GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2012) **4**, 859–874, doi: 10.1111/j.1757-1707.2011.01147.x

Spatiotemporal land use modelling to assess land availability for energy crops – illustrated for Mozambique

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Abstract

A method and tool have been developed to assess future developments in land availability for bioenergy crops in a spatially explicit way, while taking into account both the developments in other land use functions, such as land for food, livestock and material production, and the uncertainties in the key determinant factors of land use change (LUC). This spatiotemporal LUC model is demonstrated with a case study on the developments in the land availability for bioenergy crops in Mozambique in the timeframe 2005–2030. The developments in the main drivers for agricultural land use, demand for food, animal products and materials were assessed, based on the projected developments in population, diet, GDP and self-sufficiency ratio. Two scenarios were developed: a business-as-usual (BAU) scenario and a progressive scenario. Land allocation was based on land use class-specific sets of suitability factors. The LUC dynamics were mapped on a 1 km^2 grid level for each individual year up to 2030. In the BAU scenario, 7.7 Mha and in the progressive scenario 16.4 Mha could become available for bioenergy crop production in 2030. Based on the Monte Carlo analysis, a 95% confidence interval of the amount of land available and the spatially explicit probability of available land was found. The bottom-up approach, the number of dynamic land uses, the diverse portfolio of LUC drivers and suitability factors, and the possibility to model uncertainty mean that this model is a step forward in modelling land availability for bioenergy potentials.

Keywords: bioenergy potentials, GIS, land use change, model, Mozambique, spatiotemporal uncertainty modelling

Received 5 September 2011 and accepted 14 October 2011

Introduction

Dedicated bioenergy crops are assumed to be the main contributors to future bioenergy supplies (Smeets *et al.*, 2007; Dornburg *et al.*, 2010). Therefore, land availability for energy crop production is one of the key determining factors for bioenergy potentials. As competition for land and related indirect land use changes (iLUC) is to be avoided (IPCC, 2011), the land available for bioenergy crops depends on the land required for other land use functions.

In recent years, an increasing number of studies have been published on bioenergy potentials on a global (e.g. Berndes *et al.*, 2003; Hoogwijk *et al.*, 2005; Smeets *et al.*, 2007; Dornburg *et al.*, 2010), European (e.g. Ericsson & Nilsson, 2006; EEA, 2007; Fischer *et al.*, 2007; de Wit & Faaij, 2010), national (e.g. Faaij *et al.*, 1998; van den Broek *et al.*, 2001; Walsh *et al.*, 2003; Sang & Zhu, 2011) and regional levels (e.g. van Dam *et al.*, 2009a). However, most of these studies have assessed biomass potentials on a spatially aggregated level. The disadvantage of such studies is that they provide only limited information on the location of the land available for bioenergy crops. Potential yield levels and environmental and socioeconomic impacts of energy crop production are strongly related to the physical and socioeconomic conditions of a location (van Dam *et al.*, 2009a,b; Van der Hilst *et al.*, 2010; Beringer *et al.*, 2011); therefore, it is important to assess where land is (or could become) available for bioenergy production.

Land use changes (LUC) result from complex interactions between human and biophysical driving forces that act over a wide range of temporal and spatial scales (Verburg *et al.*, 1999). Several methodologies and models have been developed to simulate and explore LUC (Veldkamp & Lambin, 2001). These models differ in terms of scale (e.g. regional, global), process (e.g. deforestation, urbanization), discipline (e.g. economic, environmental), approach (e.g. extrapolating historical

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trends, driving forces) and complexity (e.g. methods, resolution). A review of several land use models is provided by Agarwal *et al.* (2001) and Verburg *et al.* (2004). The Integrated Model to Assess the Global Environment (IMAGE) is an example of a framework that models LUC on a global level (Alcamo *et al.*, 1998; MNP, 2006). However, the global modelling level, the aggregated modelling approach and the low number of both dynamic land use types and allocation factors make it less suitable for regional or national assessments. Lapola *et al.* (2010) used the LandSHIFT model to simulate LUC on a national level to assess iLUC and related carbon emissions for a fixed biofuel production target in Brazil for 2020. However, due to the low resolution and the limited number of both dynamic land use classes and allocation factors, this type of modelling is less suitable for spatially detailed analyses of multiple dynamic land use types. The Conversion of Land Use and its Effects (CLUE) modelling framework was developed in 1996 and has progressively been improved since then (CLUE-s and Dyna-CLUE) (e.g.Veldkamp & Fresco, 1996; Verburg *et al.*, 1999; Overmars *et al.*, 2007; Verburg & Overmars, 2009). The CLUE modelling framework proves that it is possible to model LUC on a more detailed level, taking into account driving forces at different spatial levels. However, as the CLUE modelling approach is based on the competition between land use functions, it suggests some form of top-down land use planning. However, LUC is not always policy driven and is in less developed countries often related to local mechanisms. Moreover, CLUE does not consider the effects of the uncertainties in the input data on the results of LUC modelling.

The objective of this study is to develop a new LUC model to assess the development in land availability for bioenergy crops on a detailed spatial level, taking into account the dynamics of several other land use functions and the uncertainties in drivers of LUC. The model is specifically developed for less developed countries characterized by subsistence farming, a low density of infrastructure and a lack of top-down land use planning. The LUCs in these types of countries are driven by environmental and socioeconomic factors and are influenced by national or regional land use planning and policies to a much lesser extent. A multitude of driving forces and suitability factors are included in the model. The detailed spatial level, the number of dynamic land uses, the diversity in driving forces and suitability factors, and the possibility to model uncertainties in a spatially explicit way serve as a step forward in LUC modelling for less developed countries. This model is especially developed to assess the land availability for bioenergy crops and therefore provides opportunities to assess how iLUC effects are to be avoided. The technical characteristics of the model are described in Verstegen *et al.* (2011). This paper will show the functionality of the model and methodological issues related to LUC modelling with a case study on the development of land availability for bioenergy crops in Mozambique towards 2030. Mozambique was selected as a case study area as it is a promising region for biomass production within southern Africa as a result of the availability of land (Batidzirai *et al.*, 2006; Namburete, 2006), the favourable environmental conditions for agricultural production (INE, 2003; Batidzirai *et al.*, 2006) and the current low agricultural productivity which offers a great potential for improvement. The main incentives for the government of Mozambique to focus on the development of a bioenergy industry are to decrease the country's dependence on oil imports and to enhance energy security and socioeconomic and sustainable development, especially in rural areas (Conselho de Ministros da república de Moçambique, 2009). The fragmentation of current land use and the high spatial variation in climate and soil conditions in Mozambique requires a high spatial resolution of LUC and bioenergy potential modelling.

The methodology section will elaborate on the steps required to model LUC over time in a spatially explicit way. The online supporting information provides all input data used for the land use modelling of Mozambique. The Results section examines the typical results that can be produced with the model, including the uncertainties in output calculated from uncertainties in input and model parameters. The Discussion and conclusion section will elaborate on the relevant outcomes of the Mozambique case study and the consequences of the characteristics of the model and of the methodological choices made.

Methodology

It is of key interest to assess how competition for land and related effects of iLUC can be avoided; therefore, the modelling of the land availability for energy crop production needs to take into account the land required for other land use functions. Land use requirements for crop and livestock production depend on the developments in food demand and agricultural productivity. Consequently, land use is dynamic over time. This study includes the demand for food, feed and materials (including wood) which results in a claim on land for crop production and grazing area as well as in deforestation. To project the dynamics in these land use functions over time, future developments regarding the main drivers for LUC need to be identified and quantified.

