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ORIGINAL ARTICLE

# Spatial and temporal land use and carbon stock changes in Uganda: implications for a future REDD strategy

**Charlotte Anne Nakakaawa · Paul O. Vedeld · Jens B. Aune**

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**Abstract** Using a map overlay procedure in a Geographical Information System environment, we quantify and map major land use and land cover (LULC) change patterns in Uganda period 1990–2005 and determine whether the transitions were random or systematic. The analysis reveals that the most dominant systematic land use change processes were deforestation (woodland to subsistence farmland—3.32%); forest degradation (woodland to bushland (4.01%) and grassland (4.08%) and bush/grassland conversion to cropland (5.5%) all resulting in a net reduction in forests (6.1%). Applying an inductive approach based on logistic regression and trend analyses of observed changes we analyzed key drivers of LULC change. Significant predictors of forest land use change included protection status, market access, poverty, slope, soil quality and presence/absence of a stream network. Market access, poverty and population all decreased the log odds of retaining forests. In addition, poverty also increased the likelihood of degradation. An increase in slope decreased the likelihood of deforestation. Using the stock change and gain/loss approaches we estimated the change in forest carbon stocks and emissions from deforestation and forest degradation. Results indicate a negligible increase in forest carbon stocks (3,260 t C yr-1) in the period 1990–2005 when compared to the emissions due to deforestation and forest degradation (2.67 million t C yr-1). In light of the dominant forest land use change patterns, the drivers and change in carbon stocks, we discuss options which could be pursued to implement a future national REDD plus strategy which considers livelihood, biodiversity and climate change mitigation objectives.

**Keywords** Land use change · Logistic regression · Carbon stocks · Forest persistence · REDD plus · Uganda

## 1 Introduction

Forest ecosystems are critical components in the global carbon (C) estimated to contain 80% of the aboveground and 40% of the below ground terrestrial C stocks

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(Brown and Lugo 1984; Dixon et al. 1994). Forest loss-accounts for a significant share of the global greenhouse gas (GHG) emissions estimated between 12% (van der Werf et al. 2009) and 17% (IPCC 2007). The international community confirmed the important role of forests in climate change mitigation and embraced the concept of REDD-plus, which includes reducing emissions from deforestation and degradation (REDD); conservation of forest carbon stocks, sustainable forest management and enhancement of forest carbon stocks in developing countries. REDD-plus incentives are expected to form part of a post-2012 climate change regime (UNFCCC 2009). Several international donors and industrialized countries have earmarked substantial funding for conditional cash transfers to tropical countries that commit to reducing deforestation rates (Angelsen et al. 2009).

The Millennium Ecosystem Assessment also clearly demonstrated that the majority of our ecosystem services are being degraded resulting in loss of other important ecosystem goods and services. Efforts are required to restore these ecosystems in order to ensure the long-term continued flow of the various ecosystem goods and services (MEA 2005). National policy makers are now in the process of designing policies and incentive mechanisms to influence patterns of land use change on the ground. In order to formulate viable REDD + strategies for climate change mitigation, it is critical to understand the Land Use Land Cover (LULC) change dynamics, the drivers of LULC change and the change in carbon stocks. One of the first crucial steps to achieve these goals is to obtain basic information on the carbon content associated with the various LULC classes. This will require a clear understanding of the drivers of land use change, carbon stocks and changes.

Examining land use change allows trends to be detected and hence assists in environmental planning. Analyses combining systematic and random transitions are useful for improved understanding of LULC change processes, and for supporting interventions aimed at mitigating the adverse effects of dramatic land use change (Braimoh 2006) and within the context of the current efforts to reduce emissions from deforestation and forest degradation (UNFCCC 2009). Carbon emission estimates from deforestation and forest degradation vary widely (Gibbs et al. 2007). Biomass estimates are an important source of uncertainty in the carbon balance from the tropical regions in part due to a scarcity of reliable estimates of live aboveground biomass (AGB) and its variation across landscapes and forest types (Houghton 2007; Houghton et al. 2009). Therefore, improved local and regional estimates provide essential data that enable the extrapolation of biomass stocks to ecosystems or biome-wide carbon cycle modeling, as well as to allow reliable emission estimates from land use change scenarios (Houghton and Goodale 2004; Houghton et al. 2009).

The paper generates data on the dynamics of LULC change, potential drivers of forest land use change and change in forest carbon stocks in Uganda for the period 1990–2005. We present a detailed analysis of the nature and spatial pattern of LULC at a national scale. Identifying patterns in LULC transitions could assist with linking patterns to processes of LULC (Pontius et al. 2004a, b). The in-depth analysis of LULC change patterns, such as presented here, would enable scientists and policy makers to focus on the strongest signals of systematic landscape transitions, which ultimately should be linked to factors driving the transitions. We investigate the LULC changes in terms of: (i) quantity of change; (ii) spatial distribution of the changes; and (iii) patterns of change (identify any systematic transitions). Using logistic regression and trend analyses of observed changes we analyzed key drivers of LULC change. Using the stock change approach, we estimate change in carbon stocks and discuss the implication of the observed changes for a national REDD strategy.

## 2 Study area

Uganda is located astride the equator in East Africa stretching from 4° 12′ north to 1° 29′ south and from 29° 34′ west to 35° 0′ east covering a total area of about 240,000 km$^2$ of which 18% is open water (NFA 2009). The population is over 30 million people and with an annual growth rate exceeding 3%. Despite a shift from a largely agriculture-based economy towards construction, manufacturing and regional trade, Uganda's population is still predominantly rural (88%) with agriculture employing over 80% of the economically active population (UBOS 2008). The rural population is heavily reliant on forest ecosystems for their livelihoods. Thus continued access to forest land will be important for securing rural livelihoods and national development goals (Bush et al. 2005).

More than half of the tree cover has been lost over the past 100 years. Increasing population growth, export production and high poverty levels continue to increase pressure on the remaining forest resources (Hamilton et al. 1986; MWLE 2003; NFA 2009). The population has increased from 4.8 million in 1948 to 29.6 in July 2008, and is likely to reach 103.2 million by 2050 (UBOS 2008). The population growth rate (3.2%) is one of the highest in the world. There are now six times more people trying to survive on the same amount of natural resources 60 years ago (NEMA 2009b).

LULUCF activities in Uganda account for 80% of total GHG emissions (MWLE 2002). Deforestation and subsequent intensification of land use and also land degradation in Uganda have resulted in biodiversity and other ecosystems services losses (Bolwig et al. 2006; NEMA 2009a; Ruhweza and Masiga 2005). Uganda is ranked among the top 20 on the global list of tropical countries emitting carbon from deforestation (Gibbs and Brown 2007; Gibbs et al. 2007; Murray and Olander 2008). The energy sector is highly dependent on woody biomass (over 90% of Uganda's energy consumption) as the primary source of energy (consumed as firewood (rural population) and charcoal (urban population) thereby accelerating deforestation[1] (Hartter and Boston 2008; MEMD 2007; Tabuti et al. 2003; Naughton-Treves et al. 2007). Wood fuel is one of the major causes of both deforestation and forest degradation (Namaalwa et al. 2007; Cooke et al. 2008).

Payments for carbon sequestration services/REDD may provide economic incentives for more sustainable resource management at local and national levels. REDD may provide a unique opportunity for developing countries with limited conservation funding to sustainably conserve and manage forest biodiversity, enhance carbon sequestration and at the same time generate real livelihood benefits for the rural poor forest dependent populations; a triple win-win-win situation (IUCN 2009). However, successful implementation of REDD requires clear identification and nurturing of viable conservation projects (Hartig and Drechsler 2009).

Uganda developed a Readiness Plan Idea Note[2] which explicitly outlines policy recommendations for REDD implementation (NFA 2008) and has received support from

[1] Wood fuel is the major source of energy for domestic cooking. Annual timber consumption in the country estimated at 100,000 m$^3$ in 2005/06, is projected to rise mainly driven by the booming construction industry (Drichi 2005).

[2] In May 2009, NFA applied to the World Bank's Forest Carbon Partnership Facility (FCPF) for funds to develop a National Readiness Plan (R-PIN) to implement a REDD program (World Bank 2008). It was accepted as a country participant and; signed a 'grant agreement for formulating and executing a Readiness Preparation Proposal (R-PP)'in September 2009. This makes Uganda entitled to a grant of up to US$3.6 million (World Bank 2009). The REDD-PIN is supposed to provide a common framework for effective coordination and implementation of REDD.

the World Bank Forest Carbon Partnership Facility (FCPF) to develop a national REDD strategy (World Bank 2009). Despite the importance of land use history in designing and implementing schemes such as REDD, few studies have reconstructed detailed large scale land use and land cover (LULC) change processes. Land use/cover change research in Uganda has mainly been conducted at local small-scale which permits fine-resolution analysis, but that only cover over small areas (Mugisha 2002; Mwavu and Witkowski 2008; Vogt et al. 2006a, b) and more recently at a regional level (Babigumira et al. 2008). This has been attributed to lack of good sources of historical data. National level land use change analysis, which is detailed enough to reveal critical land use change processes, but extensive enough to be broadly applicable, can play a pivotal role in bridging between these studies.

## 3 Methods and data sources

### 3.1 Analyzing LULC changes

The land use data used derive to the LULC transition matrix was obtained from the National Forestry Authority (NFA). The 1990 land use map was based on manual interpretation of SPOT satellite imagery taken between February 1989 and December 1992 combined with Landsat and aerial photographs from early 1995 (MWLE 2003). We considered this map to represent a 1990 situation. The 2005 map was based on interpretation of Landsat images from 2004–2005. The maps were verified through extensive, systematic ground truthing conducted by NFA staff (NFA 2009).

The original land use data included 13 land use/cover classes, characterized by varying biomass densities. Detailed land use/cover descriptions are presented in Langdale-Brown et al. (1964) and MWLE (2003). In this study, the data was reclassified into five (5) classes to reduce the land use conversion categories and to simplify the LULC change drivers analysis (Table 1). The aggregation was based on a combination of knowledge on land use structural (biomass densities) and compositional characteristics (MWLE 2003).

All classes with trees as the dominant cover were included in the broader category of “forest”; areas with grasslands and bushlands which predominantly support pastoral livelihoods were categorized as “pastoral lands”; agricultural land (subsistence and commercial) was assigned “cropland” and combined with built up areas; and the rest (wetlands and impediments) were grouped under “other land uses”. Open water was maintained as a separate category and eliminated from further analysis based on the assumption that it will not change. The aggregation also aimed at reducing the computational requirements when analyzing the drivers of land use change. We analyzed all the possible land use conversions but we focus on changes in forests in the results presented in this paper.

The two reclassified maps (Fig. 1) were converted to a uniform spatial resolution of 1 km × 1 km. Assuming stationarity in land use, the maps were overlay to derive a LULC transition matrix for the period 1990 and 2005. Each cell represents a transition between two land use types or no change in use (Table 2).

Using the methodology for determining random and systematic transitions developed by Pontius et al. (2004a, b) and Braimoh (2006) we estimated the persistence and quantity of change in terms of gross gains, losses, net change, and swap in the different land use categories.

**Table 1** Land use/cover classification for Uganda

| Original land use code and class | | Brief description | Aggregate land use class |
|---|---|---|---|
| 1 | Hardwood plantations | Deciduous trees (e.g *Eucalyptus* sp.) | Forests |
| 2 | Softwood plantations | Coniferous trees (e.g *Pine*, *Cypressus*) | |
| 3 | THF Norm | Tropical High Forests–Normally Stocked | |
| 4 | THF Deg | Tropical High Forests–Depleted/encroached | |
| 5 | Woodland | Trees and shrubs (average height > 4 m) | |
| 6 | Bushland | Bush, thickets, scrub (average height < 4 m) | Pastoral land |
| 7 | Grassland | Rangelands, pasture land, open savannah; mainly in the cattle corridor (some scattered trees shrubs, scrubs and thickets may occur) | |
| 9 | Subsistence | Mixed farmland, small holdings, in use or recently used, with or without trees | Cropland and settled areas |
| 10 | Commercial farmlands | Uniform/mono-cropped, non-seasonal farmland usually without trees eg tea and sugarcane estates | |
| 11 | Built up area | Urban or rural built up areas | |
| 8 | Wetlands | Wetland vegetation; swamp areas, papyrus and other sedges | Others |
| 13 | Impediments | bare rocks and soils | |
| 12 | Open water | large rivers, ponds and lakes | Water |

*3.1.1 Gross gains, losses, net change, and swap*

In Table 2, the rows display the area or proportions of the four classes in 1990, whereas the columns display the area or proportions in 2005. Thus, the notation $C_{ij}$ ($\forall\ i \neq j$)

