local markets generates an income for farmers. The food crops that are commercialised also depends on cereal imports, which are assumed to complement the consumption of the urban population only. The model defines the demand for cropland as

1. Food crops for the subsistence needs of the rural population

$$\text{CropY} * \text{CropS}_\text{d} = \text{Pop}_\text{rur} * \text{FoodC} \tag{6}$$

where *CropY* is the crop yield in kg/ha, $CropS_d$ the cropland demand for subsistence in ha, Pop_{rur} the rural population in inhab, and *FoodC* the food consumption per capita in kg/inhab.

2. Food crops for the subsistence needs of the urban population

$$\text{CropY} * \text{CropM}_\text{d} = (\text{Pop}_\text{urb} * \text{FoodC}) - \text{CImp} \tag{7}$$

where $CropM_d$ is the cropland demand for market in ha, Pop_{urb} the urban population in inhab, and *CImp* the cereal imports in kg. The basic consumption of the population is estimated at an average value of 300 kg of grains per inhabitant, including losses at different stages of grain processing. Local-scale studies in the Sudano-sahelian countries estimate an average of 250–375 kg of millet and sorghum production to feed an average person during 1 year (Raynaut, 1985; Lambin, 1988; Bolwig, 1995). In these countries, the diet is composed by cereals for up to 83% (FAO, 1998) to 90% (Claude et al., 1991) of the total consumption. About 20% of the harvested grain is lost by shelling and wastage, or is kept for seeds (Bolwig, 1995). Estimates of the actual consumption per capita vary between 230 kg (Claude et al., 1991), 200 kg (Boulier and Jouve, 1990), and 180 kg (Gueymard, 1985). Based on minimum diet requirements of 2182–2470 kcal for an average person (Banque Mondiale, 1989), and knowing the caloric supply of cereals (Ministère de la Coopération, 1984) and the conversion factor between production and actual consumption, we estimate an average value of cereal consumption of 360 kg/inhabitant.

In Eqs. (6) and (7), rural and urban populations, and cereal imports are exogenous variables derived from FAO (1995). Crop yield is defined as a linear function of rainfall (Vossen, 1988; Sicot, 1989; Ellis and Galvin, 1994; Larsson, 1996). Groten (1991) defines the relationship between millet production and annual rainfall as

$$\text{CropY} = 0.91 * \text{R} \tag{8}$$

The cropland area includes fallow

$$\text{Crop} = \text{CropS}_\text{d} + \text{CropM}_\text{d} + \text{Fal} \tag{9}$$

where *Fal* is the fallow area. At the most extensive level of cultivation, corresponding to a pre-intensification stage (see below), the crop-fallow cycle is 2 years of fallow for 1 year of cultivation (i.e. cultivation frequency (CF) = 2 (dimensionless)) (Ruthenberg, 1976). The crop-fallow cycle is modified endogenously under population pressure (see below).

4.3. Fuelwood extraction area

The Sudano-sahelian population uses fuelwood harvested from natural vegetation areas as its main energy source. These areas also provide a number of other ecological services: biodiversity conservation, source of natural food and pharmaceutical products, wildlife for hunting, hydrological balance, etc. Therefore, in the model, fuelwood extraction areas are treated differently than cropland and pastoral land. It assumes that the fuelwood extraction areas can be reduced on an annual basis by the expansion of cropland and pastoral land. The vegetation cover types where fuelwood extraction takes place need 20 years to be reconstituted if they are left unused. Moreover, not all natural vegetation areas can be destroyed. Actually, the local population will always protect a certain fuelwood extraction area: minimum area to satisfy some of the fuelwood requirements for domestic consumption, forest reserves, national parks, sacred forests, inaccessible forests or forests with a high incidence of tse-tse flies or onchocerciasis. Some authors already noted that, at the exception of critical situations, one generally observes a sustainable use of natural vegetation resources in the Sudano-sahelian region (Benjaminsen, 1993; Ite and Adams, 1998). If fuelwood needs exceed the wood production through natural regrowth of vegetation, rural households will turn to other energy sources.

The demand for fuelwood is estimated as

$$\mathrm{VegPy} * \mathrm{Veg_d} = \mathrm{Pop_{rur}} * \mathrm{FuelC_{rur}} + \mathrm{Pop_{urb}} * \mathrm{FuelC_{urb}} \quad (10)$$

where *VegPy* is the productivity in fuelwood in m^3/ha, Veg_d the demand for fuelwood extraction area in ha, $FuelC_{rur}$ the rural fuelwood consumption per capita in m^3/inhab, and $FuelC_{urb}$ is the urban fuelwood consumption per capita in m^3/inhab. Wood consumption and productivity in fuelwood are estimated from the literature. Local-scale studies and regional surveys in the Sudano-sahelian region estimate that 90% of the energy needs of households are covered by wood (USED, 1985). An average person uses a minimum of 1 kg of fuelwood per day (Lambin, 1988), using a conversion factor of 750 kg/m^3 (CTFT, 1989). Some studies establish that the consumption needs vary from 0.5 to 1 m^3/inhab∗year (USED, 1985; CTFT, 1989). Rural and urban consumptions of fuelwood are slightly different. In the model, the fuelwood consumption is 0.65 m^3 per inhabitant on average for the rural population. It rises to 0.85 m^3 per inhabitant on average for the urban population. The productivity in woody biomass in Sudano-sahelian savannahs is estimated at an average value of 0.75 m^3/ha (Pieri, 1989; Yung and Bosc, 1992). In reality, this value ranges from around 0.1 to 2 m^3/ha∗year depending on rainfall, vegetation cover and soil type.