Drivers of land use change

The main LUC drivers are the developments in the demand for food, feed and materials and the productivity of the agricultural sector. The demand for domestically produced food and feed is related to developments in population size, GDP, food intake per capita and self-sufficiency ratio (SSR, i.e. the extent to which domestic supply meets domestic demand) (FAO, 2003b). The amount of land required to meet the total demand for food, animal products and materials depends on the efficiency of the agricultural sector. Developments in the efficiency of crop production are related both to the exploitable yield gap, i.e. the gap between current yields and agro-ecological or maximum attainable yields (FAO, 2003b), and to the rate of technology adoption, i.e. the implementation pace of improvements in crop production. The efficiency of livestock production is related to the distribution of supply between types of production system (pastoral or mixed), the feed composition (the share of feed supplied by grazing, scavenging, residues and feed crops) and the feed conversion efficiency (the amount of animal product per unit feed) of the production systems. The land requirements for feed crops and pastures depend on the feed crop yield and the carrying capacity of pastures. The development in drivers of demand and the development in agricultural productivity in Mozambique are described in Table 1 and are quantified in more detail in the online supporting information (section A1.1 Table A1 and A2).

Developments in the demand for wood are related to the developments in total population, the ratio between urban and rural population, the adoption of improved cooking technologies, the domestic use of poles and other timber, and the export quantity of industrial round wood. The domestic wood supply can be roughly divided into two categories: wood that is sustainably extracted from the forest and wood whose logging results in deforestation. As this study focuses on LUC dynamics, only the wood demand that leads to deforestation has been included, defined as the illegal and unsustainable wood harvesting in forest areas. Thus, sustainable logging and logging in other woodland is not included. The developments in wood demand and deforestation in Mozambique are quantified in the online supporting information (section A1.1 Table 3).

Scenario approach

As it is uncertain how LUC drivers evolve and the prediction of land use developments is problematic (Verburg *et al.*, 2004), a scenario approach was used to explore potential long-term developments in LUC driving forces. The use of scenarios to explore potential LUC developments has already been demonstrated by Strengers *et al.* (2004),, Hoogwijk *et al.* (2005, 2009), Westhoek *et al.* (2006) and de Vries *et al.* (2007). In this study, the narratives developed for the Special Report on Emissions Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC) (Nakicenovic *et al.*, 2000) were translated into specific scenarios for Mozambique to develop a consistent set of assumptions for the assessment of future land use dynamics. Two divergent storylines were developed: a business-as-usual (BAU) scenario based on the B2 storyline and a progressive scenario based on the A1 storyline. The developments in the key drivers of LUC, demographics, consumption patterns and GDP are rather unpredictable, which justifies the creation of divergent scenarios regarding the development of these driving forces. Still, for reasons of transparency, the developments in these main drivers are kept equal for the two scenarios and an uncertainty analysis in which these drivers are modelled stochastically is assumed to be the most suitable way to address the sensitivity of the results to these parameters. This implies that population, GDP, diet and SSR will change over time, but that the rate of change is equal for the two scenarios. The divergent storylines were used to explore possible developments in technological, institutional and societal changes which result in changes in productivity in the agricultural sector. Table 1 presents a qualitative description of the current status and the characteristics of the scenarios. The development in the drivers is quantified for the two scenarios in the online supporting information (section A1.1, Table A1, A2 and A3).

Land use modelling

Due to variations in agro-ecological conditions, the yields of crops, pasture and wood are spatially highly heterogeneous. Therefore, the total amount of land required to meet the demand for food, wood and animal products is directly related to the location of the specific land use class. Several studies on LUC have developed methodologies for land use allocation. Land use classes can be modelled dynamically (related to LUC drivers), passively dynamically (not linked to a demand but susceptible to change when other land use functions expand) or statically (excluded from any LUC). The characteristics of the land use classes that are modelled dynamically, passively dynamically and statically in this study are described in section A1.2 and Table A4 of the online supporting information.

In this study, the allocation of land to dynamic land uses classes is based on the suitability of the location for a specific land use class which is defined by a combination of several selected spatially explicit suitability factors. In some LUC models, a multiple regression model is applied to identify the driving forces and assess the influence of these factors on land use, e.g. in Veldkamp & Fresco (1996) and Verburg *et al.* (1999). However, these models require historical data of the land use patterns, and these are not available for Mozambique. Moreover, extrapolation of regression analysis may produce dubious results as historical driving forces for LUC may no longer be detected or no longer be relevant. This is especially true for countries where historical developments are characterized by discontinuities, such as war or natural disasters. The limited predictive value and uncertainty of the causality are drawbacks of the statistical quantification based on historical developments (Veldkamp & Verburg, 2004). In this study, driving forces have been identified by expert consultation and literature review. In addition to environmental driving forces, land use modifications are strongly influenced by socioeconomic and policy-related issues (Lambin *et al.*, 2001). However, incorporating such factors is hampered by a lack of spatially explicit socioeconomic data and the methodological difficulties in linking socioeconomic and environmental data (Veldkamp & Lambin, 2001). In this study, both environmental and socioeconomic drivers are taken into account. In line with Veldkamp & Lambin (2001), proxy indicators have been selected to represent socioeconomic driving forces. The suitability factors selected in

Table 1 Current status and development of key drivers of land use change for the business-as-usual (BAU) and progressive scenarios

	Current	BAU scenario	Progressive scenario
Population*	Population size: 22.9 million people Average population density: 29 p km^{-2} Rural population: 63.5%	Population size: 33.9 million people by 2030 Average population density: 43 p km^{-2} in 2030 Rural population: 46% in 2030	
GDP†	Average annual growth rate: 8% (1994–2007)	Average annual growth rate: 6.6% up to 2030	
Diet‡	Average caloric intake: 2050 kcal cap^{-1} day^{-1} Animal product consumption: 1.4% of caloric intake. The average diet consists mainly of roots and tubers and to a lesser extent of cereals	Average caloric intake: 2550 kcal cap^{-1} day^{-1} (2030) Animal product consumption: 3.7% of caloric intake The proportion of the total diet supplied by cereals increases at the cost of roots and tubers	
SSR	Self sufficient for most food crops. Main import products: cereals and animal products Main export products: tobacco, cotton, sugar and wood	The SSR ratios will remain constant up to 2030 and export will remain at today's levels	
Farming practices	Farming system: subsistence farmers (95%) Cultivation area size of 0.5–1.4 ha in shifting cultivation, clearing by burning	Continuation of current practices, a modest shift towards commercial farming	Shift towards commercial farming, shifting cultivation is progressively abandoned
Technological adoption§	Low adoption of improved seeds (5–10% of farmers), fertilizers (3.9%), pesticides (4.5%), irrigation (5%) and animal or mechanical traction (11% and 3%)	Continuation of current trends in input levels	Increasing share of farmers have access to improved seeds, fertilizers, agro-chemicals, knowledge, machinery and irrigation
Agricultural productivity¶	Very low agricultural productivity (e.g. average maize yields are <1 ton ha^{-1}) and cropping intensity (60%)	A modest increase in yield (0.6% p.a.) and cropping intensity (0.5% p.a.), in line with historical trends	Higher agricultural productivity due to higher yields (3.5% p.a.) and increased cropping intensity (2% p.a.)
Livestock sector**	Low livestock numbers. Development of the sector is hampered by the lack of disease control. Cattle and ruminants are kept in pastoral systems and extensive mixed systems. Low feed conversion efficiencies in both systems	No additional policies to prevent diseases. Partial shift from pastoral systems to mixed systems. Modest growth in feed conversion efficiency	Effective policies focusing on disease control. Strong shift towards mixed systems. Increased feed conversion efficiencies in both pastoral and mixed systems
Deforestation††	High deforestation rates due to high wood demands and lack of enforcement	No additional policies, regulation and enforcement. Continuation of current trends in deforestation	Additional policies, regulation and enforcement to prevent further deforestation

Table 1 (continued)

	Current	BAU scenario	Progressive scenario
Bioenergy implementation	Bioenergy projects implemented in a developing institutional and regulatory framework	No major changes in policies, technologies and current practices	Bioenergy is implemented in a controlled and sustainable environment

*Population figures are based on FAO (2010a) and UNDP (2008). Population density varies strongly between regions.

†GDP figures are based on IMF (2007, 2010). Despite the high economic growth, about 54% of the population remains in poverty today. The poverty line is set based on the value of a basket of basic needs goods based on consumption patterns of the poor and varies by province (Fox *et al.*, 2005).