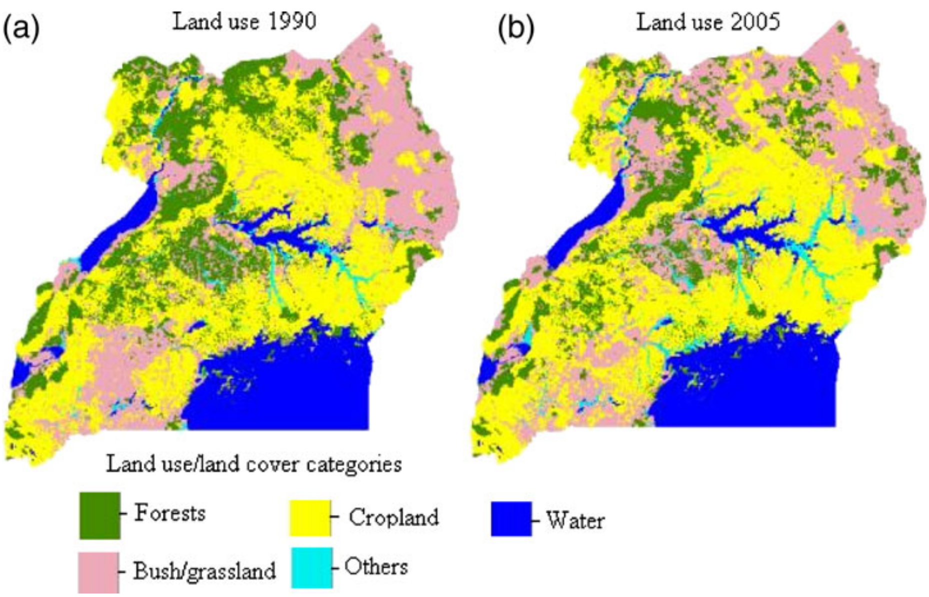



**Fig. 1** Classified land use/cover maps for Uganda (**a**) 1990 and (**b**) 2005

**Table 2** A 4×4 land use transition matrix

| Land use/cover | 2005 | | | | | |
|---|---|---|---|---|---|---|
| 1990 | Forest | Bush/grassland | Cropland | Others | Total 1990 | Gross Loss[a] |
| Forest | $\mathbf{C_{11}}$ | $C_{12}$ | $C_{13}$ | $C_{14}$ | $C_{1+}$ | $C_{1+}–C_{11}$ |
| Bush/grassland | $C_{21}$ | $\mathbf{C_{22}}$ | $C_{23}$ | $C_{24}$ | $C_{2+}$ | $C_{2+}–C_{22}$ |
| Cropland | $C_{31}$ | $C_{32}$ | $\mathbf{C_{33}}$ | $C_{34}$ | $C_{3+}$ | $C_{3+}–C_{33}$ |
| Others | $C_{41}$ | $C_{42}$ | $C_{43}$ | $\mathbf{C_{44}}$ | $C_{4+}$ | $C_{4+}–C_{44}$ |
| Total 2005 | $C_{+1}$ | $C_{+2}$ | $C_{+3}$ | $C_{+4}$ | 1 | |
| Gross Gain[b] | $C_{+1}–C_{11}$ | $C_{+2}–C_{22}$ | $C_{+3}–C_{33}$ | $C_{+4}–C_{44}$ | | |
| Total change | Gross gain + gross loss | | | | | |
| Net change | $C_{+1}–C_{1+}$ | $C_{+2}–C_{2+}$ | $C_{+3}–C_{3+}$ | $C_{+4}–C_{4+}$ | | |

[a] Proportional decrease in area of class $i$ between 1990 and 2005;

[b] Proportional increase in area of class $j$ between 1990 and 2005

indicates the area (hectares) or proportion (percentage) of the landscape that experiences a transition from class $i$ to class $j$ between 1990 and 2005. The main diagonal elements ($C_{jj}$) indicate the proportion of land classes that show persistence of class $j$. Off diagonal entries indicate a transition from class $i$ to a different class $j$. The total column ($C_{i+}$) denotes the proportion of the landscape occupied by class $i$ in 1990 which is the sum over all j of ($C_{ij}$) given by;

$$C_{i+} = \sum_{i=1}^{n} C_{ij} \tag{1}$$

Similarly, the total row ($C_{+j}$) denotes the proportion of the landscape in class $j$ in 2005, which is the sum over all $i$ of ($C_{ij}$) given by;

$$C_{+j} = \sum_{j=1}^{n} C_{ij} \tag{2}$$

where $n$ is the total number of classes. The gross gain and loss for each category is derived by subtracting the diagonal entries (persistence) from the column and row totals respectively. The total change is the sum of the gross gain and the gross loss. Swap is defined as the change in location of a land cover between 1990 and 2005, which derives from simultaneous gross gain and gross loss. The net change is the difference in area of a land cover between 1990 and 2005.

### *3.1.2 Land use/cover persistence*

Analysis of LULC persistence offers additional information concerning the vulnerability of land covers to transition to other classes and guide the design and implementation of targeted strategies to secure important ecosystem goods and services. The persistence indices from (Braimoh 2006) were used to assess the persistence characteristics of the different land covers in relation to gain, loss, and net change. The gain-to-persistence ($g_p$); loss-to-persistence ($l_p$) and net change-to-persistence ($n_p$) ratios were calculated as; $g_p$ = gain/persistence, $l_p$ = loss/persistence, and $n_p = g_p – l_p$ respectively. The loss-to-persistence ratio, assesses the vulnerability of land classes to transition. Values of $l_p$ above 1 indicate a higher tendency of land covers to transition to other land classes than to persist (Braimoh 2006).

### 3.1.3 Identifying patterns of land use change: random and systematic transitions

Further analysis of gains and losses can determine whether landscape transitions were of a random or systematic nature. The expected gain ($G_{ij}$) of each LULC category under a random process of gain was estimated by distributing the gain of each class across other categories relative to their proportions in year 1 (1990) based on detailed procedures and formulae documented by Pontius et al. (2004a, b) as;

$$G_{ij} = C_{+j} - C_{jj}\left(\frac{C_{i+}}{\sum_{i=1,i\neq j}^{n} C_{i+}}\right) \tag{3}$$

The expected losses ($L_{ij}$) under a random process of change were estimated by distributing the observed losses among the different LULC categories based upon their relative proportions in year 2 (2005) as given by;

$$L_{ij} = C_{i+} - C_{jj}\left(\frac{C_{+j}}{\sum_{j=1,j\neq i}^{n} C_{+j}}\right) \tag{4}$$

Under a random process of change, a category that gains will replace other categories in proportion to how those other categories populate the landscape in year 1 (1990); and when a category losses, it will be replaced by other categories in proportion to how those categories populate the landscape in year 2 (2005), if it replaces or is replaced by other categories at random. When computing the expected proportions under a random gain or loss process, the diagonal entries are kept constant to account for the observed persistence in the landscape. This is then followed by calculating the difference between the observed and expected proportions under a random process of gain and loss as; $C_{ij}$-$G_{ij}$ and $C_{ij}$-$L_{ij}$ respectively. Values close to zero indicate that the landscape transition was random, whereas values further from zero indicate a systematic transition (Pontius et al. 2004a, b).

## 3.2 Estimating change in carbon stocks and emissions from deforestation and forest degradation

We used data from National Forestry Authority (NFA) from biomass inventories conducted in the period 1989–1992; 1996–2000 (MWLE 2003) and 2004–2007 (NFA 2009). The plots were established on a 5×10 km grid all over the country. A detailed description of the inventory design and data collection methods is presented in the technical reports (Forest Department 1992; MWLE 2003). The inventory was specifically designed to supply statistically sound measurements of biomass stocks and growth across the country. The data contains details on species, diameter at breast height, height, foliage, bole length and crown width for each tree. Above-ground biomass (ABG) was estimated using allometric equations developed for Uganda (Velle 1995). The general form of the equation is:

$$\ln(PWS) = a + b^* \ln(D) + c^* \ln(HT) + d^* \ln(CR) \tag{5}$$

where: PWS = predicted weight of tree; D = diameter at breast height; HT = tree height; CR = crown width; a,b,c and d are constants which vary for three diameter class levels as indicated in Table 3.

Use of these generalized allometric equations is justified because even in highly diverse systems, more than 95% of the variation in AGB is explained by Diameter at Breast Height (DBH) alone (Brown 2002). The available inventory data does not include below ground biomass. To estimate the total live tree biomass, we applied a ratio of 0.22 (Brown 1997) to the AGB estimates. This estimate is also within the range of the estimates (0.2–0.29) of below ground root biomass as a proportion of AGB derived based on predictive relationships established from extensive literature surveys (Cairns et al. 1997; Mokany et al. 2006). The total biomass was equal to the sum of the above and below ground biomass. The biomass was converted to carbon (C) by assuming a 50% biomass to carbon content (IPCC 2003; 2006). Soil organic matter is not included in the analysis due to lack of data and great scientific uncertainty regarding its amount and dynamics when land use changes (Houghton and Goodale 2004). The carbon stocks in the different land uses were estimated according to Eq. 6

$$C = \sum A_i * B_i \tag{6}$$

where

$A_i$ Total area (ha) occupied by land use i
$B_i$ Above ground area weighted woody biomass carbon in land use i (t C $ha^{-1}$)

The total biomass carbon in any year is equal to the summation of the biomass carbon in the different land uses. Change in C stocks was estimated using the stock change method which utilizes data from repeated inventories (Winjum et al. 1998). Carbon losses due to degradation were estimated as the difference between carbon stocks in normally stocked forests and degraded forests while those due to deforestation were estimated as a product of the deforested area and the corresponding forest area weighted biomass as in Eq. 7

$$Ec = B_{def} * \Delta A_{def} \tag{7}$$

where

$B_{def}$ Area weighted forest biomass carbon in the area deforested, t C $ha^{-1}$
$\Delta A_{def}$ Deforested area, ha

To estimate change in carbon stocks following changes in land use, we assumed similar biomass use patterns and that a conversion from a land use with a high density to one with a low density land use would result in a carbon loss and biomass growth would follow the growth curve characteristic of the new land use based on observed trends.

**Table 3** Constants used for the different diameter classes to convert vegetation measures to above ground biomass

| Diameter class | Constants | | | |
|---|---|---|---|---|
| | a | b | c | d |
| DBH<20 cm | −0.85989 | 1.544561 | 0.50663 | 0.333346 |
| 20≥DBH≤60 cm | −1.750891 | 1.943912 | 0.473731 | 0.245776 |
| DBH>60 cm | −2.166502 | 2.032931 | 0.31292 | 0.436348 |

Velle (1995)

## 3.3 Analyzing drivers of land use change

The drivers of land use change were analyzed based on logistic regression models derived from overlaying and relating the observed land use transitions between 1990 and 2005 to multiple types of geospatial data layers to capture variations in biophysical and topographic factors such as soil, rainfall, slope, aspect, and elevation; socioeconomic factors (population, market access and agro ecological zone) and management related issues such as protection status. All the variables and data sources are presented in Table 4. The selection of variables was based on a review of general literature on land use change (Kaimowitz and Angelsen 1998; Lambin and Geist 2006; Verburg et al. 2002) and some specific studies conducted in Uganda (Mugisha 2002; Babigumira et al. 2008; Namaalwa et al. 2007).

### *3.3.1 Test for multicollinearity and model variable selection*

There were modest correlations between some variables (agro ecological zone and rainfall ($\rho$= 0.5); cost distance and rain ($\rho$=−0.57); cost distance and poverty ($\rho$=0.57) slope and elevation ($\rho$=0.54)). Thus multicollinearity does not appear to be a serious problem. Collinearity was accounted for by eliminating variables with the least significant (Wald statistic) contribution to the model and with a correlation coefficient greater than or equal to of 0.5.

### *3.3.2 Spatial logistic regression*

To generate the regression models, all the data sets were converted to raster at a uniform spatial scale of 1 km×1 km.[3] All layers were integrated under the same coordinate system (Grid UTM Zone 36, Projection: Transverse Mercator, Spheroid; Clarke 1880 (Modified), Datum: New (1950) Arc. The rasters were then converted to ASCII format, imported to the R Programme in a Geographical Information System (GIS) environment which were then used in estimating the models. Each cell was characterized by a number of attributes such as soil type, rainfall, topographical elevation, slope, aspect, presence or absence of a stream, distance from major water bodies, population density and change and market access as independent variables. Model selection was based on a stepwise logistic regression procedure (Menard 2002) in SAS (SAS 2006). Only those variables which were significant at 0.05 were included in the final models which were run using R 2.10.0 (The R Development Core Team 2009).

The regression coefficients were used to calculate the probability of a grid cell changing from one land use type to another as follows:

$$P(1) = \frac{1}{1 + \exp^{-(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots\ldots + \beta_n X_n + \varepsilon)}} \tag{8}$$

Where

| | |
|---|---|
| $P(1)$ | Probability that the dependent variable is 1 (change in land use) |
| exp | base of the natural logarithm |
| $\beta_0$ | Intercept |
| $\beta_1, \ldots \beta_n$, | coefficients |
| $x_1, x_2, \ldots x_n$ | independent variables |
| n | number of independent variables |
| e | error term. |

[3] Initially the land use maps and multi-scale factor datasets were transformed into a uniform grid of 5 km X 5 km but we were not able to simulate important small-scale relationships such as the observed numerous small forest patches along streams (NFA 2009).

**Table 4** Variables included in the stepwise logistic regression analysis and data sources

| Variable | Description | Nature of variable | Data source |
|---|---|---|---|
| Dependent variable (land use) | | | |
| Presence of land use/change category | Land use change (16 categories) | Dichotomous Yes -1; No - 0 | Derived from land use/cover maps for 1990 (MWLE 2003) and 2005 (NFA 2009) |
| Independent variables (land use drivers) | | | |
| Biophysical/location specific variables | | | |
| Agro-ecological zone | 4 different zones | Categorical | NEMA 2009b |
| Rainfall | | Continuous | NEMA 2009b |
| Soil | | Continuous | NEMA 2009b |
| Aspect (exposition) | Derived from the Digital Elevation Model (DEM) | Continuous | Shuttle Radar Topography Mission SRTM 90 m version 3 DEM (Jarvis et al. 2006) |
| Slope (%) | | Continuous | |
| Elevation (Meters) | | Continuous | |
| Lake buffer | Buffer around major lakes | Continuous | NFA 2009 |
| Streams[a] | Presence/absence of a stream draining 1 km | Categorical | NFA 2009 |
| Eastings | UTM coordinates (m) used to correct for spatial autocorrelation | Continuous | NFA 2009 |
| Northings | | | NFA 2009 |
| Socio-economic variables | | | |
| Population density | Persons/km$^2$ | Continuous | Gridded population of the World |
| Change in population | Difference in population between two reference periods | Continuous | Gridded population of the World |
| Cost distance surface - captures difference in market access | Derived from a combination of distance to major roads, cities and existing population centres | Continuous | FAO Africover, NFA database |
| Poverty distribution | Percentage population in poverty | Continuous | UBOS |
| Institutional related variable | | | |
| Restricted areas | Includes protected and built up areas | Categorical dichotomous 1 – restricted; 0 not restricted | IUCN, NFA database |

[a] In the 2005 land use data, we observed a relation between forest occurrence and location of valleys. We included a stream network raster draining an area of at least 1 km to capture the small forests located along the streams

Fitted values were generated by assigning each pixel to the land use category with the highest predicted probability[4] based on the land use change probability maps.