Initially, all unused land is covered by natural vegetation

$$\mathrm{Veg_i} = \mathrm{N} - \mathrm{Crop} - \mathrm{Fal} - \mathrm{Past} \quad (11)$$

where Veg_i is the initial natural vegetation area in ha. The fuelwood demand is thus easily satisfied. As the energy demand increases (with population growth) and the offer for fuelwood decreases (due to agricultural expansion at the expenses of fuelwood extraction areas), a threshold is reached at which a minimum fuelwood extraction area is conserved

$$\text{If } \mathrm{Veg} - (\mathrm{Land_d} - \mathrm{UN}) > \mathrm{Veg_d},\ \text{then } \Delta\mathrm{veg} = (\mathrm{Land_d} - \mathrm{UN}),\ \text{else } \Delta\mathrm{veg} = 0 \quad (12)$$

where Δveg is the annual variation in fuelwood extraction area in ha. This minimum fuelwood extraction area is defined such that it satisfies a certain proportion of the fuelwood requirements for domestic consumption of the population (Veg_d) at the time when this threshold is reached, i.e. the demand for fuelwood extraction areas defined in Eq. (10). Once this threshold is reached, the population has to satisfy an increasing fraction of its energy needs through alternative sources such as kerosene. A standard family in Senegal buys for 3600 FCFA/month, or 4320 FCFA/year∗person, of alternative energy (Legendre, 1997). A World Bank report on West Africa (quoted by Jensen, 1997) estimates the alternative energy consumption in Senegal at 84,000 TOE/year (tons of oil equivalent (TOE) = 41.8 GJ). The average cost of energy substitution per inhabitant and per year is estimated at 4320 FCFA per approximately 0.01 TOE. This represents a substitution cost of 66,900 FCFA/m^3 to replace fuelwood by kerosene (6 m^3/TOE, CTFT, 1989)

$$\mathrm{EnergC} = (\mathrm{For_d} - \mathrm{For}) * \mathrm{VegPy} * \mathrm{FuelS} \quad (13)$$

where *EnergC* is the energy cost in FCFA, *FuelS* the fuel substitution cost in FCFA/m^3.

5. Processes of land-use changes

In agreement with farming system research, including the work of Boserup (1965), the model simulates two processes of land-use change: agricultural expansion at the most extensive technological level, followed by agricultural intensification once some land threshold is reached.

5.1. Agricultural expansion and deforestation

Expansion of cultivation can take place into previously uncultivated area or by migration into unsettled areas without involving any change in the technological level of agriculture. Agricultural expansion thus leads to deforestation or to a regression of pastoral land. Pastoral land can also expand into natural vegetation areas and cropland. Expansion of cropland and pastoral land is driven by two sets of factors: changes in human and animal population, which increase the consumption demand for food crops and forage, and interannual variability in rainfall, which modifies land productivity and therefore increases or decreases production for a given area under a pastoral or cultivation use. If rainfall decreases in a given year, farmers are expected to compensate the decrease in yield by an expansion of the area under use. If rainfall is above average, farmers use a smaller portion of land to produce the same amount of food, thanks to the higher yields. In this case, some fields are abandoned, all other things being equal. This (temporarily) unused area becomes available for another land-use, or for expansion of cropland or pastoral land in a subsequent year. Expansion of cropland and pastoral land in unused land is associated with a lower environmental cost than in the case of deforestation. The effects of demographic and rainfall changes can concur or be opposed.

5.2. Agricultural intensification and decrease of pastoral land

Once the expansion of cropland and pastoral land has occupied all unused land, and once fuelwood extraction areas have reached their minimal area, the land is saturated. In that case, another process of land-use change would take place

$$\text{If UN} < \text{Land}_d \text{ and if } \Delta\text{for} = 0, \quad \text{then } \Delta\text{CF} < 0 \text{ and } \Delta\text{past} < 0 \tag{14}$$

where *Δfor* is the annual variation in fuelwood extraction area in ha, *ΔCF* the annual variation in CF (dimensionless) and *Δpast* the annual variation in pastoral land in ha.