‡Figures on dietary intake are based on FAO (2003b, 2010a). Due to an unequal distribution of food and to the dietary composition, a large proportion of the population suffers from undernourishment.

§Figures on the use of inputs are derived from Bias & Donovan (2003), INE (2003) and the World Bank (2006). The lack of both financial resources and markets causes the low adoption of inputs (World Bank, 2006).

¶Figures are based on INE (INE, 2003)and FAO (FAO, 2010a). There is little incentive to increase production because of a lack of markets, insufficient access to markets, a lack of a viable market prices and insufficient storage capacity. The cropping intensity is the area harvested expressed as a percentage of the arable area (FAO, 2003a). Arable land includes temporarily (less than 5 years) fallow land, but abandoned land resulting from shifting cultivation is not included in this category (FAO, 2005a).

**Livestock figures are based on (Otte & Chilonda, 2002; INE, 2003; FAO, 2005b; FAO & WFP, 2010). Pastoral systems are based on extensive grazing, whereas mixed systems are based on both grazing and feed crops. There is a strong spatial variation in the distribution of livestock: cattle is mainly concentrated in the south, due to the prevalence of the Tsetse fly and related diseases in central and northern parts of Mozambique (Timberlake & Reddy, 1986; INE, 2003; Maposse *et al.*, 2003). Pigs, chickens and small ruminants are kept all over the country with higher concentrations in the central and northern parts of Mozambique.

††Estimations of deforestation rates in Mozambique vary between 0.2% and 5.6% (Mangue, 2000; Pereira *et al.*, 2001; Del Gatto, 2003; Nhancale *et al.*, 2009; FAO, 2010b). Causes of deforestation are high demands for fuel wood and charcoal (Cuvilas *et al.*, 2010), high export rates of industrial round wood (80%) (FAO, 2010b), poor control on temporarily logging concessions and illegal logging (Del Gatto, 2003; MacKenzie, 2006; Nhancale *et al.*, 2009; Cuvilas *et al.*, 2010).

this study are proximity to same land use class, distance to roads, distance to water, distance to cities, distance to forest edge, potential yield level, population density, cattle density and conversion elasticity. For each land use class, a suitability map was constructed based on the spatially weighted summation of a specific set of individual suitability factors. For each suitability factor, the direction of the relation (e.g. does the suitability increase or decrease with distance to road), the type of correlation (exponential, linear, inversely related) and the maximum distance of effect (e.g. up to what distance from the road does the road still influence LUC) were determined. The characteristics of the suitability factors for land use allocation are further explained in the online supporting information (section A1.2, Table A5).

Areas that are not suitable (e.g. steep slopes) or not allowed (e.g. conservation areas) to be converted to agricultural land were excluded. Table A6 of the online supporting information provides an overview of the excluded areas and the spatial data used. In some land use models (such as CLUE), the allocation of land has been based on the highest suitability of one land use class compared with the other land use classes (Verburg & Overmars, 2009). This approach serves top-down land use planning, which regulates land use in such a way that land is used for the best possible application. Yet, in this study, a fixed order for allocation is used. The order of allocation applied in this study is (1) forest (deforestation does not compete with other land use functions), (2) cropland, (3) mosaic cropland-pasture, (4) mosaic cropland-grassland and (5) pasture. This implies that the land use category 'deforestation' is allocated first to the best suitable places for deforestation until the demand (for wood that results in deforestation) is met. Deforestation can only occur on land currently in use as forest. Subsequently, cropland is allocated to the locations best suitable for cropland, until the demand of that particular year is met by the production (Area × Location specific productivity × Management level). Subsequently, mosaic cropland-pasture, mosaic cropland-grassland and pastures are allocated. This order of allocation is based on the assumed economic importance and the labour requirements of these land use classes from the individual farmer's perspective. This allocation mechanism is considered to be more realistic for less developed countries, where there is usually no top-down land use planning but a more locally driven LUC.

Land is allocated to a land use class in time steps of 1 year. This allocation of land within one time step stops when the production of that land use class has met the demand for that particular time step. The amount of land required to meet the demand depends on the productivity of the land allocated and on the agricultural efficiency during that time step. Once the land has been allocated, it cannot change to another land use class during the same time step (because in that case supply will not meet demand). The total allocation is completed for one time step when all the land use classes have been allocated and the production of these land use classes meets the total demand for that particular time step. This results in a new land use map for that time step. The modelling comprises a feedback loop: the

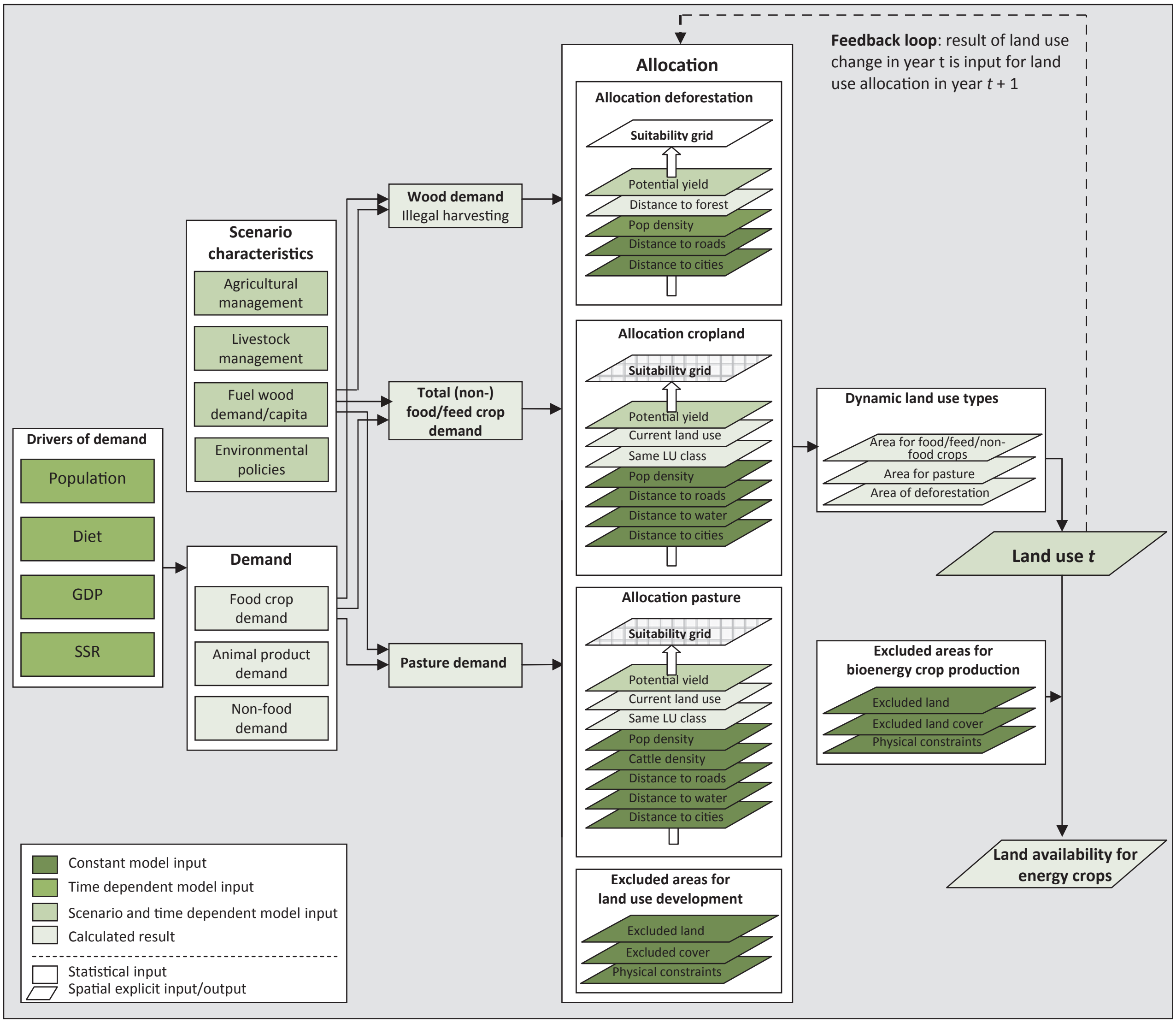

Fig. 1 Overview of the modelling of land availability for bioenergy crops.

land use resulting from the allocation in time step *t* serves as input for the allocation in time step *t* + 1.