### *3.3.3 Land use model evaluation*

A land use change model is useful if it can predict the future or explain the past (Veldkamp and Lambin 2001). We used the Relative Operating Characteristic (ROC) to evaluate the performance of the land use change regression models (Pontius and Schneider 2001). We report the area under the ROC curve (AUC) as an indication of the strength of model prediction. This is considered to be a better indicator than percent success as it compares both the quantity and location of past actual and predicted changes (Pontius et al. 2004a). The kappa statistic was used to assess model goodness of fit (Cohen 1960).

[4] The maximum probability assignment rule was used in allocating a pixel to a particular land use. In reality, most of the pixels in the images are not covered by one land cover type, but varying proportions of land cover types.

## 4 Results and discussion

### 4.1 Land use/cover changes

Between 1990 and 2005, the total forested area decreased by about 27% (1,329,570 ha) while the total area under pastoral land, cropland and other land uses increased by 8%, 6% and 56% respectively (Table 5). By 2005, about 24% of the tropical high forests were degraded. Among different forest categories, there was a slight increase (14%) in softwood plantations while the other forest categories decreased. The decrease in woodlands accounted for about 90% (1,196,510 ha) of total forest cover loss. The increase in what is categorized as pastoral land was accounted for by increase in bushlands (109%), especially in northern Uganda where the security situation led to cropland abandonment in some areas and woodland forests in other areas degraded to bushlands by high influx of refugees from both within the region and from southern Sudan (Nampindo et al. 2005). There was also an increase in subsistence farmlands.

**Table 5** Historical land use/cover in Uganda as of 1990 and 2005

| Land use/cover | Area ′000 ha | | Change 1990–2005 | |
|---|---|---|---|---|
| | 1990[a] | 2005[b] | Total ′000 ha | Annual % |
| Forests | | | | |
| Hardwoods plantations | 18.68 | 14.79 | −3.9 | −0.00 |
| Softwoods plantations | 16.38 | 18.74 | 2.36 | 0.00 |
| Tropical high forest – Normal | 651.11 | 600.96 | −50.15 | −0.02 |
| Tropical high forest – Degraded | 273.06 | 191.69 | −81.37 | −0.03 |
| Woodlands | 3,974.51 | 2,778.00 | −1,196.51 | −0.39 |
| Total forest land | 4,933.75 | 3,604.18 | −1.329.57 | −0.43 |
| Pastoral land | | | | |
| Bushlands | 1,422.19 | 2,968.68 | 1,546.48 | 0.5 |
| Grasslands | 5,115.43 | 4,063.58 | −1,051.84 | −0.34 |
| Total pastoral land | 6,537.62 | 7,032.26 | 494.64 | 0.16 |
| Croplands & settled areas | | | | |
| Subsistence farmlands | 8,400.79 | 8,847.59 | 446.8 | 0.15 |
| Commercial farmlands | 68.45 | 106.63 | 38.18 | 0.01 |
| Built up areas | 36.57 | 97.27 | 60.7 | 0.02 |
| Total cropland & settled areas | 8,505.81 | 9,051.49 | 545.68 | 0.18 |
| Other land uses | | | | |
| Wetlands | 484.03 | 753.04 | 269.01 | 0.09 |
| Impediments | 3.74 | 7.8 | 4.06 | 0.00 |
| Unmapped area | 0.7 | 0.09 | −0.61 | 0.00 |
| Total other land uses | 488.47 | 760.93 | 272.46 | 0.09 |
| Total landscape | 20,448.86 | | | |

[a] MWLE (2003)

[b] NFA (2009)

#### *4.1.1 Gross gains, losses, net change, and swap*

The simplified interpretation of land use changes presented in section 4.1 based on the net changes in Table 5 can dramatically underestimate the total change on the landscape (Pontius et al. 2004a, b). A more informative detailed analysis of the transition matrix (Table 6a) shows that total change in forest was almost three times (19.2% of the landscape) as much as the net change (6.1% of the landscape). Change in all categories consists of both swap and net change. Considering the whole landscape, the change attributable to swap (25% of the landscape) is greater than that attributable to quantity (6.1% of the landscape). Most of the change in the landscape is associated with bush/grassland and forest categories. Figure 2 shows the spatial distribution of the changes in the landscape, focusing on the change in the forest category from 1990–2005. Dark green shows the persistence of forest, red shows forest loss/deforestation while light green shows forest regrowth and/or areas which have been reforested or afforested. The gain (6.5% of the landscape) in forest was almost half of the lose (12.6% of the landscape) thus there was a net loss in forest.

**Table 6** Summary of landscape changes (%), 1990–2005, Uganda

| | Total 1990 | Total 2005 | Gain[a] | Loss | Total change[b] | Swap[c] | Absolute net change[d] |
|---|---|---|---|---|---|---|---|
| (a) Aggregated classes | | | | | | | |
| Forest | 23.2 | 17.1 | 6.5 | 12.6 | 19.2 | 13 | 6.1 |
| Bush/grassland | 30.4 | 33.1 | 12.9 | 10.3 | 23.2 | 20.5 | 2.7 |
| Cropland | 44.5 | 46.4 | 9.8 | 7.9 | 17.7 | 15.9 | 1.9 |
| Others | 1.8 | 3.4 | 1.9 | 0.3 | 2.2 | 0.7 | 1.5 |
| Total | 100 | 100 | 31.2 | 31.2 | 31.2 | 25 | 6.1 |
| (b) Disaggregated classes | | | | | | | |
| Forest | | | | | | | |
| Hardwood plantations | 0.03 | 0.07 | 0.07 | 0.03 | 0.10 | 0.06 | 0.04 |
| Softwood plantations | 0.07 | 0.09 | 0.05 | 0.03 | 0.08 | 0.06 | 0.02 |
| THF Normal | 3.26 | 2.98 | 0.65 | 0.93 | 1.58 | 1.30 | 0.27 |
| THF Degraded | 1.09 | 0.88 | 0.72 | 0.93 | 1.64 | 1.43 | 0.21 |
| Woodland | 18.77 | 13.08 | 6.43 | 12.11 | 18.54 | 12.85 | 5.69 |
| Non forest | | | | | | | |
| Bushlands | 6.71 | 13.45 | 11.19 | 4.45 | 15.65 | 8.90 | 6.74 |
| Grasslands | 23.70 | 19.65 | 9.00 | 13.05 | 22.05 | 18.00 | 4.05 |
| Wetlands | 1.83 | 3.37 | 1.88 | 0.34 | 2.22 | 0.68 | 1.54 |
| Subsistence | 44.10 | 45.81 | 9.68 | 7.98 | 17.66 | 15.96 | 1.70 |
| Commercial | 0.32 | 0.28 | 0.28 | 0.32 | 0.61 | 0.56 | 0.04 |
| Built up | 0.11 | 0.33 | 0.24 | 0.02 | 0.26 | 0.03 | 0.23 |
| Total | 100.00 | 100.00 | 40.19 | 40.19 | 40.19 | 29.92 | 10.27 |

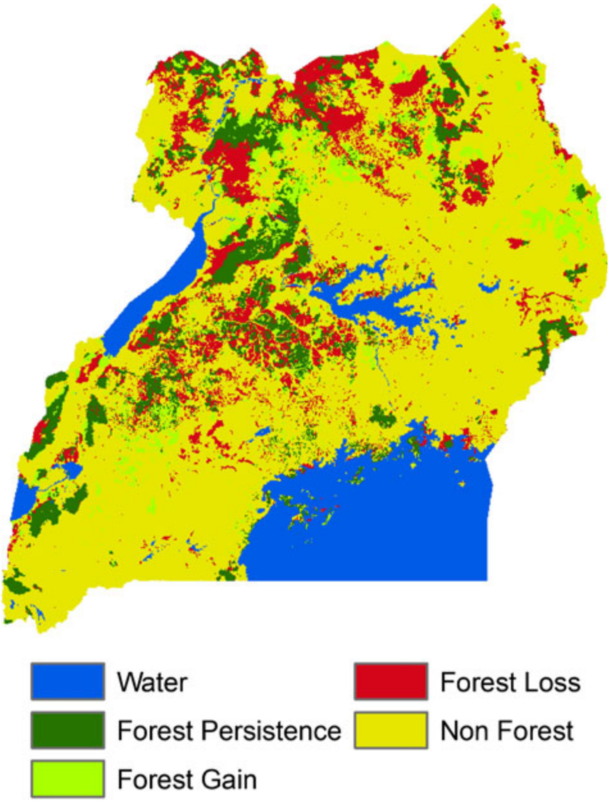
[a] The total gain is equivalent to the total loss in a landscape since a gain one category is always accompanied by a loss in another category

[b] Sum of the gross gain and loss in a land use category

[c] Difference between the total change and net change (results from a simultaneous gain and loss of a given land use/cover category in different locations)

[d] Difference between the gross gain and gross loss for a given land use category

**Fig. 2** Change in forest land use/cover, Uganda, 1990–2005




Bush/grassland experienced more gain (12.9%) (Table 6a). Gain to loss ratio indicates that others experienced almost 6 times more gain than lose; while the ratio for bush/grassland was about 1:1 and that for forest was less than 1 (0.5).

A further detailed analysis of within category changes (Table 6b) reveals more important information especially in relation to the design and implementation of national REDD plus strategies which take into account changes within the forest landscape. There was a decline in natural forests (6.17%) attributed mainly to loss of woodlands which experienced the highest loss constituting over 92% of the total loss in forest (Tables 7 and 8). The transitions include woodland to bushlands (4% or 816,500 ha) and grassland (4.1% or 831,700 ha) and woodland to cropland (3.3% or 675,900 ha). As a result, in the matrix where the LULC categories were aggregated, the loss in forest is mostly due to a transition of forest to bush/grassland (8.2%) and cropland (4.2% of the landscape). There was a slight increase in plantations (0.06%). The gain in forest plantations can be attributed to several on-going national tree planting programmes[5] but this is still less than the loss.

[5] These include the Saw log Production Grant Scheme (SPGS) for the private sector, the Farm Income Enhancement and Forest Conservation Programme (FIEFCO); the Northern Uganda Reforestation Programme; the Community Tree Planting Programme (at least 5% of degraded CFR is allocated to local communities living around the CFRs for tree planting); New forest plantations and re-planting of harvested forest reserves and the International tree planting programme (TIST). However, despite similarities in the objectives of these programs, they lack coordination.

**Table 7** Land use/cover change matrix 1990–2005, Uganda (%)

| Land use/cover From 1990 | To 2005 | | | | | |
|---|---|---|---|---|---|---|
| | Forest | Bush/grassland | Cropland | Others | Total 1990 | Gross Loss |
| Forest | **10.6** | 8.2 | 4.2 | 0.3 | 23.2 | 12.6 |
| Bush/grassland | 3.6 | **20.2** | 5.5 | 1.2 | 30.4 | 10.3 |
| Cropland | 2.9 | 4.5 | **36.6** | 0.5 | 44.5 | 7.9 |
| Others | 0 | 0.2 | 0.1 | **1.5** | 1.8 | 0.3 |
| Total 2005 | 17.1 | 33.1 | 46.4 | 3.4 | 100 | 31.2 |
| Gross Gain | 6.5 | 12.9 | 9.8 | 1.9 | 31.2 | |

In bold = Proportion which remained under the same land use (persistence) over the period 1990–2005

### *4.1.2 Land use/cover persistence*

Persistence dominates most land use/cover categories accounting for 69% of the landscape (sum of the diagonal entries in bold in Table 7). This implies that about 31% (sum of the off diagonal entries or total gross gain/loss in Table 7) of the landscape did change (exhibiting a transition from one category to another during the 15-year period). Most of the persistence was accounted for by a persistence of cropland (37%) and bush/grassland (20%) which also covered the highest percentage of the total landscape in both 1990 and 2005. These categories support both commercial and rural livelihoods and are characterized by both extensification and intensification of land use (Nkonya et al. 2004) to the extent that despite increasing population densities, there are still some forest remnants even within the agricultural and pastoral landscapes. However, Areas where forests have persisted are mainly protected as forest reserves and national parks (Fig. 2). The remaining unprotected forests are becoming degraded and fragmented (NFA 2009; Hartter and Southworth 2009) and their future is threatened by their high tendency to lose (transition to other categories) than to gain or persist across the study period as revealed by the persistence analysis (Table 9).

Gain-to-persistence ratios exceeding 1 indicate that a land cover experiences more gain than persistence while loss-to-persistence ratios exceeding 1 indicate a higher tendency to lose (transition) to other land categories than to persist (Braimoh 2006). Forest was the only category with a loss-to-persistence ratio greater than 1. All cropland and bush/grassland persistence ratios were less than 1. The high tendency for forests to lose than to gain has ecological, social and economic implications. Forests are a source of income and livelihood for rural poor populations and are a refugee for important plant and animal biodiversity (NEMA 2009a, b; Plumptre et al. 2007).

In Table 9 the gain-to-persistence ratio is greater than 1 for others indicating a tendency to expand relative to their initial (in 1990) size. Others had a higher tendency to gain across the study period. The increase in others which mainly include wetlands can be attributed to the fact that most of the wetlands have been officially protected as RAMSAR sites of international conservation value and can not be individually owned. Although some under go conversions and become degraded, they have been continuously rehabilitated over the last ten years (NEMA 2009a, b). Other small scale studies have also reported an increase in wetlands (Hartter and Southworth 2009).