Additional demand for food crops will result mainly in agricultural intensification with livestock being increasingly fed on crop residues, but also, in a lesser way, in expansion of cultivation in pastoral land. Intensification is defined as the substitution of capital, labour or technology for land in order to produce more on the same area. In Sudano-sahelian agriculture, intensification mostly takes place as a shortening of fallow cycle, compensated by the use of labour and agricultural inputs such as organic or mineral fertilisers to maintain soil fertility (Sanders et al., 1990; Diop, 1992; Gray, 1999). Because of deficiencies in output and input data, the crop-fallow cycle is used as a proxy variable to measure intensification (following Boserup, 1965 and Turner II and Brush, 1987). This indicator is expressed by the ratio between fallow area and cropland

$$\text{CF} = \frac{\text{Fal}}{(\text{CropS}_d + \text{CropM}_d)} \tag{15}$$

$$\Delta\text{fal} = (\Delta\text{Crop}_d * \text{CF}_{1961}) - ((\text{Land}_d - \text{UN}) * (1 - \text{r})) \tag{16}$$

where *Δfal* is the annual variation in fallow area in ha, CF_{1961} the CF in 1961 and *r* the ratio of pastoral land to cropland . These two last indicators are dimensionless. Part of the additional demand for food crops will also lead to the expansion of cultivation in pastoral land. Actually, the economic value of the output per unit of area is much higher for cultivated fields than for pastoral land in an extensive system (de la Masselière, 1984; Okoruwa et al., 1996). The exact proportion of additional food demand which is satisfied by intensification of cultivation and expansion of cultivated fields in pastoral land is set arbitrarily at 80% for the former and 20% for the later.

The increase in livestock population combined with shrinking pastoral lands (due to agricultural expansion) will result in partial sedentarisation of livestock, with greater reliance on crop residues for consumption, and overgrazing on pastoral land (Sinclair and Fryxell, 1985; Hellden, 1991). Sedentarisation is modelled by an increase in the share of crop residues in livestock consumption ($\frac{2}{3}$ of biomass consumed, see above). The modelling of overgrazing is described below. There are few reported instances of intensification of livestock grazing in the Sudano-sahelian region. Practices such as artificial fertilisation, livestock stabling and cultivation of fodder crops are unusual in this region (Le Houérou and Hoste, 1977).

6. Endogenous pressure indicators

Agricultural intensification leads to a decrease in labour productivity and requires the use of organic or chemical inputs. A shortening of the fallow cycle without input use would deplete soil fertility. Several "pressure indicators" are generated endogenously by the model: labour productivity, agricultural input use as a function of the average household budget, maintenance of soil fertility in cultivated fields, and rate of land degradation in pastoral land due to overgrazing. These indicators are symptoms of changes in the system and can be interpreted to identify some sustainability thresholds, which might affect decision-making processes by farmers and pastoralists.

6.1. Labour productivity

Labour productivity is defined by the output per hour of labour, or the income per unit of time invested (Stomal-Weigel, 1988). In the intensification process, labour productivity decreases because the increase in labour input is more than proportional than the production increase (Bonnefond and Couty, 1988). Estimating the time allocated to agricultural work is difficult due to differences by gender and age, varying labour efficiencies, seasonal distribution of tasks, and inherent difficulties in labour time estimation. The model defines the labour quantity as the number of hour per day allocated to agriculture per rural worker. This time allocated to agricultural work is proportional to CF, as a proxy for intensification:

$$\mathrm{LabourQy} = \mathrm{a} + \mathrm{b} * \mathrm{CF} \tag{17}$$

where *LabourQy* is the labour quantity in hours in agricultural work/day∗inhab, and *a* and *b* are dimensionless parameters. From several studies in Africa (Cleave, 1974; Raynaut et al., 1988; Stomal-Weigel, 1988), an average labour time allocated to agriculture is 200 h per year per inhabitant under an extensive farming system, i.e. with a CF of 2. The highest level of agricultural intensity found in West African agriculture, i.e. with a CF of 0.5 (Ruthenberg, 1976; Raynaut, 1985), is characterised by an addition of 4 h per day of farming work (Netting et al., 1993). Based on this reference, we estimated empirically the parameters of the above relationship ($a = 5.833$ and $b = -2.667$). Labour productivity is then computed by the ratio between the agricultural output and the amount of labour performed by the rural workers for a given year. Agricultural output is measured by the cultivated area multiplied by the average crop yield.

$$\mathrm{LabourPy} = \frac{\mathrm{Crop} * \mathrm{CropY}}{\mathrm{Pop}_{\mathrm{rur}} * \mathrm{LabourQy} * 365} \tag{18}$$

where *LabourPy* is the labour productivity in kg/hour of work.

6.2. Agricultural input use and household budget

When the length of fallow decreases, farmers introduce technological inputs to maintain soil fertility. By reference to a detailed study in Senegal (Diop, 1992) and various other studies in West Africa (Retaille, 1984; Raynaut, 1985; Claude et al., 1991; Seini et al., 1995), an average cost is 24,000 FCFA for agricultural inputs per agricultural exploitation in the first stage of the transformation of shifting cultivation systems into permanent farming (Boserup, 1965; Ruthenberg, 1976). The fallow is substituted by mainly natural fertilisers and selection of seeds, with only a minor use of mechanisation (Diop, 1992). The mean farm size in Senegal is estimated at 4.5 ha (Ancey, 1977; Little et al., 1987; Pieri, 1989; Saul, 1991). The model estimates the necessary investment in agricultural inputs per hectare to maintain the yield level on the entire cultivated area. We assume that the cost of inputs per hectare in Senegal and other Sudano-Sahelian countries are equal. This quantity of inputs (mostly fertilisers) is expressed in monetary value (cost of inputs)

$$\mathrm{InputC} = \mathrm{Crop} * \mathrm{InputP} * (\mathrm{CF}_{1961} - \mathrm{CF}) \tag{19}$$

where *InputC* is the input cost in FCFA and *InputP* the input price in FCFA/ha. To maintain fertility, the agricultural inputs must compensate the decrease in fallow time. If farmers are not able to afford this cost, e.g. because their monetary income would be too low, then a decrease in soil fertility in cropland takes place (Traoré and Galley, 1979). The model computes this degradation of soil fertility by comparing the investment in agricultural inputs to the shortening of the fallow (see below).