Figure 1 shows how the dynamics of land use classes are modelled and how they influence the land availability for energy crop production. LUC drivers (population, diet, GDP and SSR) determine the demand for food crops and animal products for each time step (see section Drivers of land use change). The scenario characteristics determine the developments in the productivity of both crop cultivation and the livestock sector, the fuel wood demand per capita and the deforestation rates (see section Scenario approach). Based on the demand for animal products and the efficiency of the livestock sector, the amount of feed crops and pasture is calculated. Based on population growth and the fuel wood demand per capita, the total fuel wood demand is calculated. Based on a specific set of suitability factors, the excluded land and the order of allocation, land is allocated to the different land use functions (see section Land use modelling). This results in a new land use map. Based on this land use map and a map of the areas that are excluded for bioenergy crops (such as community land) in addition to the areas already excluded for LUC, the land availability for bioenergy crops is determined. The land use map which results from the land use allocation of year *t* serves as input for the land use allocation in year *t* + 1.

To enable the modelling of future land use as depicted in Fig. 1, a spatiotemporal land use model has been developed based on the building blocks of the PCRaster Phyton framework (Karssenberg *et al.*, 2010; PCRaster, 2010). The key inputs for the PCRaster Land Use Change model (PLUC) are time series of demand and productivity development, dynamic land use classes, suitability factors per land use class, the initial land use map that designates the initial configuration of these land use classes and several maps of suitability factors (e.g. population density and distance to road). The parameterization of these and additional inputs are discussed in the online supporting information.

The major advantage of this model framework is its ability to deal with stochastic input data. This enables spatiotemporal Monte Carlo (MC) runs that evaluate uncertainty propagation. PLUC can stochastically model time series (e.g. crop demand and agricultural productivity), spatial input parameters (e.g. population density and productivity) and characteristics of suitability factors (e.g. the maximum distance of effect in the distance to road). The stochastic inputs can be based on different error models: an uniform distribution between two values, a normal distribution given the mean and fixed standard deviation (SD), and a relative distribution given the mean and a relative SD. When a uniform error model is applied, all values between the upper and lower limit have equal probability. The normal error model has a normal distribution of probabilities, with 95% of all selected values within the range of the mean ± 1.96 SD. The relative error model also has a normal distribution, but with the SD relative to the mean. The probability distribution of stochastic inputs is equal for each time step. More information on the stochastic input variables and the applied error models is provided in the online supporting information section A1.2.3 and Table A7. The probability of the availability of land for bioenergy can be calculated by means of an MC analysis. The probability can not only be analysed at a grid cell level but also at a provincial or national level. More information on the technical characteristics and stochastic input modelling of PLUC can be found in Verstegen *et al.* (2011). The software package AGUILA enables the visualization of the results of the PLUC model for every individual time step (de Jong, 2009; Karssenberg *et al.*, 2010). It can show the development in LUC and the land availability for bioenergy crops for a deterministic run, as well as the development in the probability of land availability for bioenergy crops for a MC run.

Results

This section provides some selected results and uncertainty analyses that are illustrative for the possibilities of the developed model. A more elaborate overview of typical results and uncertainty analysis can be found in Verstegen *et al.* (2011).

Developments in demand, productivity and land requirements

Figure 2 depicts the total domestic food and nonfood production for the timeframe 2005–2030. The total food demand that needs to be produced domestically is expected to increase from 11.5 Mt in 2005 to 24.7 Mt in 2030.

In the BAU scenario, the total wood demand increases from 19.4 million m^3 in 2005 to 39.0 million m^3 in 2030, of which 43% is expected to result in deforestation. In the progressive scenario, the total wood demand increases to 20.2 million m^3 for 2030. This lower wood demand results from the adoption of improved stoves and alternative fuels. As in this scenario deforestation is to be prevented, 9.2 million m^3 should be produced in alternative ways by 2030. The prevention of deforestation is a result of strong policy measures assumed in the progressive scenario.

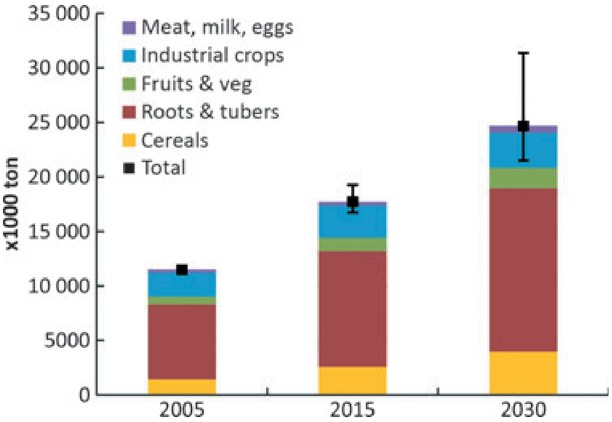

Fig. 2 Total food and nonfood crop demand in timeframe 2005–2030 considering the developments in population growth, dietary intake and SSR ratios. The error bars indicate the range in demand given the lower and higher projections for population growth (32–36 million people in 2030; UNDP, 2008) and dietary intake (2050–2980 kcal cap^{-1} day^{-1} in 2030; FAO, 2003b).

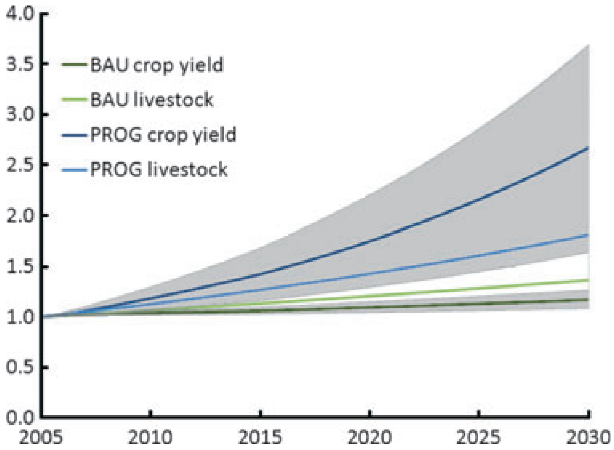

Fig. 3 Development in crop and livestock productivity in the BAU and progressive scenarios in the time frame 2005–2030, normalized for the productivity levels of 2005 (2005 = 1). The bandwidths represent the range of the uniform distribution of the stochastic input of yield developments for the BAU and progressive scenarios.

The land required to meet the demand depends on the developments in agricultural productivity. In Fig. 3, the developments in the productivity of crop cultivation and livestock production are presented for the two scenarios. It shows the normalized productivity increase compared to the level of the year 2005, based on the

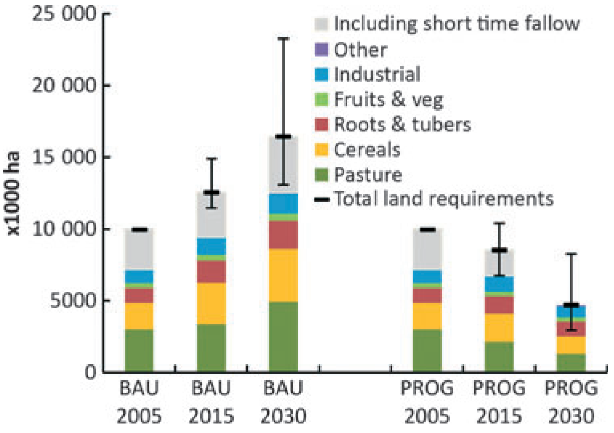

Fig. 4 Land requirements for livestock grazing and crop production for the timeframe 2005–2030 for the BAU (left) and progressive (right) scenarios, given the same distribution over productivity classes of pasture and arable land as in 2005. The error bars represent the range in total land requirement given the uncertainties in total demand (Fig. 2) and productivity (Fig. 3).

weighted summation of the productivity increase per crop (based on the proportion of cultivated area) and the weighted summation of the productivity increase per animal product (based on the proportion of total volume). The bandwidth of the curves of the development in crop productivity in the BAU and progressive scenarios represents the range of the stochastic input of the maximum attainable yield (see section A1.2.3 of the online supporting information on stochastic model inputs).