The high tendency of Croplands to persist (Table 7) is also evident from the low loss-to-persistence and gain-to-persistence ratios (Table 9). With the exception of forests (−0.6), all

**Table 8** Land use/cover change matrix 1990–2005, Uganda (%)

| | 2005 | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1990 | Hardwood | Softwood | THF_Norm | THF_Deg | Woodland | Bushlands | Grasslands | Wetlands | Subsistence | Commercial | Built_up | Total 1990 | Loss |
| Hardwood | **0.00** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.03 | 0.03 |
| Softwood | 0.00 | **0.04** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.07 | 0.03 |
| THF_Norm | 0.00 | 0.00 | **2.33** | 0.28 | 0.22 | 0.04 | 0.02 | 0.01 | 0.35 | 0.02 | 0.00 | 3.26 | 0.92 |
| THF_Deg | 0.00 | 0.01 | 0.20 | **0.17** | 0.21 | 0.05 | 0.01 | 0.01 | 0.43 | 0.01 | 0.00 | 1.09 | 0.93 |
| Woodland | 0.02 | 0.01 | 0.29 | 0.15 | **6.66** | 4.01 | 4.08 | 0.23 | 3.32 | 0.02 | 0.00 | 18.77 | 12.11 |
| Bushlands | 0.00 | 0.00 | 0.01 | 0.01 | 1.09 | **2.26** | 2.24 | 0.06 | 1.03 | 0.01 | 0.00 | 6.71 | 4.45 |
| Grasslands | 0.01 | 0.01 | 0.04 | 0.03 | 2.35 | 5.01 | **10.65** | 1.11 | 4.42 | 0.06 | 0.01 | 23.70 | 13.05 |
| Wetlands | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.06 | 0.12 | **1.49** | 0.10 | 0.01 | 0.00 | 1.83 | 0.34 |
| Subsistence | 0.03 | 0.01 | 0.10 | 0.24 | 2.52 | 2.01 | 2.45 | 0.24 | **36.12** | 0.16 | 0.22 | 44.10 | 7.98 |
| Commercial | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.07 | 0.22 | 0.00 | **0.00** | 0.00 | 0.32 | 0.32 |
| Built_up | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | **0.09** | 0.11 | 0.01 |
| Total 2005 | 0.07 | 0.09 | 2.99 | 0.88 | 13.08 | 13.45 | 19.65 | 3.37 | 45.81 | 0.28 | 0.33 | 100 | 40 |
| Gain | 0.07 | 0.05 | 0.65 | 0.72 | 6.43 | 11.19 | 9.00 | 1.88 | 9.68 | 0.28 | 0.24 | 40 | |
| Total change | 0.07 | 0.05 | 0.65 | 1.64 | 18.54 | 15.64 | 22.05 | 2.22 | 17.66 | 0.61 | 0.25 | 40 | |

**Table 9** Gain -to-persistence ($g_p$), loss-to-persistence ($l_p$) and net change-to-persistence ($n_p$) ratios of observed land use/cover 1990–2005, Uganda

| Land use/cover | $l_p$ | $g_p$ | $n_p$ |
|---|---|---|---|
| (a) Aggregated classes | | | |
| Forest | 1.2 | 0.6 | −0.6 |
| Bush/grassland | 0.5 | 0.6 | 0.1 |
| Cropland | 0.2 | 0.3 | 0.1 |
| Others | 0.2 | 1.3 | 1.0 |
| Total | 0.5 | 0.5 | – |
| Disaggregated classes | | | |
| (b) Forests | | | |
| Hardwood | 9.5 | 24.33 | 14.83 |
| Softwood | 0.69 | 1.06 | 0.37 |
| THF Norm | 0.4 | 0.28 | −0.12 |
| THF Deg | 5.62 | 4.35 | −1.27 |
| Woodland | 1.82 | 0.97 | −0.85 |
| (c) Non forests | | | |
| Bushlands | 1.97 | 4.96 | 2.99 |
| Grasslands | 1.23 | 0.85 | −0.38 |
| Wetlands | 0.23 | 1.26 | 1.03 |
| Subsistence | 0.22 | 0.27 | 0.05 |
| Commercial | 0.00 | 0.00 | 0.00 |
| Built up | 0.17 | 2.63 | 2.46 |

categories had positive net change-to-persistence ratios. Comparing categories with positive $n_p$, 'Others' had the highest value. This should be interpreted in relation to its proportional coverage of the landscape. 'Others' almost doubled increasing from 1.8% in 1990 to 3.4% of the landscape in 2005.

In Table 9, within the forest category, THF degraded, hardwood plantations and woodlands had $l_p$ ratios greater than 1, which indicates that these classes had a higher tendency to lose than persist. The $l_p$ ratios for Softwood plantations (0.69%) and THF normal (0.4%) were less than 1. This indicates that the 'Softwood plantation' and 'THF normal' area loss was about 69% and 40% of the respective persistence on the landscape (Fig. 2). The forest landscape in Uganda is highly fragmented and this increases its susceptibility for conversion to other land uses (Baranga et al. 2009; Hartter and Southworth 2009). Forest persistence (Fig. 2) is mainly observed in south western Uganda where the remaining forests occur as protected areas within an intensively cultivated agricultural landscape (NFA 2009). The gain-to-persistence ratio, $g_{p,}$ is greater than 1 for plantations and THF degraded (Table 9), indicating that these forest classes experienced more gain than persistence. THF normal had the least $g_p$ (0.28). The net change-to-persistence ratio ($n_p$), is negative for woodlands and both normal (−0.12) and degraded (−1.27) tropical high forests (THF).

Considering non forest land uses (Table 9), with the exception of bushlands and grasslands, all other classes had $l_p$ values less than 1 indicating that bushlands and grasslands had a higher tendency to lose than persist. There was a net loss of grassland (38% of its persistence in the landscape) and a net gain in bushland which was almost three times as much as its persistence on the landscape. The $l_p$ of 0.22 and 0.23 for subsistence farmland and wetlands respectively indicate that the subsistence cropland and wetland area which was converted to other classes were much smaller compared to their persistence on the landscape. This could be an indication of the increasing population pressure which has led to more intensive cultivation of farmland (Braimoh 2006). This is evident from the negligible net gain (5%) of cropland compared to its persistence in the landscape. The persistence of cropland occurs mainly within the highly populated lake shore areas in central, eastern and western Uganda (Fig. 2). The net gain of wetlands is slightly more than its persistence while the net gain of built up areas is more twice its persistence on the landscape (Table 9).

### *4.1.3 Random and systematic transitions*

The expected gains under a random process of gain are shown in Table 10 and the differences between the observed (Table 7) and expected landscape proportions (Table 10a) are given in Table 10b. Values in Table 10b closer to zero indicate random transitions between classes, while values farther from zero imply systematic changes (Braimoh 2006).

The difference between observed and expected gain for transitions from forest to bush/grassland (3.89%) and bush/grassland to forest (0.97%) have positive values (Table 10). This shows that there is a systematic exchange between forests and bush/grassland. Forests lost more to bush/grassland than would be expected under a random process of change (gain) for bush/grassland. Thus, the 8% transition from forest to bush/grassland (Table 7) was due to systematic processes of change implying that when bushland/grassland gains, new bush/grassland tends to gain systematically from forest.

Forests also systematically gained from bushland/grassland but in about 1% of the landscape (Table 7). The differences between observed and expected gains for bush/

**Table 10** Comparison of observed and expected proportions (%) under a random process of gain 1990–2005

| 1990 | 2005 | | | | Total 1990 | Loss |
|---|---|---|---|---|---|---|
| | Forest | Bush/grassland | Cropland | Others | | |
| (a) Expected proportions | | | | | | |
| Forest | 10.59 | 4.32 | 4.11 | 0.44 | 19.46 | 8.87 |
| Bush/grassland | 2.58 | 20.15 | 5.38 | 0.59 | 28.70 | 8.55 |
| Cropland | 3.78 | 8.28 | 36.61 | 0.85 | 49.52 | 12.91 |
| Others | 0.16 | 0.34 | 0.32 | 1.49 | 2.31 | 0.82 |
| Total 2005 | 17.11 | 33.09 | 46.42 | 3.37 | 100 | 31.15 |
| Gain | 6.52 | 12.94 | 9.81 | 1.88 | 31.15 | |
| (b) Difference between the observed and expected proportions (%) | | | | | | |
| Forest | 0.00 | 3.89 | 0.06 | −0.19 | 3.77 | 3.76 |
| Bush/grassland | 0.97 | 0.00 | 0.15 | 0.58 | 1.71 | 1.70 |
| Cropland | −0.85 | −3.74 | 0.00 | −0.39 | −4.99 | −4.98 |
| Others | −0.12 | −0.15 | −0.21 | 0.00 | −0.48 | −0.48 |
| Total 2005 | 0.00 | 0.00 | 0.00 | 0.00 | 0.0 | 0.0 |
| Gain | 0.00 | 0.00 | 0.0 | 0.00 | 0.0 | 0.00 |

Data MWLE, 2003; NFA, 2009

grassland to others (0.58%); bush/grassland to cropland (0.15) and forest to cropland (0.06%) are all positive but less than 1. The difference between observed and expected gains for cropland to bushland is relatively large and negative (−3.74%). This implies that when bushland gains, new bushland systematically avoided gaining from cropland.

*Inter-category losses* Table 11 shows the analysis of losses, which is analogous to the analysis of gains (Table 10). The expected losses under a random process of loss (Table 11a) and the differences between the observed and expected landscape losses (Table 11b) for forest to bush/grassland and bush/grassland to forest were 3.17% and 0.93% respectively. This indicates that forest lost systematically to bush/grassland and bush/grassland only marginally lost to forests. The difference between observed and expected losses for transitions from forest to cropland (−2.92%) and bush/grassland to cropland (−1.58%) were large and negative implying that forest and bush/grassland systematically avoided losing to cropland.

Considering the inter-category systematic gains (Table 10) and losses (Table 11), the most dominant signal of change is a conversion of about 8% of forest to bush/grassland.

*Deforestation and forest degradation* In order to differentiate between deforestation and forest degradation according to the Kyoto definitions,[6] we present the analysis without aggregating the LULC classes (Table 12). Based on these definitions, degradation accounts for 1.02% while deforestation accounts for 12.62% of the change in the landscape. Most of the deforestation occurs in woodlands (92.34%) while that in THF constitutes only 7.45%. Between 1990 and 2005, woodland forest area decreased by 30% (NFA 2009).

The positive difference between the observed and expected proportions indicate that woodland forests lost and gained more from bushlands and grassland than would be expected under random gain and loss processes respectively. The negative differences between the observed and expected proportions indicate that subsistence farmland lost less to bushlands and grassland than would be expected under a random gain process.

## 4.2 Carbon stocks and emissions from deforestation and forest degradation

### *4.2.1 Carbon stocks*

The annual yield estimates and biomass carbon density stocks in the different land uses are presented in Tables 5 and 6 respectively. Considering THF, the mean net carbon accumulation for both degraded and normally stocked forest shows an increasing trend of 0.7 t C $ha^{-1}$ $yr^{-1}$ (Table 13).

Using data collected in Africa between 1968 and 2007, Lewis et al. (2009) also show that African forests have increasing (0.63 t C/ha/yr) carbon stocks. For comparison, the average rate of carbon accumulation in tropical forests around the globe was estimated at 0.49 t C/ha/yr (Phillips et al. 1998; Chave et al. 2008).

Total forest C stocks increased (Table 14), but woodland forests are a net source due the unsustainable harvesting practices. The annual off-take exceeds growth. Therefore,

[6] Deforestation as defined under the Kyoto Protocol, refers to a permanent change of land use from forest to non-forest and, therefore, involves a loss in forest area and carbon stocks. Forest degradation refers to a decrease in biomass, and hence a reduction in forest carbon stocks without loss of forest area or change in land use (UNFCCC 2006).

**Table 11** Comparison of observed and expected proportions (%) under a random loss process 1990–2005

| 1990 | 2005 | | | | Total 1990 | Loss |
|---|---|---|---|---|---|---|
| | Forest | Bush/grassland | Cropland | Others | | |
| (a) Expected proportions (%) | | | | | | |
| Forest | 10.59 | 5.04 | 7.09 | 0.51 | 23.23 | 12.64 |
| Bush/grassland | 2.62 | 20.15 | 7.11 | 0.53 | 30.41 | 10.26 |
| Cropland | 2.52 | 4.9 | 36.61 | 0.5 | 44.53 | 7.92 |
| Others | 0.06 | 0.12 | 0.16 | 1.49 | 1.83 | 0.34 |
| Total 2005 | 15.79 | 30.21 | 50.97 | 3.03 | 100 | 31.16 |
| Gain | 5.2 | 10.06 | 14.36 | 1.54 | 31.16 | |
| (b) Difference between the observed and expected proportions (%) | | | | | | |
| Forest | 0.00 | 3.17 | −2.92 | −0.26 | 0.00 | 0.0 |
| Bush/grassland | 0.93 | 0.00 | −1.58 | 0.64 | 0.00 | 0.0 |
| Cropland | 0.41 | −0.36 | 0.00 | −0.04 | 0.00 | 0.0 |
| Others | −0.02 | 0.07 | −0.05 | 0.00 | 0.00 | 0.0 |
| Total 2005 | 1.32 | 2.88 | −4.55 | 0.34 | 0.00 | 0.0 |
| Gain | 1.32 | 2.88 | −4.54 | 0.34 | 0.00 | |

Data MWLE 2003; NFA 2009

woodlands deserve special attention when discussing the global carbon cycle. Carbon stocks in woodlands (23 t C ha$^{-1}$) are within the range of estimates for African savannas, with values of 23–24 t C ha$^{-1}$ (Brown and Lugo 1984; Montès et al. 2002) but much lower (on a unit area basis) than stocks in THF with values from 114 t C ha$^{-1}$ in normally stocked THF to 72 t C ha$^{-1}$ in degraded THF (Table 14). The difference is offset by the extent of the area covered by woodlands (76%) compared to that covered by THF (23%). Comparing current woodland biomass to the range of average estimates for sub Saharan Africa, (17–70 tons carbon/ha) (Gibbs et al. 2007); there are opportunities for improving current stocks through sustainable woodland management.

### *4.2.2 Emissions from deforestation and forest degradation*

Using the period 1990–2005 as the timeline for the historic reference period,[7] Uganda lost an average of 88,536 ha/yr of natural forests of which 10% were categorized as Tropical High Forests (THF) in 1990 and 90% as woodlands (NFA 2009).