The ability to invest in agricultural inputs depends on the household budget, which is computed as the difference between incomes and expenses. The share of production sold on the market generates incomes from which one subtracts the cost of the substitutes for fuelwood and the cost of agricultural inputs. Food demand of the urban population defines the amount of food crops sold on the market. However, this also depends on cereal imports (an exogenous variable) which are used to feed urban population. The monetary value of food crops sold on the market (50 FCFA/kg) is computed from average market prices for millet and sorghum (Bonnefond and Couty, 1988)

$$\text{HhInc} = (\text{Crop} - \text{CropS}_\text{d}) * \text{CropY} * 50\,\text{FCFA/kg} \tag{20}$$

where *HhInc* is the household income in FCFA. Note that several studies reveal that non-farm activities represent an important part of the income in rural regions of West Africa (Reardon et al., 1988; Staatz et al., 1990). Since, these activities do not modify directly land-use, they are not represented explicitly in the model. There is just a fixed income from non-farm activities which is added to the income generated from the sale of food crops on urban markets.

The household income is in part used to acquire agricultural inputs, provided that such inputs are needed (i.e. provided that the farmers have entered in the intensification phase). Only a fraction of the household income can be allocated to acquiring inputs, as there are a number of other needs (housing, clothing, taxes, leisure, etc.). Based on empirical studies, the model considers that the maximum share of the income which is allocated to buying agricultural inputs is 13% (Retaille, 1984; Diop, 1992; Seini et al., 1995). If the cost of the required inputs is inferior to this value, the land fertility is maintained. If the cost of inputs exceeds this threshold, a decline in soil fertility is taking place. Indeed, the rate of soil fertility decline depends on the amount of inputs that are used in relation with the fallow cycle.

6.3. Maintenance of soil fertility of cultivated fields

A shortening of the fallow cycle and an insufficient use of agricultural inputs reduces soil fertility of fields and, therefore, has a negative impact on crop yields. The model estimates this soil degradation as a dimensionless indicator

$$\text{Deg} = \frac{2 - \text{CF}}{2} + \frac{\text{InputC} - \text{Invest}}{\text{InputC}} \tag{21}$$

where *Deg* is the dimensionless indicator of degradation and *Invest* the investment in FCFA. In the absence of any fallow and fertilisers, yields decrease by 20% after 4 years of permanent cultivation (Pieri, 1989). In extensive farming systems in African savannahs, 4 years is the usual time limit to put the land into rest (Pieri, 1989; Olsson and Rapp, 1991; Guyer and Lambin, 1993). We extrapolate this rate of yield reduction to establish a linear relationship between the period under continuous cultivation and yield decrease, in the absence of any agricultural inputs

$$\frac{\text{CropY}_t}{\text{CropY}_{t-1}} = 1 - (0.05 * \text{y}) \tag{22}$$

where *y* is the number of years under continuous cultivation (dimensionless). The slope of this relationship varies between two extremes: (i) fertility maintenance through either adequate fallow cycle or input use and (ii) rapid loss of soil fertility due to continuous cultivation and no input use. A combination of reduced fallow and inadequate fertility conservation methods would lead to a moderate rate of yield reduction, described by

$$\frac{\text{CropY}_t}{\text{CropY}_{t-1}} = 1 - (0.05 * \text{y} * \text{Deg}) \tag{23}$$

6.4. Land degradation in pastoral land due to overgrazing

To model the process of overgrazing, the carrying capacity concept is used for the sake of simplicity (Bartels et al., 1993). It is defined here as “the stocking number supported without range degradation, with livestock being well and taking weight" (Boudet, 1975). Depending on ecoclimatic zones, pastoral exploitation systems, estimates of average carrying capacity vary from 10 ha/TLU in drier years to 3.5 ha/TLU in normal years (Boudet, 1975; Penning de Vries and Djitèye, 1982). Actual measurements of carrying capacities are 2 ha/TLU (Horowitz and Salem-Murdock, 1993) and 1.25 ha/TLU (Boulier and Jouve, 1990). Overgrazing is defined by the stocking outnumbering the carrying capacity. Tolerance levels are estimated in the literature from 160 to 200% of the carrying capacity (Picardi and Seifert, 1976; Bartels et al., 1993).