Figure 4 presents the land requirements to meet the total crop and grazing demands for the BAU and the progressive scenarios, assuming the same distribution of cropland and pasture over potential yield classes as in 2005. In the BAU scenario (left), there are two reasons why the land required for crops and pasture increases: an increased demand caused by population growth and a rise in food intake per capita, and a relatively low growth in productivity. In the progressive scenario (right), both pastures and arable land areas decline due to increased yield levels of pasture and crops and a greater efficiency in livestock production. The upper sections of the bars (grey shade) indicate the additional land required due to low cropping intensities, i.e. it accounts for the land that is left fallow for a short time. The error bars indicate the uncertainty in the total land requirements given the uncertainty in the development in demand (see Fig. 2) and the uncertainty in crop productivity in both scenarios (Fig. 3). The positive error value is bigger than the negative error value as a consequence of the uncertainty distribution of demand (see Fig. 2), which is also skewed. By 2030, the land requirements in the BAU scenario are 3.3–3.7 times higher than in the progressive scenario.

As the location of the land is an important determinant factor for the yield of crops and pastures, the actual land requirements can only be calculated when spatial land use allocation is taken into account. Therefore, the PLUC model has been applied to assess the land requirements in a spatially explicit manner.

Deterministic spatial modelling results

Figure 5 displays the results of the deterministic simulations of LUC for the BAU and the progressive scenarios. In the deterministic run, the uncertainties in input parameters have not been modelled. Figure 5 shows the land use for 2005 (time step 1, same for both scenarios), 2015 (time step 11) and 2030 (time step 26). In the subsequent maps for 2015 and 2030, it is apparent that cropland, mosaic cropland-pasture, mosaic cropland-grassland and pasture areas are expanding in the BAU scenario, whereas these land use types are contracting in the progressive scenario. In the BAU scenario, the shift towards pure or mosaic cropland and pastures is most profound close to main cities and in proximity to the road network. The expansion of agricultural land use is mainly at the expense of forest (76%) and shrubland (21%). In the progressive scenario, there is a shift from the more extensive mosaic cropland towards specialized cropland close to the main cities and in proximity to the road network. Extensive mosaic cropland and pastures are progressively abandoned due to the intensification of crop and livestock production. This is most apparent in the remote semi-arid and less populated areas (Gaza and Tete provinces). Another important difference between the scenarios is the development in autonomous deforestation, in addition to forest converted to agricultural land uses. In the BAU scenario, deforestation is most apparent along the main road network. The location of deforestation is especially influenced by the 'proximity to road infrastructure' and 'distance to forest edge' as included in the allocation procedure. This is in line with the observed LUCs in Manica province where LUCs were most common within 5 km from the roadside and where deforestation was the most dominant LUC (Jansen *et al*., 2008). The expansion of the deforested areas is most profound in the first 10 time steps. Due to the assumed regeneration of forest, the expansion of deforestation slows down in the BAU scenario. In the progressive scenario, it is assumed that deforestation can be prevented from 2011 onwards, and the effects of deforestation are no longer visible after 2020.

The developments in land availability for biofuels over the timeframe 2005–2030 are presented in Fig. 6.

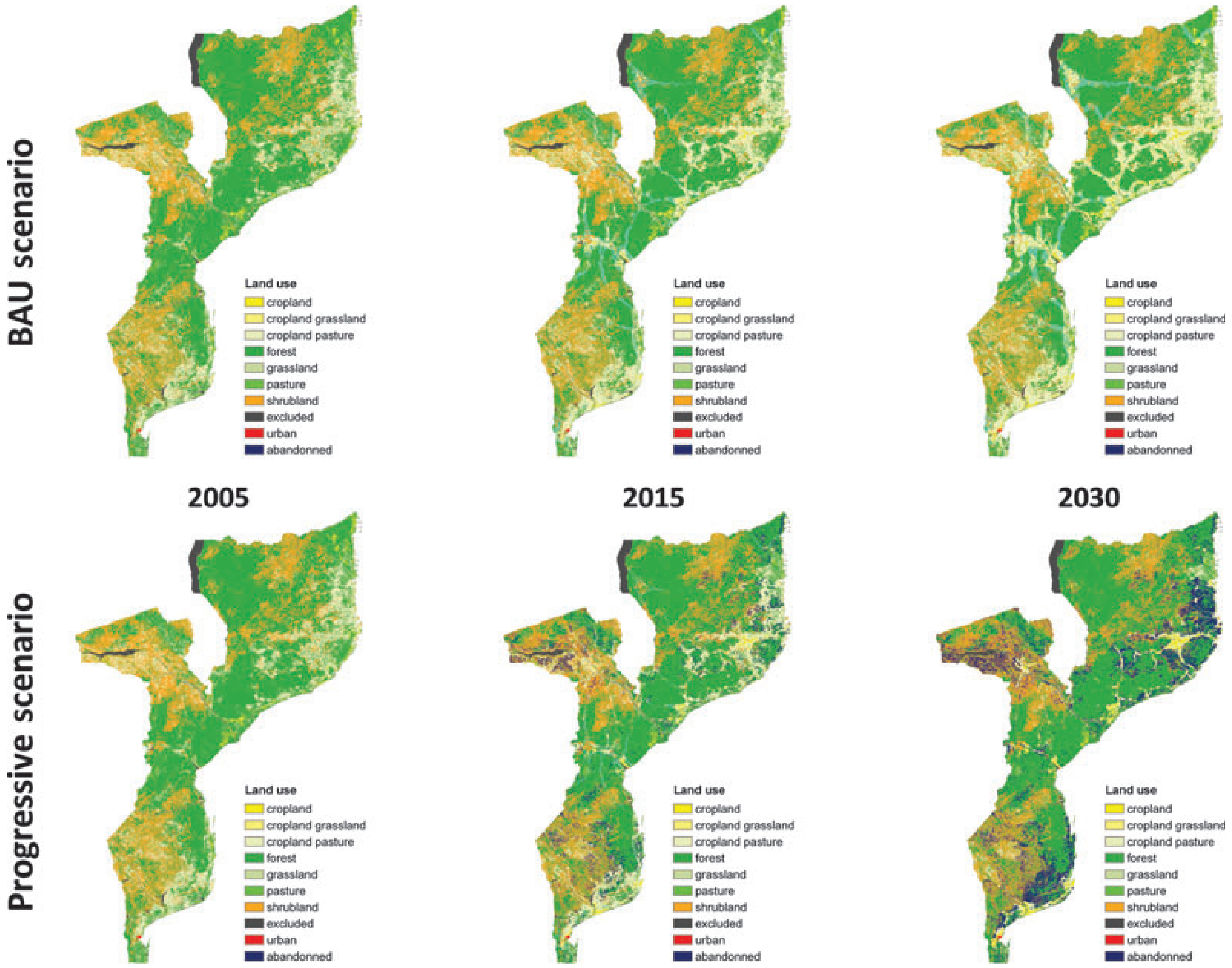

Fig. 5 Land use dynamics up to 2030 for the BAU (upper maps) and progressive scenarios (bottom maps).

The red areas indicate areas that are not available for bioenergy crops. These areas have been excluded because they are used for other land use functions, such as cropland, pasture, forest and urban areas, or because they are not suitable (e.g. regularly flooded areas or steep slopes). In the BAU scenario, the available land area decreases as land required for pasture and crops expands. As the expansion of cropland and pasture areas occurs mainly in the densely populated areas close to the main cities and road network, the land available for bioenergy is decreasing most rapidly in these areas (e.g. along the main North-South road and the Beira corridor). The areas which remain available for bioenergy crops are the more remote and less productive areas: in the central northern parts (Cabo Delgado, Niassa and Nampula provinces; mainly moderately to marginally productive), the north-western parts (Tete province; mainly marginally to nonproductive) and south-western parts (Gaza province; mainly marginally to nonproductive). In the progressive scenario, the area required for crop and livestock production decreases over time. Mainly areas with an initially high proportion of mixed cropland-grazing become available. These areas are mostly situated in the south-east (Inhambane province; moderately to very productive), north-east (Nampula province; marginally to very productive) and north-west (Tete province; marginally to nonproductive).