In addition, when THF normal become degraded, their biomass decreases significantly. Between 1990 and 2005, the LULC transition matrix indicates that about 101,100 ha of normally stocked THF became degraded resulting in a loss of 447,960 t C yr$^{-1}$. The total

[7] Considering past trends as an indication of the future, a historic reference timeline which encompasses several years such as (1990–2005) reduces the impact of anomalous years from previous trends. However, a 5 year reference period (i.e 2000–2005) may have advantages of identifying changes in land use with more relevance to the present. Our selection of the period 1990–2005 was also based on the fact that this is the period for which we have comparable reliable data on land use area and biomass carbon stocks estimates. In addition, considering the possibility of REDD + options and the current Clean Development Mechanism (CDM) framework, in order to qualify as a CDM-AR eligible activity, reforestation is limited to “those lands that did not contain forest on 31 December 1989” (UNFCCC/CP/2001/13/Add.1).

**Table 12** Difference between observed landscape transition and expected gains and loss (%)

| | | Hardwood | Softwood | THF_Norm | THF_Deg | Woodland | Bushlands | Grasslands | Wetlands | Subsistence | Commercial | Built_up | Total 1990 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hardwood | Gain | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Loss | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Softwood | Gain | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Loss | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| THF_Norm | Gain | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | −0.4 | −0.4 | −0.1 | −0.2 | 0.0 | 0.0 | −0.8 |
| | Loss | 0.00 | 0.00 | 0.00 | 0.27 | 0.09 | −0.09 | −0.17 | −0.02 | −0.09 | 0.01 | 0.00 | 0.00 |
| THF_Deg | Gain | 0.0 | 0.0 | 0.2 | 0.0 | 0.1 | −0.1 | −0.1 | 0.0 | 0.2 | 0.0 | 0.0 | 0.4 |
| | Loss | 0.00 | 0.01 | 0.17 | 0.00 | 0.08 | −0.07 | −0.17 | −0.02 | 0.00 | 0.00 | 0.00 | 0.00 |
| Woodland | Gain | 0.0 | 0.0 | 0.2 | 0.0 | 0.0 | **1.8** | **1.9** | −0.1 | 0.1 | 0.0 | 0.0 | 3.7 |
| | Loss | 0.01 | 0.00 | −0.13 | 0.03 | 0.00 | **2.13** | **1.34** | −0.24 | **−3.07** | −0.02 | −0.04 | 0.00 |
| Bushlands | Gain | 0.0 | 0.0 | 0.0 | 0.0 | 0.6 | 0.0 | **1.4** | −0.1 | −0.1 | 0.0 | 0.0 | 1.7 |
| | Loss | 0.00 | −0.01 | −0.14 | −0.04 | 0.42 | 0.00 | **1.23** | −0.11 | **−1.33** | 0.00 | −0.01 | 0.00 |
| Grasslands | Gain | 0.0 | 0.0 | −0.1 | −0.1 | 0.5 | **2.2** | 0.0 | 0.7 | 0.3 | 0.0 | 0.0 | 3.3 |
| | Loss | 0.00 | −0.01 | −0.44 | −0.11 | 0.22 | **2.83** | 0.00 | 0.56 | **−3.02** | 0.01 | −0.04 | 0.00 |
| Wetlands | Gain | 0.0 | 0.0 | 0.0 | 0.0 | −0.1 | −0.2 | −0.1 | 0.0 | −0.2 | 0.0 | 0.0 | −0.6 |
| | Loss | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | −0.1 | 0.0 | 0.0 | 0.0 |
| Subsistence | Gain | 0.0 | 0.0 | −0.2 | −0.1 | −1.0 | **−3.3** | **−2.8** | −0.6 | 0.0 | 0.0 | 0.1 | −7.7 |
| | Loss | 0.0 | 0.0 | −0.3 | 0.1 | 0.6 | 0.0 | −0.4 | −0.3 | 0.0 | 0.1 | 0.2 | 0.0 |
| Commercial | Gain | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | −0.1 | 0.0 | 0.0 | 0.2 |
| | Loss | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | −0.1 | 0.0 | 0.0 | 0.0 |
| Built_up | Gain | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Loss | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Total 2005 | Gain | 0.1 | 0.1 | 2.1 | 1.1 | 14.4 | 18.2 | 21.5 | 3.5 | 38.1 | 0.4 | 0.4 | 0.0 |
| | Loss | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

**Table 13** Annual forest biomass carbon accumulation/loss, Uganda 1989–1996 (t C $ha^{-1}$ $yr^{-1}$)

| Land cover/use | Carbon accumulation | | Carbon loss/gain | Net carbon accumulation/loss |
|---|---|---|---|---|
| | 1989 (a) | 1996 (b) | | |
| THF - Normal | 2.52 | 9.00 | −12.15 | −3.15 |
| THF - degraded | | 6.60 | −4.15 | 2.45 |
| Woodlands | 1.80 | 3.18 | −0.95 | 2.23 |

a = Calculated from FD (1992) and World Bank (1996); b = Calculated from MWLE (2003); - Indicates a loss in biomass carbon

annual losses due to deforestation and forest degradation are estimated at $2.6 \times 10^6$ t C $yr^{-1}$ (Table 15). Carbon losses from forests in Uganda are more to do with increasing woodland deforestation as a result of lack of law enforcement even within the protected areas, which have in some instances become *de facto* open access resources and a cheap source of tree products.

### 4.2.3 Comparison to other estimates

For comparison purposes, taking the biomass density estimate from FAO (2006) of 34.25 t C/ha as an approximation of the average forest biomass density; this translates into a loss of 3.032,119 t C $yr^{-1}$. If we account for growth (3,257 t C $yr^{-1}$), (Table 14); the net carbon emissions from natural forests would then be equivalent to 3,028,861 t C $yr^{-1}$. A meaningful comparison with estimates from literature requires estimates which consider the same time period and with detailed information on the forest types considered, the assumptions made on the average biomass stocks and the original sources of data. However, such detailed information is not always explicitly provided.

For the period 2000–2005 available estimates range between 2.6–26.3 million t C $yr^{-1}$ (Table 16). Our estimate (about 2.67 million t C $yr^{-1}$) is at the lower end of the this range; much lower than the upper limit of 26.3 million t C $yr^{-1}$ in Murray and Olander (2008) which is based on assumptions of biome averages for tropical forests ranging between 120–250 t C/ha (Gibbs et al. 2007). These carbon density estimates however, are higher than

**Table 14** Above and belowground woody biomass carbon stocks in different forest types, Uganda, 1990 and 2005

| Forest type | Mean carbon density (t C/ha) | | Total carbon stocks standing 000 | | Change 000 | |
|---|---|---|---|---|---|---|
| | 1990(a) | 2005(b) | 1990 | 2005 | Total t C | Annual t C $yr^{-1}$ |
| THF - Normal | 104.81 | 113.56 | 68,241 | 68,246 | 4.254 | 0.28360 |
| THF - Degraded | 50.345 | 71.98 | 13,747 | 13,798 | 51.352 | 3.42350 |
| Woodlands | 15.855 | 22.68 | 63,014 | 63,007 | −6.747 | −0.44980 |
| Total | 29.6[a] | 40.62[a] | 145,002 | 145,051 | 48.859 | 3.25730 |

a = Calculated from FD (1992); WB (1996) and MWLE (2003)

b = Mean from data collected between 2004–2007 (NFA 2009)

[a] Area weighted value

**Table 15** Emissions from deforestation and THF degradation in Uganda, 1990–2005

| Forest type | Area | Carbon loss | Total carbon loss |
|---|---|---|---|
| | 000 ha/yr | t C ha$^{-1a}$ | 000 t C yr$^{-1}$ |
| Emissions from deforestation | | | |
| THF - Normal | 3.34 | 109.19 | 365.04 |
| THF - Degraded | 5.42 | 61.16 | 331.79 |
| Woodlands | 79.77 | 19.27 | 1,536.75 |
| Total | 88.54 | 25.23[b] | 2,233.75 |
| Emissions from degradation | | | |
| THF - Normal to THF Degraded | 3.77 | 48.02 | 181.20 |
| THF - Normal to Woodland | 2.97 | 89.92 | 266.76 |
| Total | 6.74 | 66.46[b] | 447.96 |
| Total from deforestation and forest degradation | | | 2,681.71 |

Assumptions: No further degradation in 1990 degraded area

[a] since we do not know at which point in time the deforestation occurred, we assume mean carbon density for the period 1990–2005 from Table 6

[b] Area weighted value

those actually estimated in Uganda's forests (Table 14). The low densities also illustrate the potential of improving current carbon stocks.

## 4.3 Drivers of forest land use change in Uganda 1990–2005

Drivers of deforestation vary in importance across regions (for southwestern Uganda, see Babigumira et al. (2008) but generally, the large subsistence rural population characterized

**Table 16** Estimated total emissions (Million tones carbon/year) from deforestation and forest degradation for Uganda, 1990–2005

| Reference period | Carbon emissions ($10^6$) t C yr$^1$ | Source | Methods and source of data used |
|---|---|---|---|
| 2000–2005 | 2.6–8.6 | FAO 2006 | Aggregated country level information on biomass growing stock in forests.<br>Assumption: deforestation releases 30–100 metric tons of carbon/ha cleared or converted to agriculture |
| 2000–2005 | 4.6 | Gibbs and Brown 2007 | Based on a deforestation rate of 2.2% and carbon density of 35.3 t C/ha from FAO (2006) |
| 2000–2005 | 26.3 | Murray and Olander 2008 | Calculated based on carbon stocks presented by Gibbs et al. 2007 |
| 1990–2005 | 3.7 | World Bank 2008; NFA 2008 | Product of deforestation rate (1990–2005) and average biomass density data from National Forestry Authority |
| 1990–2005 | 2.7 | This study | Product of deforestation rate (1990–2005) and area weighted average biomass density, accounting for biomass growth; data from National Forestry Authority |

by unsustainable farming practices and low productivity results in increasing demand for cultivable land (Pender et al. 2004). The detailed land use change model process is presented in Appendix 1. The results of the logistic regression models for forest land conversions are presented in Table 17. Common significant predictors include agro-ecological zone (AEZ), restriction, slope, soil, and presence/absence of a water stream network. Most of the deforestation (95%) and forest degradation (80.9%) occurred in AEZ 3 and 4. Deforestation includes conversion of forests to cropland (58%) and (37%); and forest to others (46.5%) and (37.9%) in AEZ 3 and 4 respectively (Fig. 3).

As expected, restriction is significant in all the models. Restriction was assumed to have a significant role in explaining the persistence of forests and in determining their conversion processes. The intercept and the restriction variable share the main part of the explanation for the persistence of forests and their conversion to bush/grassland (degradation), cropland and others (deforestation). Restriction strongly reduces the likelihood of converting forests to cropland. An increase in both poverty and population decrease the log odds of retaining

**Table 17** Coefficients of the logistic regression models for forest land conversions, 1990–2005

| | | Land use/conversion category | | | |
|---|---|---|---|---|---|
| | | Degradation | | Deforestation | |
| | | Forest | Forest to bush/grassland | Forest to cropland | Forest to others |
| Explanatory variables and parameter estimates | (Intercept) | 0.63*** | 1.898*** | −1.971*** | −4.696*** |
| | Agroeco2 | 0.09 | −0.753*** | 0.021 | ni |
| | Agroeco3 | −0.21* | −0.739*** | 0.510** | ni |
| | Agroeco4 | 0.77*** | −2.258*** | 0.852*** | ni |
| | Aspect | 0.000*** | ni | ns | ni |
| | Market access | −0.000*** | 0.000*** | ns | −1.73E-05*** |
| | Elevation | 0.001*** | −0.002*** | ns | ni |
| | Lake buffer | ni | 0.001* | 0.002*** | ni |
| | Restriction | 0.91*** | −0.209*** | −2.381*** | 0.7*** |
| | Slope | 0.06*** | ni | −0.074*** | −1.082*** |
| | Soil | −0.002*** | ns | 0.001*** | 0.01*** |
| | Pop | ni | −0.01*** | 0.01*** | ni |
| | Poverty | −0.026*** | 0.2352*** | −0.006*** | ni |
| | Popch | −0.006*** | ni | ni | ni |
| | Streams | −0.214*** | 0.242*** | −0.134*** | 0.65*** |
| | East | −0.000*** | 0.000*** | −0.000 | 0.000*** |
| | North | 0.000*** | −0.000*** | −0.000 | −0.000*** |
| Model | ROC AUC[a] | 0.73 | 0.73 | 0.77 | 0.18 |
| performance | Sensitivity | 0.83 | 0.83 | 0.24 | 0 |
| measures | Specificity | 0.48 | 0.51 | 0.94 | 1 |

*** significant at 0.001, **0.1, *0.5

ni = not included; ns = not significant

[a] The occurrence of a land use can be explained by the location factors as indicated by the area under the ROC curve (AUC) between 0.69 and 0.94, whereas a random model has a value of 0.5 and a perfect model has a value of 1.0

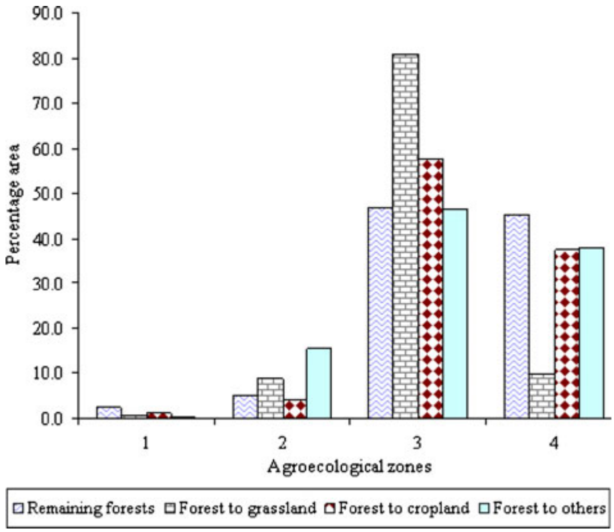



**Fig. 3** Forest land use conversions by agro ecological zones in Uganda 1990–2005

forests and at the same time reduces the likelihood of deforestation (forest converted to cropland). Poverty also increases the likelihood of degradation. An increase in slope increases the likelihood of forest persistence and reduces the likelihood of deforestation (Table 17).