The model represents a transhumant pastoral system where, beyond a certain threshold, plant biomass decreases proportionally to the increase in animal biomass. As the expansion of pastoral land is limited by other land-uses, an increase in livestock population on shrinking pastoral land decreases land productivity. The model compares the maximum carrying capacity (1.25 ha/TLU) to the available pastoral land and its stocking rate

$$\text{Overg} = \frac{\text{Liv} - (\text{Past}/\text{CC})}{\text{Past}/\text{CC}} \tag{24}$$

where *Overg* is the dimensionless indicator of overgrazing and *CC* the carrying capacity (1.25 ha/TLU). This high value of carrying capacity accounts for herds mobility and for the pastoral strategy of minimising the understocking. Once the actual stocking rate is larger than this carrying capacity, a process of rangeland degradation is set up. Empirical data in the "Mare d'Oursi" (Burkina Faso) reveal that an overstocking of 36% reduces land productivity by 30% (Claude et al., 1991). Other authors (Penning de Vries and Djitèye, 1982) suggest that these figures are grossly overestimated given the resilience of Sahelian ecosystems, and that the relationship between plant and animal biomass is negatively asymptotic. Actually, estimating quantitatively dryland degradation is almost an impossible task. In the absence of any other published quantitative study, and to be conservative, we adopted arbitrarily a value of only 10% of the land productivity reduction estimated by Claude et al. (1991) in response to overstocking. This is thought to better account for the ecological resilience of rangelands and for the adaptive strategies of pastoralists. This figure is extrapolated to a linear function where the level of overstocking determines the slope of the relation between biomass productivity and rainfall

$$\text{If } \frac{\text{Liv} - (\text{Past}/\text{CC})}{\text{Past}/\text{CC}} \geq 0, \text{ then BiomPy} = 0.15 + 0.00375R,$$

$$\text{If } \frac{\text{Liv} - (\text{Past}/\text{CC})}{\text{Past}/\text{CC}} < 0, \text{ then BiomPy} = 0.15 + \text{b} * \text{R with b} = \text{d} + \text{c(Overg)},$$

$$\text{If Liv} = \frac{\text{Past}}{\text{CC}}, \text{ then d} = \text{b} = 0.00375,$$

$$\text{If } \frac{\text{Liv} - (\text{Past}/\text{CC})}{\text{Past}/\text{CC}} = \frac{0.36}{0.30} * 10 = 12, \text{ then b} = 0 \text{ and c} = \frac{-0.00375}{12}$$

where *b*, *c* and *d* are statistically derived parameters (dimensionless). The relation becomes

$$\text{BiomPy} = 0.15 + (0.00375 - 0.0003125(\text{Overg})) * \text{R} \tag{25}$$

7. Dynamic character of the model

Fig. 1 represents the overall structure of the model. This includes: (i) the exogenous driving forces of land-use changes, (ii) the competition for land-use allocation, (iii) the different phases of land-use changes and (iv) the pressure indicators. Table 1 summarises the values of the main parameters of the model and their sources, and Table 2 lists the variables. The model is dynamic in the sense that it includes multiple interactions between processes, feedback loops and endogenous changes in "phases" of land-use change corresponding to different levels of farming technologies. For example, the processes leading to land degradation link agricultural intensification, average household income, commercialisation, rural and urban demand for food products, cereal imports, etc. (Fig. 2). Land degradation is thus the result of complex interactions between numerous factors. In no way it can be reduced to a simple population–degradation relationship. It can only be predicted using a dynamic, system approach.