Figure 7 displays the development in available land for bioenergy crop production until 2030 according to the deterministic run for the two scenarios. For the BAU scenario, land availability decreases over time from 9.1 to 7.7 Mha. For the progressive scenario, the land availability for bioenergy crop production increases from 9.1 to 16.4 Mha. As the progressive scenario assumes that no deforestation will take place, the wood demand needs to be supplied in alternative ways. In 2030, 0.4 Mha of forest plantation would be required to com-

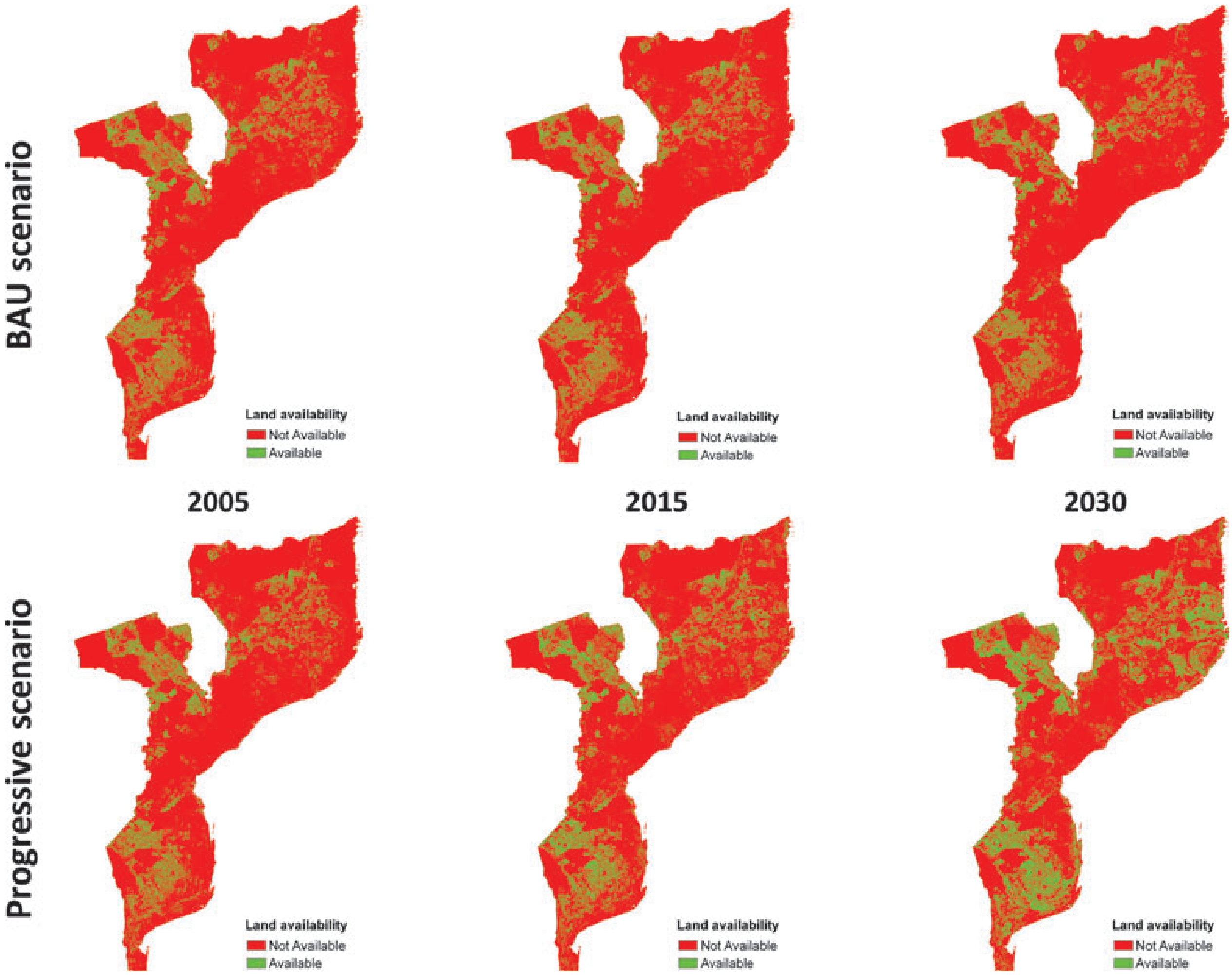

Fig. 6 Land availability for bioenergy crops in 2005, 2015 and 2030 for BAU and progressive scenarios (based on deterministic runs). Red areas indicate the areas that are not available, whereas the green areas are the areas available for bioenergy crop production.

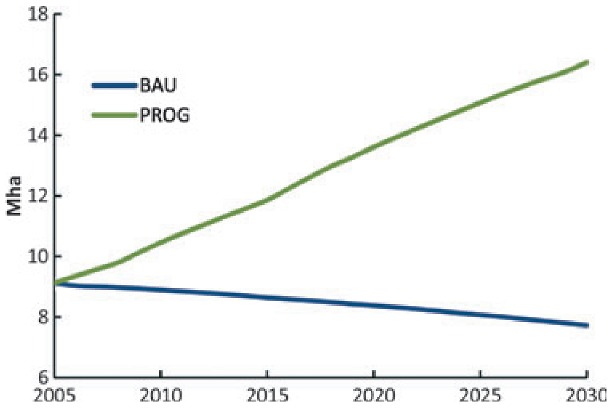

Fig. 7 The development of land availability for bioenergy crop production over time for the BAU (lower trend line) and progressive scenarios (upper trend line).

pensate for the fuel wood consumption (based on the assumed average productivity of the available land in 2030).

In Fig. 8, the developments regarding land availability for bioenergy crops for 2005, 2015 and 2030 for the two scenarios are depicted; the available land is differentiated for five productivity classes. The productivity classes provide the percentage of the maximum attainable yield given the level of agricultural management. The nonproductive category includes areas that produce <20% of the maximum attainable yield. Although the marginal suitable soils are not very productive (20–40%), these areas should not be excluded beforehand for energy crops (as productivity of the area is just one of many criteria for site selection). However, suitable bioenergy crops for these areas should be selected with

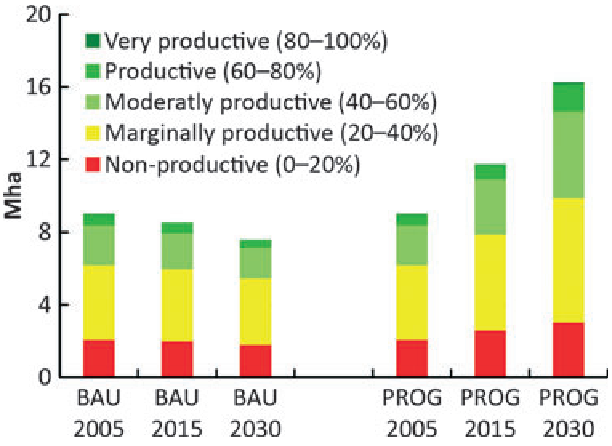

Fig. 8 The development of land availability over time differentiated for suitability classes for the BAU (left) and the progressive scenarios (right).

care. The most productive areas available for bioenergy are located close to the Malawian border and in the central north-eastern part of the country (Zambezia and Nampula provinces).