The probability of converting forests to bushlands/grasslands (0.36) is higher than that of converting forest to cropland (0.18) while the probabilities of converting croplands and other land uses are generally low. All land uses have high probabilities of remaining under the same land use with croplands having the highest (0.83) and forests the lowest (0.46) (Table 18). Forests located within the cattle corridor have high probabilities of changing to bushlands or grassland, a process here which has been considered to constitute degradation (Fig. 4b) while those within the lake region are susceptible to conversion (deforestation) to cropland (Fig. 4c). The probability of converting any land use to forest is low (Table 13 and Fig. 5).

## 5 Conclusions

This paper provides a detailed analysis of the LULC change dynamics in Uganda for the period 1990–2005. The study generated useful information on patterns and drivers of

**Table 18** Mean (Minimum and maximum) transition probabilities estimated from the logistic regression models derived based on observed changes between land use/cover types in Uganda, between 1990 and 2005

| From Land use/cover | To | | | | |
|---|---|---|---|---|---|
| | Forest | Bush/grassland | Cropland | Others | Total |
| Forest | **0.46 (0.00–0.99)** | 0.36 (0.00–0.94) | 0.18 (0.00–1.00) | 0.01(0.00–0.40) | 1 |
| Bush/grassland | 0.12 (0.00–0.68) | **0.66 (0.00–0.98)** | 0.18 (0.00–1.00) | 0.04 (0.00–0.99) | 1 |
| Cropland | 0.07 (0.00–0.61) | 0.10 (0.00–0.81) | **0.83 (0.12–1.00)** | 0.01 (0.00–0.13) | 1 |
| Others | 0.10 (0.00–0.86) | 0.09 (0.00–0.96) | 0.06 (0.00–0.98) | **0.76 (0.03–0.97)** | 1 |

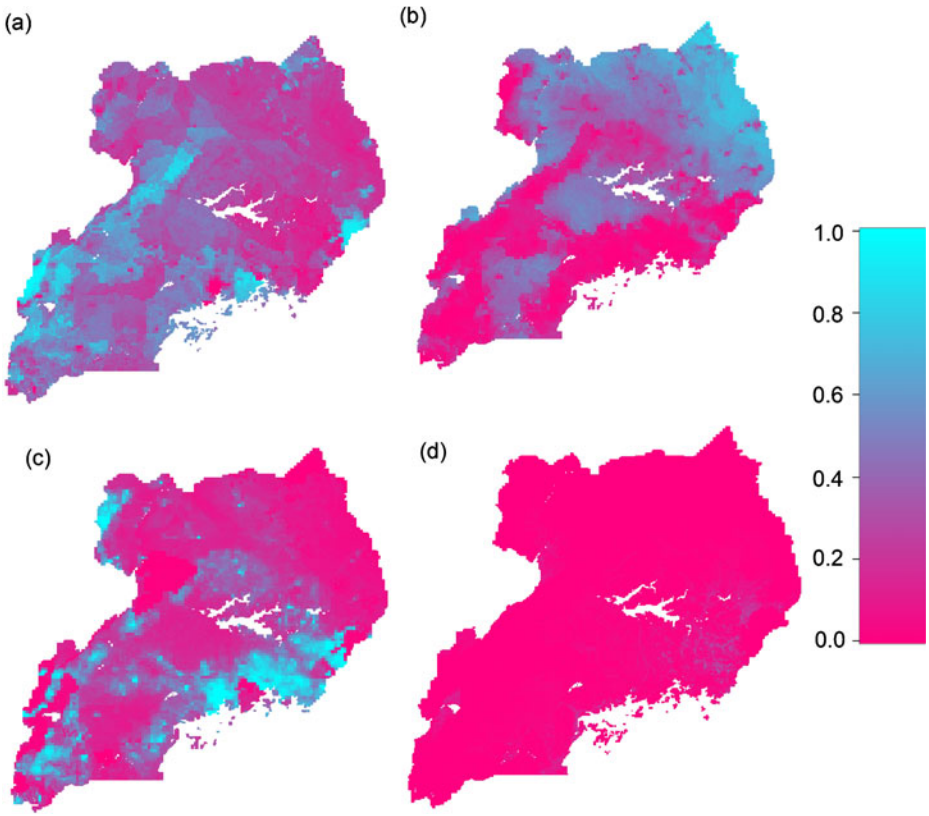



**Fig. 4** Forest land use/conversion probability maps derived based on observed conversions 1990–2005 (**a**) Forest remaining forest; and converting (**b**) Forest to grassland (**c**) Forest to cropland (**d**) Forest to others

LULC change, and also on change in carbon stocks. This information, on the one hand, provides a foundation for more comprehensive studies of alternative baseline and mitigation scenarios associated with LULC change processes. Thus, although it involves use of a simple projection models based on trends, we believe it is a valuable step forward in advancing our knowledge of the complex LULC change processes and the carbon cycle.

The most dominant systematic land use change processes are woodland forest degradation (transition of woodland to bushland (4.01%) and grassland (4.08%) and deforestation (transition of woodland to subsistence farmland—3.32%) resulting in a net reduction in forests (6.1%). Woodland loss occurs in the Central and Northern Uganda mainly within the cattle corridor, where woodlands have converted to bushlands and grasslands mainly as a result of over use for subsistence grazing and commercial fuelwood.

Although there was a net loss in forest to other uses, total carbon stocks increased. Within the different forest types, there was an increase in tropical high forest carbon stocks (1.85 t C/yr) and a decline in woodland stocks (0.45 t C/yr). Emissions due to deforestation and degradation for the period 1990–2005 were estimated at 2.67 million tonnes C/year. The observed carbon dynamics could be related to the potential drivers of forest land use

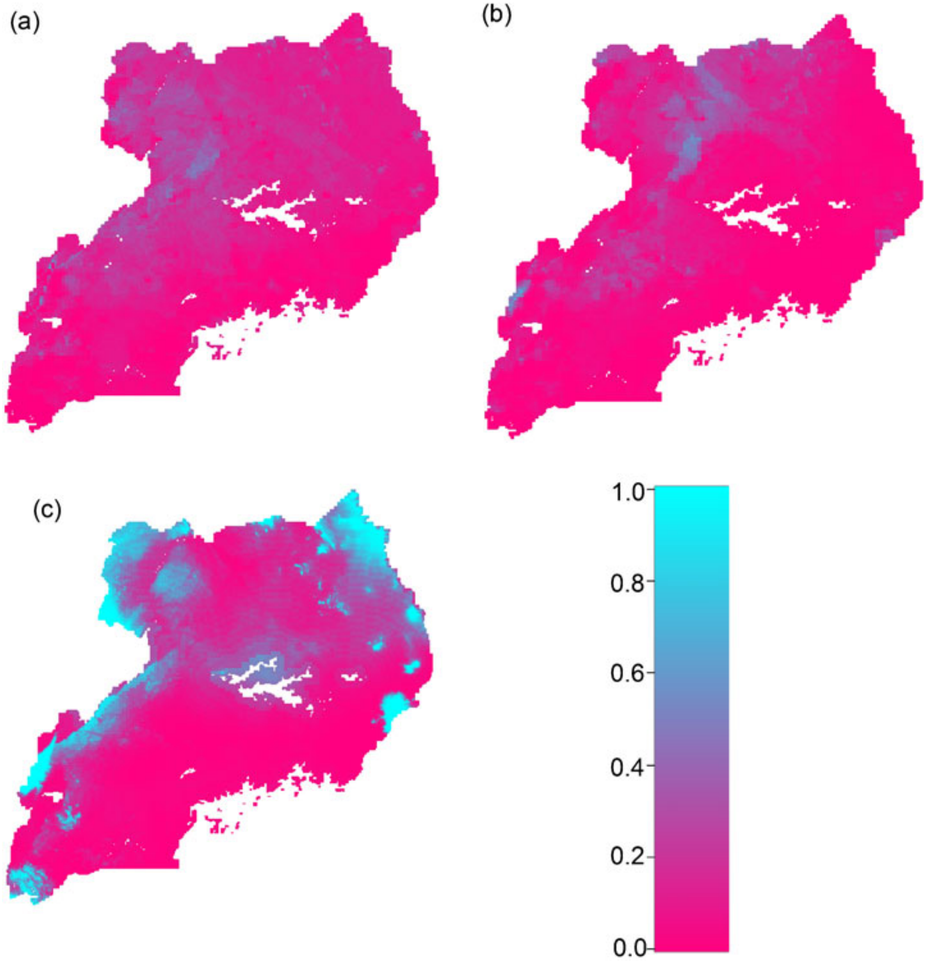



**Fig. 5** Probability maps for conversion of (**a**) Grassland to forest; Cropland to forest (**b**) Others to forests (**c**) derived based on observed conversions 1990–2005

change, with restriction strongly reducing likelihood of forest conversion. With most of the remaining tropical high forests under protection they experience an increase in carbon stocks while woodlands without any institutionalized management are prone to deforestation and over use. Other significant drivers included poverty and population which decreased the log odds of retaining forests. Poverty also increased the likelihood of degradation. An increase in slope decreased the likelihood of deforestation. Although our assumptions may not hold for a comprehensive understanding of the drivers of LULC change, we believe it contributes to improving the available related literature especially on patterns of land use change in Uganda and it is a useful forward step in the direction towards developing a more complex model when one has access to more relevant data. Future investigations might address how the addition of other relevant factors would alter the model's predictions compared to empirical observations. Future efforts could consider incorporating more complex dynamic biomass growth models for the different land uses, to be able to determine more precisely the differences between C pools in the different LULC classes and the changes associated with the various conversions. We are conducting further work to determine regional differences in LULC change and drivers of land use change. This will help to provide information on the regional drivers of LULC change associated with forest and non forest ecosystems. Improving future estimates will require addition of important components of forest biomass including soil, coarse wood debris (necromass) and litter fall stocks in the national inventories.

## 6 Implications for the design of a national REDD strategy

The implications for a future REDD plus strategy are: considering the significance of the restriction variable and its role in containing forest conversions, enhancing protection especially in THF which contain high and increasing biomass carbon stocks and serve other ecological and livelihood functions will be necessary while sustainable forest management will be relevant in woodlands which are currently under intensive use. Given the fact that non forest land uses dominant the landscape, adoption of multifunctional agroforestry production systems in these ecosystems will also serve important climate mitigation and direct livelihood benefits.

### 6.1 Role of protected areas

Establishing new protected areas (PAs) and subsequently improving their effectiveness may be cost efficient and could offer opportunities for harnessing synergies under the REDD plus mechanism by availing multiple benefits (Campbell et al. 2008). However, increasing PAs might be particularly challenging in Uganda where most of the remaining intact forests already lie within the PA network (NFA 2009). The PAs have high and increasing carbon stocks but are also located in areas with high population densities, with high agricultural potential (Ruecker et al. 2003) subjecting them to severe pressure from encroachers for land for agriculture and developments[8] (NEMA 2009a, b).

Some PAs in Uganda contain forest villages located within (enclaves) or outside the administrative boundaries and are surrounded by intensive cropland making them highly susceptible for conversion to agriculture (Hartter 2008). Thus while PAs are generally quite successful at reducing deforestation and conserving biodiversity within their boundaries (Brooks et al. 2009), strategies to enhance carbon stocks and conserve biodiversity within human modified landscapes are also required (Koh and Gardner 2010). It is also important to address issues related to sustainable forest management outside PAs (Putz et al. 2008).

### 6.2 Agroforestry in non forested landscapes

Since Uganda has an agro based economy, maintaining sustainable agricultural and pastoral production systems has economic and environmental implications. Sustainable agricultural production systems can provide a wide range of other goods and services including on farm biodiversity (Eilu et al. 2003; Bolwig et al. 2006) and can serve as multifunctional

[8] A census carried out by the NFA in May 2005 indicated that there were over 180,000 encroachers in the 506 Central Forest Reserves (NFA 2005) and the number has more than doubled in the last 5 years (Annon. 2009).

production systems to promote both national development interests and global climate change mitigation interests. A wide range of activities could be undertaken to avoid emissions from and enhance carbon sequestration in landscapes outside forests, many of which could yield positive impacts on ecosystems and rural livelihoods. In pastoral lands and croplands, agroforestry systems which do not require full land use conversion can be particularly useful and could play a larger role in the efforts to mitigate climate change while addressing national development concerns (Nair et al. 2009). Such agroforestry systems could play an important role in sustaining a variety of other ecosystem services while improving livelihoods (Aune et al. 2005) and contributing to climate mitigation by reducing the need for clearing new land (Kirby and Potvin 2007). Carbon/REDD payments could be used as an incentive to encourage adoption of multi functional agroforestry production systems such as the traditional banana-coffee agroforestry systems. This can also be an option for protecting the numerous small forests scattered all over the country outside the PA network. However, although the carbon payments are not meant to cover the opportunity costs of alternative land uses, they may not be competitive when compared to highly lucrative cash crops such as palm oil which are replacing natural forests and are increasingly promoted by the global interest in biofuels (Butler et al. 2009). Given the high dependency of the rural poor on forest resources especially as safety nets, REDD payments should go beyond enhancing carbon stocks and embrace strategies for improving rural livelihoods by promoting good governance which provides for sustainable use and protection of forest and non forest ecosystems within the landscape. Given the limited use of fertilizer in Uganda and their potential negative environmental effects, integrating leguminous tree species on farm can decrease the need to clear new land and fertilizer requirements by 75% among smallholder poor farmers, while doubling crop yields (Sileshi et al. 2008).