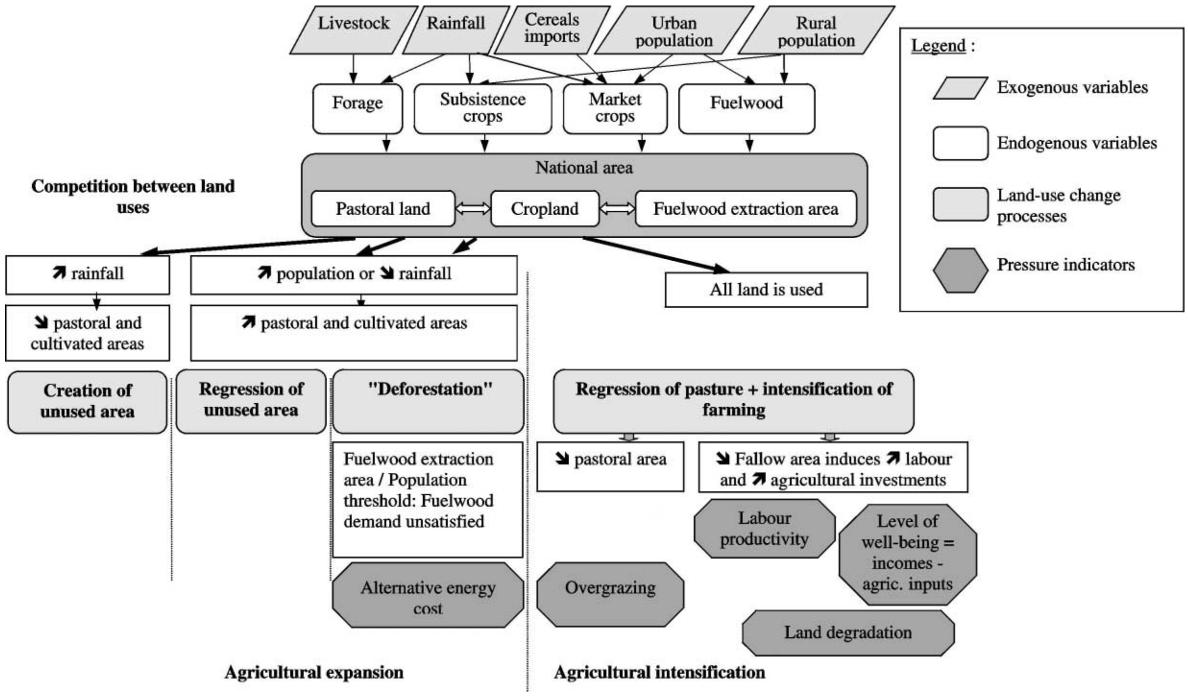

Fig. 1. Overall structure of the model.

Table 1
Summary of the values retained for the main parameters of the model, and literature sources from which these values where derived

Consumption parameters			
Food consumption	FoodC	300 kg/inhab∗year	Bolwig (1995), Boulier and Jouve (1990), Claude et al. (1991), Gueymard (1985), Lambin (1988), Netting et al. (1993), Raynaut (1985), Reardon et al. (1988), USED (1985)
Livestock forage consumption	BiomC	4.6 tonnes/equiv TLU∗year	Behnke and Scoones (1993), Boudet (1975), Claude et al. (1991), Groten (1991), Lambin (1988), Ministère de la Coopération (1984), Penning de Vries and Djitèye (1982), Pieri (1989)
Fuelwood needs: urban consumption	$FuelC_{urb}$	0.85 m^3/inhab∗year	CTFT (1989), Jensen (1997), Lambin (1988), Pieri (1989), USED (1985)
Fuelwood needs: rural consumption	$FuelC_{rur}$	0.65 m^3/inhab∗year	CTFT (1989), USED (1985)
Productivity parameters			
Fuelwood productivity in natural vegetation	VegPy	0.75 m^3/year	CTFT (1989), Lambin (1988), Pieri (1989), van Lavieren and van Wetten (1990) quoted by Horowitz and Salem-Murdock (1993), Yung and Bosc (1992)
Crop-fallow cycle/cultivation frequency	CF	2 years/3 under crops	Boulier and Jouve (1990), Claude et al. (1991), CTFT (1989), Guyer and Lambin (1993), Pieri (1989), Raynaut (1985), Ruthenberg (1976)
Carrying capacity	CC	1.25 ha/TLU	Boudet (1975), Boulier and Jouve (1990), Horowitz and Salem-Murdock (1993), Penning de Vries and Djitèye (1982)
Fuel substitution	FuelS	66,900 FCFA/m^3	CTFT (1989), Jensen (1997), Legendre (1997)

Table 2
Summary of the notations and dimensions for the main exogenous and endogenous variables of the model

Main variables	Notation	Dimension
Exogenous variables		
Cereal imports	CImp	kg
Livestock	Liv	equivalent TLU
Rainfall (annual average)	R	mm
Rural population	Pop_{rur}	inhab
Urban population	Pop_{urb}	inhab
Land-use variables		
Used area	U	ha
Unused area	UN	ha
National area	N	ha
Land demand	$Land_d$	ha
Cropland	Crop	ha
Cropland demand for market	$CropM_d$	ha
Cropland demand for subsistence	$CropS_d$	ha
Fallow area	Fal	ha
Fuelwood extraction area (natural vegetation)	Veg	ha
Initial forest area	Veg_i	ha
Demand for forest area	Veg_d	ha
Pastoral land	Past	ha
Demand for pastoral land	$Past_d$	ha
Annual variation (in most of the preceding variables)	ΔD	ha
Biomass productivity	BiomPy	tonnes/ha
Crop yield	CropY	kg/ha
Endogenous processes		
Overgrazing	Overg	Dimensionless
Cultivation frequency	CF	Dimensionless
Cultivation frequency in 1961	CF_{1961}	Dimensionless
Degradation	Deg	Dimensionless
Energy cost	EnergC	FCFA
Household income	HhInc	FCFA
Input cost	InputC	FCFA
Input price	InputP	FCFA/ha
Investment	Invest	FCFA
Labour productivity	LabourPy	kg/hour of work
Labour quantity	LabourQy	hours/day∗inhab
Ratio pastoral land to cropland	r	Dimensionless
Number of years under continuous cultivation	y	Dimensionless

8. Application of the model to Burkina Faso

The model was first tested at a national scale using data from Burkina Faso, over the period 1960–1997. The annual rate of population growth was 2.4% in Burkina Faso during the 1960–1990 period. Droughts have been frequent in the Sahel over the 1972–1984 period (Nicholson, 1989; Jouve, 1991). The model simulates changes in land-use over the study period for all land-use categories (Fig. 3).