Uncertainty in spatial modelling results

The results described above were generated with deterministic runs of the model. By running an MC sample of 500 realizations, the effect of the uncertainties in input variables and model parameters can be assessed on the land availability for bioenergy crops. The uncertainties included in this MC analysis are listed in Table A7 of the online supporting information. Figure 9 presents the uncertainty in land availability for bioenergy crops in the BAU scenario for the time frame 2005–2030. The blue-grey area indicates the 95% confidence interval, which ranges from 6.1 to 8.2 Mha for 2030. This means that 95% of all realizations of the MC sample result in a land availability within this range. The median, represented by the black line, is slightly different from the deterministic run of the BAU scenario (see Fig. 7), because the deterministic input of demand is not equal to the mean of the uniform distribution of the stochastic input of demand (see Fig. 2) and because the nonlinear relationships between the uncertainty in input parameters and the uncertainty in the results.

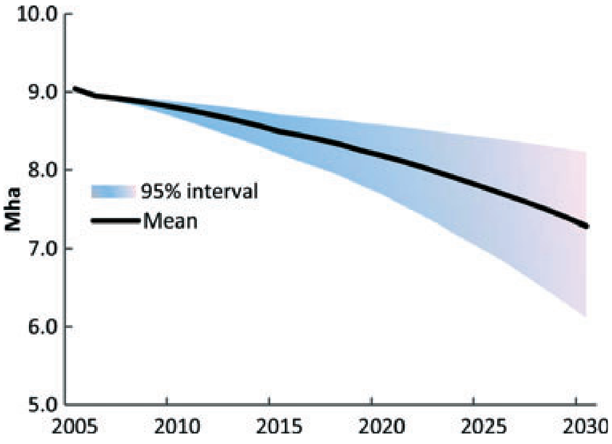

Fig. 9 Uncertainty in land availability for bioenergy crops in the BAU scenario for the time frame 2005–2030.

For all the realizations of the MC sample, the land availability for bioenergy crops has also been mapped spatially. The probability of the availability of the grid cell for bioenergy crops was determined by combining the maps of all these realizations of the MC sample. Figure 10 depicts the probability of land availability for bioenergy crops in the BAU scenario for three time steps. A value 0 indicates that the grid cell is unavailable in all realizations, whereas 1 indicates that the grid cell is available in all realizations. In 2005 (time step 1), there is already some uncertainty (the grid cells do not only have the values 0 and 1, but also values between 0 and 1). This is because the initial land use map was calibrated based on the yield map, whereas the yield map is a stochastic inputs in this uncertainty assessment in time step 1. The uncertainty increases over time because the uncertainties of the input parameters increase over time and because of the feedback loop in the model. As the rate and shape of expansion of the dynamic land uses differ for each realization in the MC sample, the uncertainty is most apparent at the edges of expansion (see Fig. 10). The areas that are excluded based on non-dynamic land use (e.g. nature conservation areas) do not contribute to the uncertainty and dominate the total excluded land area. Therefore, the uncertainty in land availability is restricted to certain areas.

The MC assessment can be used to exclude areas for which it is uncertain whether they will be occupied by other land use functions. For example, only the land that is available in 95% of the realizations of the MC analysis could be labelled 'available for bioenergy crops'. The application of this threshold results in a lower estimation of land available for bioenergy crops than the results of the deterministic run. For the BAU scenario, the deterministic run results in 9.1 Mha available in 2005, but when a threshold of 95% is applied in the MC run, only 9.0 Mha is available. For 2030, the deterministic run indicates a land availability of 7.7 Mha, whereas the 95% confidence interval of the MC analysis indicates 5.7 Mha. As uncertainty is propagated over time, the difference increases over time between the results of the deterministic run and the 95% confidence thresholds of the MC analysis. The amount of land labelled as available decreases when the confidence threshold is increased (e.g. to 99% confidence).

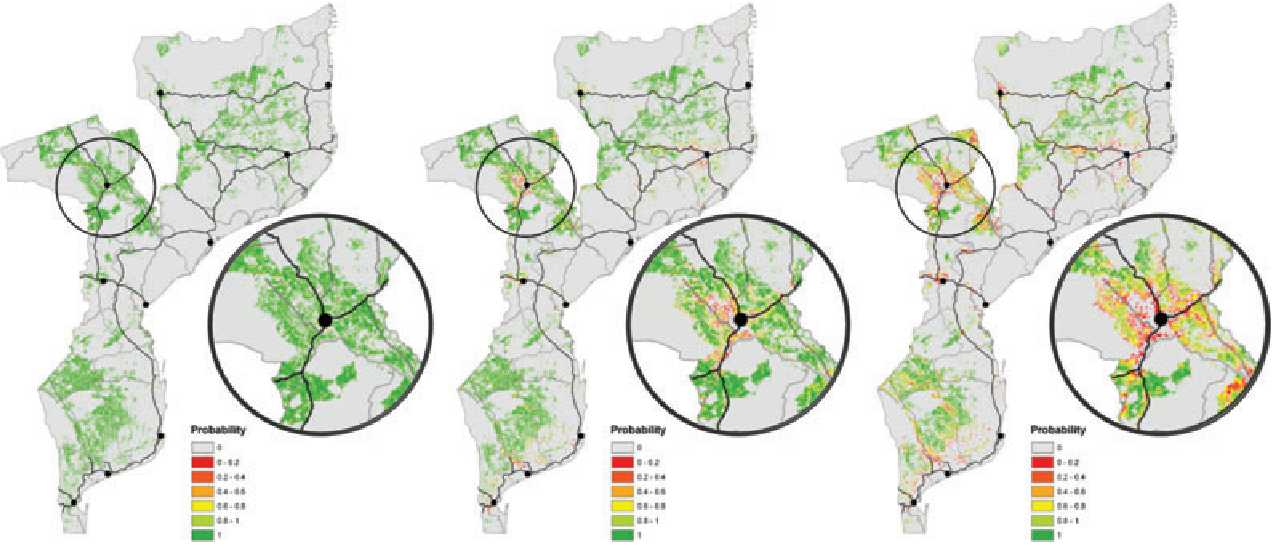

Fig. 10 Probability of land availability for bioenergy crops at grid cell level for several time steps for the BAU scenario based on stochastic input variables of several parameters (see the online supporting information section A1.2.3 and Table A7).

In addition to the probability on grid cell level based on several stochastic inputs, the PLUC model enables other types of uncertainty analyses, such as the probability of land availability based on uncertainty in a single parameter, the probability of land availability at a provincial level or the probability of exceeding the threshold of total biomass production given a specific bioenergy crop. More information on error propagation and uncertainty assessments on several spatial levels can be found in Verstegen *et al.* (2011).

Discussion and conclusion

This study has determined the potential development of spatially explicit land availability for bioenergy crop production, taking into account the dynamics in agricultural land use and deforestation. As bioenergy crop production was not included as a dynamic land use class, the competition for LUC or iLUC as a result of bioenergy crop production has not been modelled in this study. If competition between bioenergy crops and other land uses is to be modelled, the implementation of bioenergy crops should relate to a projected demand (e.g. national biofuel blending targets), as demonstrated for Brazil by Lapola *et al.* (2010). However, the starting point of this study is that competition for land is to be avoided, and therefore, land was excluded if it was (potentially) in use for other land use functions. In this study, a fixed allocation order was applied to the other land use classes; consequently, the competition between the land use functions based on macroeconomic parameters was not modelled. To properly model competition between land uses, extensive information is required on market developments, price elasticity and policies. The interaction between macroeconomic and land use modelling is beyond the scope of this study.

Land required for food production has been excluded from the conversion to bioenergy crop production. As the estimated average food intake by 2030 (2550 kcal cap^{-1} day^{-1}) is still below the estimated average of developing countries in 2030 (2980 kcal cap^{-1} day^{-1}) (FAO, 2003b), it can be argued that for food security reasons the domestic production and the related claim of land should be higher. On the other hand, food security is not only an issue of food availability but also of food accessibility. It is assumed that the current SSRs of food continue towards 2030. However, it may be argued that the SSR ratios will decrease, in line with the FAO projection for sub-Saharan countries (Otte & Chilonda, 2002; FAO, 2003b). This would imply a lower domestic production and therefore a reduced land claim. The returns from biofuel export and/or the decreased expenditure on oil imports could contribute to food security by increasing purchasing power.