### 6.3 Sustainable forest management (SFM)

Although the persistence of forests in PAs signals the important role of command-and-control approaches in controlling forest conversions, it is also important to address issues related to sustainable forest management outside protected areas (Putz et al. 2008). The transitions from woodland forest to bushlands and grasslands, are important signals that need to be addressed in managing the landscape. Available literature indicates that woodland loss in Central Uganda has been attributed to unsustainable fuelwood production which is aimed at meeting the increasing urban demand for charcoal (Namaalwa et al. 2007). Halting woodland degradation may therefore require enforcing national legislation which controls charcoal production. Currently most of the degraded woodland forests are being converted to plantations to meet the country's timber requirements and relive pressure on the remaining THF. Despite the success stories of current reforestation efforts (Jacovelli 2009), this has in some cases had negative livelihood impacts (Eraker 2000; Lang and Byakola 2006) and should proceed with caution.

Considering the fact that about 68% of Uganda's forests occur as fragments scattered all over the country on private unprotected land (NFA 2009), enforcing protection policies will be daunting and politically unpopular. Sustainable management of these forests will inevitably require involving communities in the design and implementation of strategies aimed at achieving broader environmental and development policy goals. Though this is not a panacea for forest conservation (Skutsch et al. 2009) some evidence already suggests that forests managed by communities store more carbon (Chhatre and Agrawal 2009).

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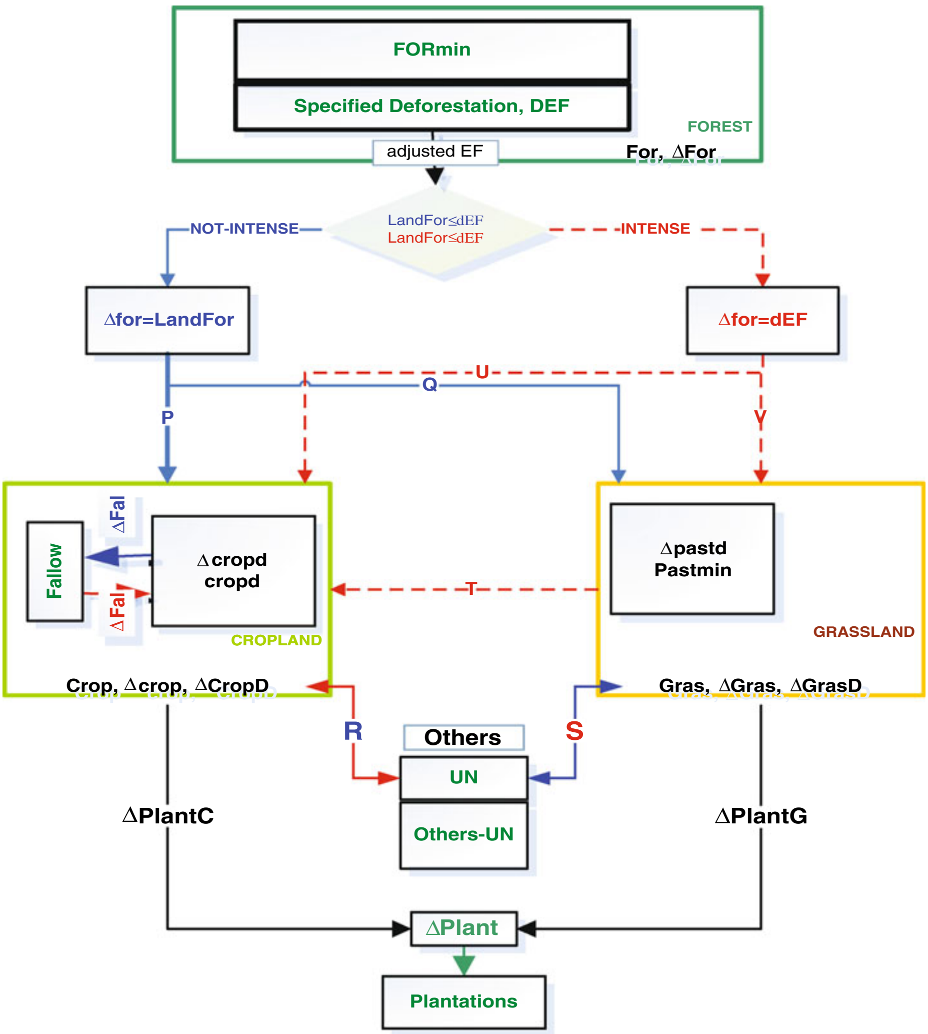
## Appendix 1: Detailed description of the model processes




[i] current year, [i-1] refers to previous year, [i+1] is the next year, [0] then refers to the initial-year

Forests & new plantations

$$Plant[i] = Plant[i-1] + \Delta Plant[\mathrm{i}] \tag{1}$$

Plant[i] is the cumulative new-plantation area in year i.
ΔPlant[i] is new area that has been converted to plantations from grasslands and cropland during year i. This is manually specified every year according to the desired scenario by a user.

$$\Delta Plant[i] = \Delta PlantC[i] + \Delta PlantG[i] \tag{2}$$

ΔPlantC[i] and ΔPlantG[i] are user specified land area transfers from cropland and grassland to new plantations. This may have implications for satisfying cropland demand.

$$For[i] = For[i-1] + \Delta For \tag{3}$$

For[i] is the forest area for year i (the current year)
ΔFor then refers to the change in forest area

Grassland

$$Gras[i] = \max(Gras^*[i], Past\min) - \Delta PlantG[i] \tag{4}$$

$$Gras^*[i] = Gras[i-1] + \Delta Gras^*[i] \tag{5}$$

$$\Delta Gras[i] = Gras[i] - Gras[i-1] \tag{6}$$

ΔGras [i] is the Actual change in grassland

$$\Delta GrasDfct[i] = \Delta GrasD[i] - \Delta Gras[i] \tag{7}$$

ΔGrasDfct is the Deficit or unsatisfied grassland demand at current consumption and yield
Gras[i] is the grassland area for year i (the current year)
[i-1] then refers to the previous year
ΔGras then refers to the change in grassland based on demand and constraints such as the user defined minimum value of Pastmin.

ΔGras* is the change in grassland before correction to ensure that Pastmin is maintained
ΔGrasD is the change in demand for grassland as driven by livestock and biomass yields.

Cropland

$$Crop[i] = if\,(Gras^*[i] \geq Past\min, Crop[i-1] + \Delta Crop^*[i], Crop[i-1] + \Delta Crop^*[i] - (Past\min - Gras^*[i]) - \Delta PlantC[i] \quad (8)$$

$$\Delta Crop[i] = Crop[i] - crop[i-1] \quad (9)$$

Crop[i] = the cropland area in current year
Gras*[i] = specified in Eq. 5
Past min = minimum grassland area. (It is specified by the user)
ΔCrop[i-1] = cropland area in previous year
Δcrop* = change in cropland before ensuring that the Pastmin is maintained.
ΔCrop[i] = Actual change in cropland which may be constrained by availability of land and Pastmin.

$$\Delta CropDfct[i] = \Delta CropD[i] - \Delta crop[i] \quad (10)$$

ΔCropDfct = Deficit or unsatisfied crop demand at current consumption and yield

Others

$$Oth[i] = Oth[i-1] - \Delta UN[i] \quad (11)$$

Crop[i] is the cropland area for year i (the current year)
UN[i] is the component of the Others' area that is user specified as available to transfer from Others(if positive) or to return to others (if negative)
ΔUN[i] is the change in the UN as an effect of transfers to/from Others.

## Computing the land demand & supply for each land-use type

No-intensification process (BiomC = 4.6)

i.e when For[i-1]-LandFor[i]>Formin[i] i.e, LandFor<dEF)

$$\mathrm{dEF[i] = dEF[i-1]} - \Delta F\mathrm{or[i-1] + DEF[i]} \quad (12)$$

$$FOR\min\,\mathrm{[i]} = For[i-1] - dEF[i] \quad (13)$$

LandFor[i] is the sum of the changes in demand for cropland and pastures that are not satisfied by UN.i.e P+Q in the diagram.
FORmin[i] is the minimum area beyond which the forest should not reduce in year i.
dEF[i] is the actual deforestation that is allowed in a given year that ensures a correction to the deforestation rate for the next year in order to ensure that the cumulative value of DEF[i], the user specified rate, is maintained over a long period.

Grassland

$$past_d[i] = f(BiomC = 4.6, Liv[i], BiomPY[i]) \tag{14}$$

$$BiomPY[i]) = k^*Rain[i] \tag{15}$$

K may vary from 0.001 to 0.004. This value has to be calibrated. Rain[i] is the average rainfall (mm) in particular year i.
Pastd is the demand for pastures by livestock
BiomC is the livestock Biomass consumption by an equivalent livestock unit
Liv is the number of livestock equivalent
BiomPY is the Biomass Yield in the grasslands

$$GrasD[i] = \max(Gras[i-1], past_d[i]) \tag{16}$$

GrasD is the required grassland area which may be equal to the existing area or the demanded pasture area, whichever is greater.

$$\Delta GrasD[i] = \max(0, GrasD[i] - GrasD[i-1]) \tag{17}$$

ΔGrasD is the change is GrasD. If it is negative, it not assigned, hence a value of zero is taken to mean there was no real change demanded. The negative value can be due to reduction in livestock numbers and or increase in biomass yields.

Cropland

$$crop_d[i] = f(FoodC, Popn[i], cropY[i], net\mathrm{Im}\,p[i]) \tag{18}$$

Cropd is the cropland area demand for crops intended for human consumption
FoodC is the food consumption per capita
Popn is the population
cropY is the crop yield (equivalent yield of a composite crop)

netImp is the difference between agricultural imports and exports

$$\Delta crop_d[i] = \max(0, crop_d[i] - crop_d[i-1]) \tag{19}$$

$\Delta$cropd is the difference between cropd for the current year and crop d for the previous year. If it is negative, it not assigned, hence a value of zero is taken to mean there was no real change demanded. The negative value can be due to a large increase in crop yield or net-agricultural imports netImp.

$$Fal[0] = crop[0] - crop_d[0] \tag{20}$$

Fal is the the Fallow area in year i. We calculate the fallow for [i-1] as the fallow for [i] is unknown until $\Delta$fal, the change in fallow, has been calculated

$$cf[i] = \frac{Fal[i]}{crop_d[i]} \tag{21}$$

cf1 is the reference fallow for a year in the past. Usually the first year in the simulation. [i = 0] indicates the starting year.

$$\begin{aligned} \Delta Fal[i] = {} & (\Delta crop_d[i]^* cf1) - (\Delta cropd[i] + \Delta GrasD[i] \\ & - UN[i])^* \left(1 - \frac{past[i-1]}{crop[i-1]}\right) \end{aligned} \tag{22}$$

(Stéphenne and Lambin 2001)

$$Fal[i] = Fal[i-1] + \Delta Fal[i] \tag{23}$$

$$\Delta cropD[i] = \Delta crop_d[i-1] + \Delta Fal[i] \tag{24}$$

$\Delta$cropD is the change in total cropland demand including the change in Fallow.

Transfers

$$R[i] = \min(\Delta cropD[i], UN[i]) \tag{25}$$

R[i] is the transfer of area between Others to Cropland

$$S[i] = \min((UN[i] - R[i]), \Delta GrasD[i]). \tag{26}$$

S[i] is the transfer of area between Others and Grasslands

$$P[i] = \max(\Delta cropD[i] - R[i], 0) \tag{27}$$

P[i] is the transfer from Forests to Croplands

$$Q[i] = \max(\Delta GrasD[i] - S[i], 0) \tag{28}$$

Q[i] is the transfer from Forests to Grasslands

$$LandFor[i] = P[i] + Q[i] \tag{29}$$

Check for intensification

$$if\,(For[i-1] - LandFor > FOR\min[i] ... then ... \Delta For = LandFor \tag{30}$$

If this condition is true then the changes in Land-use in Eqs. 2,4,5 and 6 are calculated as follows for year I (No intensification);

$$\begin{aligned} &\Delta For[i] = LandFor[i],\\ &\Delta Gras^*[i] = \Delta GrasD[i],\\ &\Delta Crop^*[i] = \Delta CropD[i],\\ &\Delta UN[i] = (R[i] + S[i]) \end{aligned} \tag{31a, b, c, d}$$

If this condition is False, then all above calculations from Eq. 8 are repeated as explained below.