Results show land-use changes at two time frequencies: high frequency, as driven by climatic variability, and low frequency, as driven by demographic trends. Concerning the short-term events, every drought period is associated with a slight expansion of cropland and pastoral land in fuelwood extraction areas (until 1988) and in unused land. Once rainfall recovers to a normal level, a peak increase in unused land is observed (e.g. in 1985, after the 1984 drought). Concerning the longer term trends, a phase of expansion

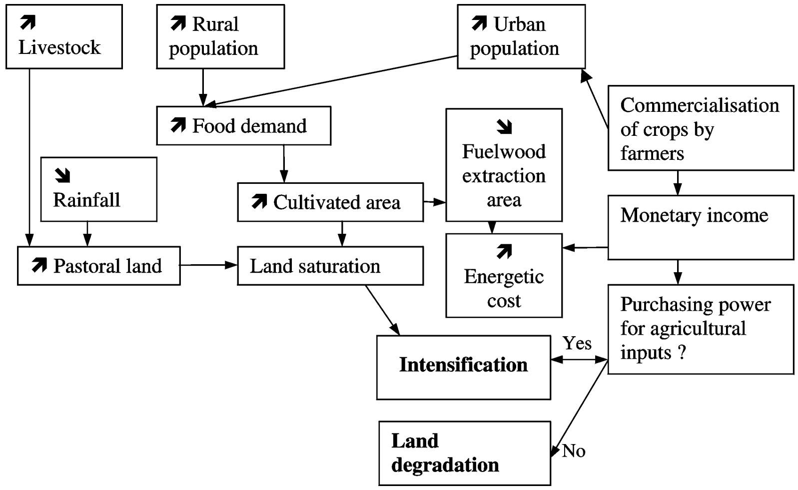

Fig. 2. Dynamic interactions between the processes leading to land degradation.

of cropland, fallow and pastoral land accompanied by deforestation first appears in 1970s and early 1980s. At the end of this phase, deforestation is stopped, due to constraints on the conservation of a minimum fuelwood extraction area. Cultivated areas and fallows continue to increase. The area allocated to crops for the market increases steadily, as a response to the rapid increase in urbanisation. This increase takes place at a faster rate than the total cropland area as the urban population grows faster than the rural population. After 1983, the system oscillates between the phases of agricultural expansion and intensification. The first signs of land degradation in cropland appear in 1991. Degradation in pastoral land, caused by overgrazing, appears sporadically, mostly in 1980s.

At a first glance, by reference to the literature on land-use changes in the Sudano-sahelian countries, this simulation is a plausible representation of the land-use evolution in Burkina Faso. In the expansion phase, from 1960 to 1983, case studies evidence from the Burkina Faso provide quantitative information mainly for the change in cropland. The rate of change

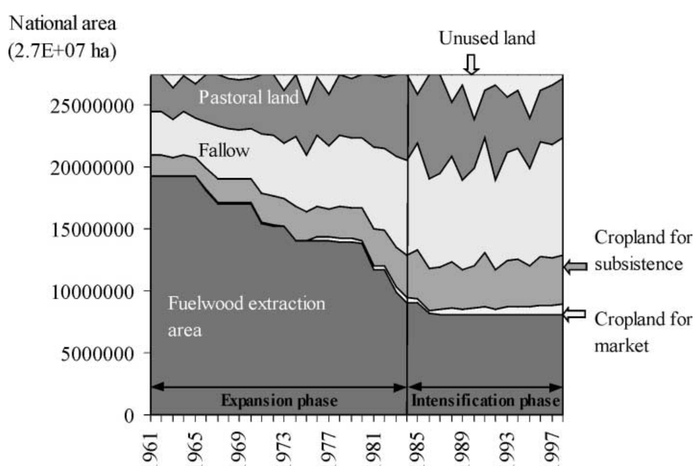

Fig. 3. Model simulations of land-use changes in Burkina Faso.

Table 3
Annual rates of land-use changes in the expansion phase from the model simulation and from literature sources

Expansion phase (1961–1983)		Annual rates of change in cropland (%)
SALU model Burkina Faso[a]		4.91
Lindqvist and Tengberg (1993)	1955–1974	4.87
Northern Burkina Faso		
Gilruth and Hutchinson (1990)	1953–1989	5.31
Fouta Djallon, Guinea		
Raynaut et al. (1988)	1957–1975	5.80
Maradi, Niger Tarka		
Magami		4.00
Sharken H.		1.40
Gourjae		2.90
Average		3.00
Reenberg et al. (1998)	1945–1955	3.44
Oudalan Province, Burkina Faso		
	1955–1986	1.83
Moussa (1999)	1956–1996	2.00
SO Niger Bogodjotou		
Ticko		1.60
FAO (1995), Faostat — series statistics, Burkina Faso	1961–1984	1.65

[a] BF: Burkina Faso.

of 4.9% predicted by the model simulations is similar to the rate of change measured by Lindqvist and Tengberg (1993) — 4.9% in northern Burkina Faso. Over the same period, other studies throughout the Sudano-sahelian region report cropland expansion at annual rates from 3 to 5.8% (Table 2). Note that, the rate of cropland expansion for Burkina Faso based on the Faostat data is only 1.6%. In the period after the first occurrence of intensification (1984), expansion of cropland is predicted by the model to take place at a rate of 1.4%. This is lower than the figure provided by Lindqvist and Tengberg (1993) for northern Burkina Faso (2.9%). Other studies in the Sudano-sahelian countries reveal a similar range of values (Tables 3 and 4).