Only two of the nine suitability factors for land use allocation ('number of neighbouring cells in the same land use class' and 'conversion elasticity matrix') change over time as a result of the output of the model (output of t is input for $t + 1$). However, other suitability factors such as 'population density', 'distance to road' and 'distance to cities' are expected to change over time due to a shift from rural to urban population, the development of new infrastructure and the emergence of new economic centres. This will affect future

LUC and will therefore influence the location and the amount of land available for bioenergy crops. However, the dynamics of these suitability factors were not modelled over time in a spatially explicit manner because of a lack of knowledge and data regarding these future developments.

The calibration of the ESA 2005 land use map with statistics was used as a starting point for the land use modelling. The ESA 2005 land cover map was the most recent detailed map available. In addition, 3 year averages of production statistics were used to correct for weather-related annual fluctuations, and statistics were only available up to 2008. Validation of high spatial resolution is difficult and sometimes even impossible when validating future land use (Verburg *et al*., 1999). Historical analyses could contribute to the validation of the model, but in the case of Mozambique, this was not realistic because of the lack of historical (spatial) data and discontinuities in historical land use developments due to the struggle for independence and the civil war. Therefore, it was not possible to assess whether modelled patterns in LUC match historical and current LUC dynamics. With more spatially detailed datasets of land use becoming available, future validation of the model will be possible.

For the model developed in this study and the developments in detailed spatial land use modelling in general, there is an increased requirement for high quality and more detailed spatial data. This was also concluded by Schmit *et al.* (2006) for assessments in Europe. However, it is especially true for less developed countries such as Mozambique, which are characterized by dynamic developments and where systematic (statistical) data gathering is still in a developing phase.

As the scenarios developed in this study are highly divergent, the outcomes of the assessment provide a wide range of possible future developments. The land available for bioenergy crops in the BAU scenario decreases over time from 9.1 to 7.7 Mha. This is caused by the expansion of cropland and pastures required to meet the increasing demand for food and animal products. The areas which will remain available for bioenergy crops are the more remote and less productive areas: in the central northern parts (Cabo Delgado, Niassa and Nampula provinces; mainly moderately to marginally productive), the north-western parts (Tete province; marginally and nonproductive) and south-western parts (Gaza province; marginally and nonproductive). In contrast, the progressive scenario shows increasing land availability for bioenergy crops: from 9.1 Mha in 2005 to 16.4 Mha in 2030. In this scenario, mainly areas with an initially high proportion of mixed cropland-grazing will become available, and this is caused by more efficient agricultural production. These areas are mainly situated in the south-east (Inhambane province; marginally to very productive), north-east (Nampula province) and north-west (Tete province). By 2030, the land available in the progressive scenario is almost twice as high as in the BAU scenario. This estimated potentially available land for bioenergy crops in the timeframe 2005–2015 is in the same order of magnitude as the range found in other studies, namely 6.0–13.2 Mha (Batidzirai *et al.*, 2006; DNTF, IIAM & CeneCarta, 2008; Econergy, 2008). However, in this paper, the potential is determined in a spatially and temporal explicit and probabilistic way. In the progressive scenario it is assumed that deforestation is prevented from 2011 on. This implies that in this scenario, 0.4 Mha of forest plantation is required in 2030 to meet the wood demand that was alternatively fulfilled by illegal logging. However, as current developments show that deforestation is still continuing, a total halt of deforestation by 2011 is clearly unrealistic. The assumptions made in the progressives scenario are only to illustrate how land use dynamics would look like if deforestation would have been prevented from 2011 on.

The 95% confidence interval for the amount of available land for biofuels in the BAU scenario in 2030 ranges from 6.1 to 8.2 Mha. The spatial assessment of the MC analysis of land availability shows the probability of land availability on a grid cell level. This demonstrates that especially on the edges of the expansion of land use classes, the availability of land is uncertain. If a threshold of 95% certainty is applied, i.e. only land that is available for bioenergy in 95% of the realizations, 26% less land is labelled as available for biofuels in 2030 compared to the deterministic runs. The significant effect of the uncertainty in input parameters on the modelled land availability demonstrates the importance of the spatiotemporal modelling of uncertainty. However, only the uncertainty in some of the model input and parameters was included in the MC analysis (time series demand and productivity; spatial maps of productivity, population density, cattle density and elevation; window length and maximum distance of effect of the suitability factors), while the impact of uncertainties in other inputs and parameters could also be significant (such as the efficiency of livestock sector, proportion of the demand fulfilled by each land use class, the weighting of the suitability factors and the conversion elasticity matrix). By modelling the uncertainty in single parameters, it would be possible to further assess the relative contribution to the uncertainty in the amount and location of land available for bioenergy crops. Additional research into the uncertainties in land use modelling is therefore required.

It can be concluded that in both scenarios a considerable amount of land may become available for energy crops, which does not conflict with food production. However, the decreasing potential in the BAU scenario indicates a higher competition for land in the future, which could hamper the development of a sustainable large-scale bioenergy sector in Mozambique. Therefore, it must be stressed that a large-scale sustainable bioenergy sector can only be established if it is developed simultaneously with a more productive and sustainable agricultural sector. This implies a discontinuation of current trends: a shift away from subsistence towards commercial farming and from pastoral towards mixed livestock systems. This should result in an annual yield increase of 3.5%[1] and an increase in livestock efficiency of 2.5% per annum. This requires changes in agricultural management (especially deployment of fertilizer and improved seeds), development of regional or national markets, improved logistics, training and better overall capacities and governance of the agricultural sector. However, it is questionable if, and within what timeframe, the required conditions for such a transition could be met in Mozambique to realise the outcomes of the progressive scenario. The land availability for bioenergy crops modelled in this study is the land available when ILUC is to be prevented. In this approach, bioenergy production may not displace agricultural land. However in practice, bioenergy production will compete with other land use functions. It is likely that bioenergy producers will look for best suitable locations based on agro-ecological suitability and accessibility, which will (partly) be the locations also best suitable for current agricultural practices. Therefore, other land (than indicated as available in this study) could be used for bioenergy crops, but this will most likely result in iLUC. To what extent this displacement will occur depends on the corporate social responsibility of the company, policies and regulations of the Mozambican government and the criteria set for international trade of bioenergy.

The land use model developed in this study is an advanced tool to assess future dynamic land use and land availability for bioenergy crops. The bottom-up approach, the number of dynamic land uses, the diverse portfolio of LUC drivers and suitability factors, and the possibility to model uncertainty is a step forward in modelling the land availability for bioenergy potentials. Spatially explicit assessment of land availability for bioenergy crops is an important precondition to assess potential bioenergy production, to design and implement bioenergy supply chains and logistics and to assess the environmental and socioeconomic impact of bioenergy production. The model has now been tailored to and demonstrated for Mozambique. Still, it is a flexible model which can be used for other countries when input data, rules and characteristics of suitability factors are adapted.

Acknowledgements

This study is part of the Climate Changes Spatial Planning Programme and has been funded by the Dutch government, the European Commission and Shell. In addition, it has been partly funded by the Biorenewable Resources Platform, SASOL and UNEP. The authors gratefully acknowledge the following people, governmental and nongovernmental institutions, and agricultural, forestry and biofuel companies for their contribution to the data gathering and for sharing their knowledge and expertise: CAPAGRI, DNER, DNTF, IIAM, ANE, CFM, Marc Schut, Anna Lerner, Célia Jordão, Peter de Koning, Helen Watson and many others. In addition, the authors would like to thank Professor Johan Sanders for his contribution to this study, Janske van Eijck for her contribution to the field work, Birka Wicke for commenting on the draft paper, Maarten Zeylmans van Emmichoven for his help with GIS and for bringing the team of authors together, and Kees Kwant, Marieke Harteveld and the members of the Biorenewable Resources Platform for their reflections on this study.

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[1] For maize, this means an increase of 0.9 ton ha^{-1} in 2005 to 4.5 ton ha^{-1} in 2030.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1. Online supporting information: input data and model rules case study Mozambique.