Intensification process (BiomC = 2.3) In Eq. 8, BiomC becomes 2.3

Also recalculate Eqs. 9 to 15 which remain unchanged

Transfers

Recalculate Eqs. 25 and 26 which also remain unchanged. P& Q change slightly, but to avoid confusion we now call them U & V respectively and renumber to 23 and 24.

$$U[i] = \min(\Delta cropD[i] - R[i], dEF[i]) \tag{32}$$

U[i] is the transfer from Forests to Croplands

$$V[i] = \min(dEF[i] - U[i], \Delta GrasD[i] - S[i]) \tag{33}$$

Q[i] is the transfer from Forests to Grasslands

A new term T[i] to represent transfers from Grasslands to cropland. These transfers are possible during the intensification phase as livestock is increasingly fed on crop residues.

$$T[i] = \Delta cropD - (R + U) \tag{34}$$

It then follows that the changes in Land-use in Eqs. 2,4,5 and 6 are calculated as follows for year i (under-intensification);

$$\begin{aligned} &\Delta For[i] = U[i] + V[i], \\ &\Delta Gras^*[i] = S[i] + V[i] - T[i], \\ &\Delta Crop^*[i] = \Delta cropD[i], \\ &\Delta UN[i] = (R[i] + S[i]) \end{aligned} \tag{35}$$

## References


Anonymous (2009) Communication from National Forestry Authority

Angelsen A, Brockhaus M, Kanninen M et al (2009) Realising REDD+: National strategy and policy options. Center for International Forestry Research (CIFOR), Bogor, Indonesia. Available at http://www.cifor.cgiar.org/Knowledge/Publications/Detail?pid=2871

Aune JB, Alemu AT, Gautam KP (2005) Carbon sequestration in rural communities: is it worth the effort? J Sustain For 21:69–79

Babigumira R, Muller D, Angelsen A (2008) An integrated socio-economic study of deforestation in Western Uganda, 1990-2000. In: Aspinall RJ, Hill MJ (eds) Land use change: science, policy and management. CRC Press, Taylor & Francis Group, Boca Raton, pp 63–79

Baranga D, Chapman CA, Kasenene JM (2009) The structure and status of forest fragments outside protected areas in central Uganda. Afr J Ecol 47(4):664–669

Bolwig S, Pomeroy D, Tushabe H et al (2006) Crops, trees, and birds: Biodiversity change under agricultural intensification in Uganda's farmed landscapes. Danish Journal of Geography 106(2)

Braimoh AK (2006) Random and systematic land-cover transitions in northern Ghana. Agric Ecosyst Environ 113(1–4):254–263

Brooks TM, Wright SJ, Sheil D (2009) Evaluating the success of conservation actions in safeguarding tropical forest biodiversity. Conserv Biol 23:1448–1457

Brown S (1997) Estimating biomass and biomass change of tropical forests: a primer. FAO Forestry Paper 134, Rome, Italy

Brown S (2002) Measuring carbon in forests: current status and future challenges. Environ Pollut 116:363–372

Brown S, Lugo A (1984) Biomass of tropical forests: a new estimate based on forest volumes. Science 223:1290–1293

Bush G, Nampindo S, Aguti C et al (2005) The value of Uganda's forests: A livelihoods and ecosystems approach. Consultancy Report to Wildlife Conservation Society, Albertine Rift Programme. EU Forest Resources and Conservation Management Programme. National Forest Authority, Kampala, Uganda

Butler R, Koh A, Ghazoul J (2009) REDD in the red: palm oil could undermine carbon payment schemes. Conserv Lett 2:67–73

Cairns MA, Brown S, Helmer EH et al (1997) Root biomass allocation in the world's upland forests. Oecologia 111:1–11

Campbell A, Kapos V, Lysenko I et al (2008) Carbon emissions from forest loss in protected areas. UNEP World Conservation Monitoring Centre

Chave J, Condit R, Muller-Landau HC et al (2008) Assessing evidence for a pervasive alteration in tropical tree communities. PLoS Biology 6

Chhatre A, Agrawal A (2009) Trade-offs and synergies between carbon storage and livelihood benefits from forest commons. Proc Natl Acad Sci USA 106(42):17667–17670

Cohen J (1960) A coefficient of agreement for nominal scales. Educ Psychol Meas 20(1):37–46

Cooke P, Kohlin G, Hyde W (2008) Fuelwood, forests and community management: evidence from household studies. Environ Dev Econ 13:103–135

Dixon RK, Brown S, Houghton RA et al (1994) Carbon pools and flux of global forest ecosystems. Science 263:185–190
Drichi P (2005) Global forest resources assessment 2005. Uganda Country Report 223. Food and Agricultural Organisation of the United Nations, Rome
Eilu G, Obua J, Tumuhairwe JK et al (2003) Traditional farming and plant species diversity in agricultural landscapes of south-western Uganda. Agric Ecosyst Environ 99:125–134
Eraker H (2000) CO2Colonialism: Norwegian Tree Plantations, Carbon Credits, and Land Conflicts in Uganda, NorWatch
FAO (2006) Global Forest Resources Assessment 2005: Progress Towards Sustainable Forest Management. FAO Forestry Paper 147. Food and Agricultural Organization of the United Nations (FAO), Rome
Forest Department (1992) National Biomass Study Technical Report 1991. Kampala, Uganda
Gibbs HK, Brown S (2007) Geographical distribution of woody biomass carbon stocks in tropical Africa: an updated database for 2000. Available at http://cdiac.ornl.gov/epubs/ndp/ndp0555/ndp05b.html from the Carbon Dioxide Information Center, Oak Ridge National Laboratory, Oak Ridge, TN
Gibbs HK, Brown S, Niles JO et al (2007) Monitoring and estimating tropical forest carbon stocks: making REDD a reality. Environ Res Lett 2:1–13
Hamilton A, Taylor D, Vogel JC (1986) Early forest clearance and environmental degradation in south-west Uganda. Lett Nat 320(13):164–167
Hartig F, Drechsler M (2009) Smart spatial incentives for market-based conservation. Biol Conserv 142(4):779–788
Hartter J (2008) Resource use and ecosystem services in a forest park landscape. Soc Nat Resour 23:207–223
Hartter J, Boston K (2008) Consuming fuel and fueling consumption: modeling human caloric demands and fuelwood use. Small Scale For 7(1):1–15
Hartter J, Southworth J (2009) Dwindling resources and fragmentation of landscapes around parks: wetlands and forest patches around Kibale National Park, Uganda. Landsc Ecol 24(5):643–656
Houghton J (2007) Balancing the global carbon budget. Annu Rev Earth Planet Sci 35:313–347
Houghton RA, Goodale CL (2004) Effects of land-use change on the carbon balance of terrestrial ecosystems. American Geophysical Union, Washington DC
Houghton RA, Hall F, Goetz SJ (2009) Importance of biomass in the global carbon cycle. J Geophys Res 114:G00E03
IPCC (2003) Good practice guidance for land use, land-use change and forestry. Intergovernmental panel on climate change. National Greenhouse Gas Inventories Programme and Institute for Global Environmental Strategies, Kanagawa
IPCC (2006) IPCC Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programme. In: Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K (eds) Institute for Global Environmental Strategies, Japan
IPCC (2007) Climate change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, 996 pp
IUCN (2009) Biodiversity and livelihoods: REDD benefits. Available at www.cbd.int/doc/publications/for-redd-en.pdf
Jacovelli PA (2009) Uganda's Sawlog Production grant scheme: a success story from Africa. Int For Rev 11 (1):119–125
Jarvis A, Reuter H, Nelson A et al (2006) Hole-filled seamless SRTM data V3. International Centre for Tropical Agriculture (CIAT). Available at http://srtm.csi.cgiar.org
Kaimowitz D, Angelsen A (1998) Economic models of tropical deforestation—a review. Center for International Forestry Research, Indonesia
Kirby KR, Potvin C (2007) Variation in carbon storage among tree species: implications for the management of small-scale carbon sink project. For Ecol Manage 246:208–221
Koh LP, Gardner TA (2010) Conservation in human-modified landscapes. In: Sodhi NS, Ehrlich PR (eds) Conservation biology for all. Oxford University Press, Oxford, pp 236–261
Lambin EF, Geist H (2006) Land-use and land-cover change: local processes and global impacts (Global Change—The IGBP Series). Springer-Verlag, Berlin
Lang C, Byakola T (2006) "A funny place to store carbon: UWA-FACE Foundation's tree planting projetc in Mount Elgon national park, Uganda" World Rainforest Movement. Volume, DOI
Langdale-Brown I, Osmaston HA, Wilson JG (1964) The vegetation of Uganda and its bearing on land use. Government Printer, Entebbe
Lewis SL, Lopez-Gonzalez G, Sonke B et al (2009) Increasing carbon storage in intact African tropical forests. Nature 457(7232):1003–1006
MEA (2005) Ecosystems and human well-being: current state and trends. millennium ecosystem assessment. Island, Washington

MEMD (2007) The renewable energy policy for Uganda. Ministry of Energy and Mineral Development
Menard S (2002) Applied logistic regression analysis. Sage, Thousand Oaks, VIII, 111 s. pp
Mokany K, Raison JR, Prokushkin AS (2006) Critical analysis of root-shoot rations in terrestrial biomes. Glob Change Biol 12:84–96
Montès N, Bertaudière-Montes V, Zaoui EH et al (2002) Biomass and nutrient content of a semi-arid mountain ecosystem: the Juniperus thurifera L. woodland of Azzaden Valley (Morocco). For Ecol Manage 166:35–43
Mugisha S (2002) Patterns and root causes of land cover/use change in Uganda: An account of the past 100 years. The Land Use Change, Impacts and Dynamics (LUCID) Project. Working paper number 14. Nairobi, Kenya
Murray B, Olander L (2008) A core participation requirement for creation of a REDD market
Mwavu EN, Witkowski ETF (2008) Land-use and cover changes (1988–2002) around budongo forest reserve, NW Uganda: implications for forest and woodland sustainability. Land Degrad Dev 19(6):606–622
MWLE (2002) Uganda Initial National Communication to the United Nations Framework Convention on Climate Change, Department of Meteorology, Ministry of Water, Lands and Environment, Kampala, Uganda
MWLE (2003) National biomass study technical report 1996–2003. Ministry of Water, Lands and Environment, Kampala, Uganda
Nair PKR, Kumar BM, Nair VD (2009) Agroforestry as a strategy for carbon sequestration. J Plant Nutri Soil Sci 172:10–23
Nampindo S, Phillipps GP, Plumptre A (2005) The impact of conflict in Northern Uganda on the Environment and Natural Resource Management. Wildlife Conservation Society and USAID
Namaalwa J, Sankhayan PL, Hofstad O (2007) A dynamic bio-economic model for analyzing deforestation and degradation: an application to woodlands in Uganda. Forest Pol Econ 9:479–495
Naughton-Treves L, Kammen DM, Chapman C (2007) Burning biodiversity: Woody biomass use by commercial and subsistence groups in Western Uganda's forests. Biol Conserv 134(2):232–241
NEMA (2009a) Environmental sensitivity Atlas for the Albertine Graben. National Environment Management Authority (NEMA)
NEMA (2009b) Uganda: Atlas of our changing environment. National Environment Management Authority (NEMA)
NFA (2005) Brief to his excellency the president on encroachment and functions of central forest reserves in Uganda. National Forest Authority (NFA)
NFA (2008) RIN for Uganda. Available at World Bank Website
NFA (2009) Draft land Cover technical report of Uganda 2005. National Forestry Authority
Pender J, Nkonya E, Jagger P et al (2004) Strategies to increase agricultural productivity and reduce land degradation: evidence from Uganda. Agric Econ 31:181–195
Plumptre AJ, Davenport TRB, Behangana M et al (2007) The biodiversity of the Albertine Rift. Biol Conserv 134(2):178–194
Pontius RG, Schneider LC (2001) Land-cover change model validation by an ROC method for the Ipswich watershed, Massachusetts, USA. Agric Ecosyst Environ 85(1–3):239–248
Pontius RG, Huffaker D, Denman K (2004a) Useful techniques of validation for spatially explicit land-change models. Ecol Modell 179(4):445–461
Pontius RG, Shusas E, McEachern M (2004b) Detecting important categorical land changes while accounting for persistence. Agric Ecosyst Environ 101(2–3):251–268
Putz FE, Zuidema P, Pinard MA et al (2008) Tropical forest management for carbon retention. PLoS Biol 6:1368–1369
Ruecker G, Park SJ, Ssali H et al (2003) Strategic targeting of development policies to a complex region: A GIS-based stratification applied to Uganda Bonn: Centre for Development Research, University of Bonn ZEF Discussion Papers on Development Policy
Ruhweza A, Masiga (2005) An inventory of initiatives/activities and legislation pertaining to ecosystem service payment schemes (PES) in Uganda
SAS (2006) The SAS system for windows. SAS Institute, Inc, Cary
Sileshi G, Akinnifesi FK, Ajayi OC et al (2008) Meta-analysis of maize yield response to woody and herbaceous legumes in the sub-Saharan Africa. Plant Soil 307:1–19
Stéphenne N, Lambin EF (2001) A dynamic simulation model of land-use changes in Sudano-sahelian countries of Africa (SALU). Agric Ecosyst Environ 85(1–3):145–161
Skutsch M, Van Laake PE, Zahabu E et al (2009) The value and feasibility of community monitoring of biomass under REDD+
Tabuti JRS, Dhillion SS, Lye KA (2003) Firewood use in Bulamogi County, Uganda: species selection, harvesting and consumption patterns. Biomass Bioenergy 25(6):581–596
The R Development Core Team (2009) R Development Core Team, 2008. R: A Language and Environment for Statistical Computing. Version 2.10.0. R Foundation for Statistical Computing, Vienna, Austria (2009). http://cran.r-project.org/doc/manuals/refman.pdf

UBOS (2008) 2008 Statistical Abstract. Uganda Bureau of Statistics (UBOS), Entebbe
UNFCCC (2006) Issues relating to reducing emissions from deforestation in developing countries and recommendations on any further process, SBSTA 24th Session, Bonn, 18–26 May
UNFCCC (2009) Policy approaches and positive incentives on issues relating to reducing emissions from deforestation and forest degradation in developing countries; and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries. FCCC/AWGLCA/2009/L.7/Add.6
van der Werf GR, Morton DC, DeFries RS et al (2009) $CO_2$ emissions from forest loss. Nat Geosci 2:737–738
Veldkamp A, Lambin EF (2001) Predicting land-use change. Agric Ecosyst Environ 85(1–3):1–6
Velle K (1995) Estimation of standing stock of woody biomass in areas where little orno baseline data are available. A study based on field measurements in Uganda. Institutt for Skogfag, Agricultural University of Norway,. Institutt for Skogfag, Agricultural University of Norway, Ås: 262
Verburg PH, Soepboer W, VeldKamp A et al (2002) Modelling the spatial dynamics of regional land use: the CLUE-S model. Environ Manage 30(3):391–405
Vogt N, Bahati J, Unruh J et al (2006a) Integrating remote sensing data and rapid appraisals for land cover cover change analyses in Uganda. Land Degrad Dev 17(1):1–31
Vogt ND, Banana AY, Gombya-Ssembajjwe W et al (2006b) Understanding the stability of forest reserve boundaries in the West Mengo region of Uganda. Ecol Soc 11(1):38
Winjum J, Brown S, Schlamadinger B (1998) Forest harvests and wood products: sources and sinks of atmospheric carbondioxide. For Sci 44:272–284
World Bank (1996) Energy Sector Management Assistance Programme (ESMAP) Uganda Energy Assessment. UNDP/World Bank Project Report No. 193/96
World Bank (2008) High demand prompts forest carbon partnership facility to expand beyond original 20 developing countries
World Bank (2009) Grant agreement for the readiness preparation proposal readiness fund for the Forest Carbon Partnership Facility (FCPF), Grant No. TF095015



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