Table 4
Annual rates of land-use changes in the period following the first occurrence of intensification (1984) from the model simulation and from literature sources

Intensification phase (1984–1997)		Annual rates of change in cropland (%)
SALU model Burkina Faso[a]		1.42
Lindqvist and Tengberg (1993)	1955–1981	2.88
Northern Burkina Faso		
Gilruth and Hutchinson (1990)	1973–1985	11.59
Fouta Djallon, Guinea		
Reenberg et al. (1998)	1988–1989	4.84
Oudalan Province, Burkina Faso		
	1989–1991	2.84
	1991–1995	1.58
Moussa (1999)	1975–1996	3.40
SO Niger Bogodjotou		
Ticko		2.80
FAO (1995), Faostat — series statistics, Burkina Faso	1985–1997	1.34

[a] BF: Burkina Faso.

However, the rate of cropland expansion in Faostat data is much lower compared to all these local studies (1.3%).

9. Discussion

Models are always based on simplifications. In this case, the computation of the area under pastoral land (Eq. (5)) assumes that land management and soil attributes do not influence biomass productivity in a significant way. Concerning the first factor, this is an acceptable assumption in the Sudano-sahelian region given the extensive character of pastoral activities. Concerning the second factor, as the model is not spatially explicit, it only represents average soil attributes. Several authors, however, caution that low availability of soil nutrients is a more serious constraint on rangeland production and quality than low rainfall (Penning de Vries and Djitèye, 1982; Breman and de Wit, 1983). The estimation of crop yield (Eq. (8)) also ignores cropping systems, soil fertility and the distribution of rainfall during the growing season. Some management factors are however introduced through the crop-fallow cycle and the use of agricultural inputs. Improving these production functions would increase the realism of the model but also its data requirements.

Particular land-uses which are of a small extent in most Sudano-sahelian countries, such as irrigated fields or forest plantations around settlements are not represented in the model, even though their importance for household economies can be significant. Protection of forest reserves, which is included in the model, is generally observed in rural regions but the satisfaction of energy requirements for the urban population does induce widespread deforestation in peri-urban areas. Finally, the model uses the concept of carrying capacity in rangelands, which has lost currency in ecology. Critics of this concept find arguments either in natural opportunistic pastoral strategies of herdsmen to avoid understocking (Sandford, 1982), or in the actual growth of herds beyond this capacity (Bartels et al., 1993). State and transition models (Westoby et al., 1989) and “non-equilibrium” models (Ellis and Swift, 1988) seem to be more appropriate to describe rangeland modifications. We are aware of these different paradigms, but we still use the carrying capacity concept as a simplification to model in a more “static” way the stocking pressure on rangelands.

A number of improvements to this initial version of the model are being considered. In the current model, the consumption pattern is assumed to be constant. In reality, it could shift towards more affluent diet with an increase in level of well-being. More fundamentally, the model is not spatially explicit but only predicts aggregated values of land-use change. We are currently disaggregating the model per eco-climatic zone within each country (e.g. mostly pastoral Sahelian zone versus Sudanian zone dominated by farming). This will allow varying key parameters such as wood productivity or carrying capacity, which can be given a different value for different ecological zones. A more systematic sensitivity analysis of the model to parameter values will also be conducted.

In the current version of the model, the “pressure indicators” are only diagnostic indicators of the system. In a more sophisticated use of the model, the pressure indicators could be used in a goal programming approach to better represent the decision process of land managers. Actually, land managers could express preferences for their labour productivity, their income or the conservation of their natural environment. They could also maximise productivity or minimise risk under certain constraints. These different attitudes, reflecting different values, will lead to a different allocation of land.

We are currently testing the model for other Sudano-sahelian countries. Currently, the study area is closed, except for food imports. For a regional application of the model, spatial interactions between countries (e.g. balanced, not prescribed trade patterns) should be represented. Finally, the model outputs are currently being validated by comparing the land-uses projected by the model for 1992–1993 to the land-cover map produced by IGBP-DIS from remote sensing data, for the same years. This “validation” only concerns the “quantity” of land-use categories and not their location.

10. Conclusion

A simulation model which was specifically aimed at generating simulations of land-cover changes at a coarse spatial resolution was developed. This model is specific to the Sudano-sahelian countries. The main characteristic of the approach lies in the definition of values for the parameters of the model on the basis of a comprehensive review of the literature, mostly of local scale case studies of land-use changes in the Sudano-sahelian countries. New values of the exogenous variables of the model are introduced in the model on a yearly time step and drive changes in land-use allocation. The model predicts endogenously changes in the technology of farming systems. Pressure indicators are also generated endogenously by the model. The model was applied at a national scale using data from Burkina Faso. Results simulate land-use changes at two time frequencies: high frequency, as driven by climatic variability, and low frequency, as driven by demographic trends. The model predicts an increase in land degradation in the early 1990s. The rates of cropland expansion predicted by the model are consistent with rates measured for several case studies, based on fine spatial resolution remote sensing data. In the model simulations, intensification appears in Burkina Faso in the mid-1980s.

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