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Understanding recent land use and land cover dynamics in the source region of the Upper Blue Nile, Ethiopia: Spatially explicit statistical modeling of systematic transitions

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ABSTRACT

The objective of this paper was to quantify long-term land use and land cover changes (LULCC) and to identify the spatial determinants of locations of most systematic transitions for the period 1957–2009 in the Jedeb watershed, Upper Blue Nile Basin. Black and white aerial photographs of 1957 and Landsat imageries of 1972 (MSS), 1986 (TM), 1994 (TM) and 2009 (TM) were used to derive ten land use and land cover classes by integrated use of Remote Sensing (RS) and Geographic Information System (GIS). Post-classification change detection analysis based on enhanced transition matrix was applied to detect the changes and identify systematic transitions. The results showed that 46% of the study area experienced a transition over the past 52 years, out of which 20% was due to a net change while 26% was attributable to swap change (i.e. simultaneous gain and loss of a given category during a certain period). The most systematic transitions are conversion of grassland to cultivated land (14.8%) followed by the degradation of natural woody vegetation and marshland to grassland (3.9%). Spatially explicit logistic regression modeling revealed that the location of these systematic transitions can be explained by a combination of accessibility, biophysical and demographic factors. The modeling approach allowed improved understanding of the processes of LULCC and for identifying explanatory factors for further in-depth analysis as well as for practical interventions for watershed planning and management.

1. Introduction

Land use and land cover change (LULCC) has been a key research priority with multi-directional impacts on both human and natural systems (Turner et al., 2007) yet also a challenging research theme in the field of land change science. LULCC can affect biodiversity (Hansen et al., 2004), hydrology (DeFries and Eshleman, 2004; Uhlenbrook, 2007), and ecosystem services (DeFries and Bounoua, 2004). LULCC can also affect climate through its influence on surface energy budgets (e.g. albedo change) and biogeochemical cycling mechanisms (e.g. carbon cycle) (Bounoua et al., 2002; Niyogi et al., 2009; Pongratz et al., 2009). Hence, it has increasingly become a topic of paramount importance for national and international research programs examining global environmental change (Turner et al., 1995; GLP, 2005).

Many studies highlighted that LULCC is a widespread phenomenon in the highlands of Ethiopia (Zeleke and Hurni, 2001; Bewket, 2002; Tegene, 2002; Amsalu et al., 2007; Teferi et al., 2010; Tsegaye et al., 2010). These studies found different types and rates of LULCC in different parts of the country over the different time periods. In most cases, however, expansion of subsistence crop production into ecologically marginal areas, deforestation and afforestation have been the common forms of transitions. These conversions have apparently contributed to the existing high rate of soil erosion and land degradation in the highlands of Ethiopia (Bewket and Teferi, 2009), which is evident from the numerous gullies in cultivated and grazing lands.

In addition to the few published researches, as mentioned above, there are also some non-published works on LULCC covering different parts of the country. For instance, the Land use Planning and Regulatory Department (LUPRD) of Ministry of Agriculture prepared a generalized LULC map of the 1970s at 1:1,000,000 scale for the whole of Ethiopia through visual analysis of Landsat Multi-spectral Scanner (MSS) (FAO, 1984). The Abbay River Basin Master Plan Project prepared the LULC map of Abbay River basin at scales of 1:2,000,000 and 1:250,000 based on Landsat Thematic Mapper

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(TM) images from 1986 to 1990 (BCEOM, 1998). Woody Biomass Inventory and Strategic Planning Project (WBISPP) carried out an unsupervised classification of Landsat TM data from 1985 to 1991 to produce LULC map at 1:250,000 scale (TECSULT, 2004). The above mentioned LULC datasets provide a generalized LULC situation for a very large area and are of limited use for a small area such as Jedeb watershed (the site of this study), the scale at which detailed land use plans can be designed. In addition to differences in the levels of detail of these data as determined by their purposes, differences also exist in the approaches and extent of field observations. Therefore, there remains a need for development of a reliable and up-to-date LULC datasets using improved image processing techniques for use in the preparation of detailed land use plans at appropriate spatial scales.

To understand how LULCC affects and interacts with earth systems (e.g. hydrosphere, biosphere, and atmosphere), accurate information is needed on what types of change occur, where and when they occur, and the rates at which changes occur (Lambin, 1997). However, a mere LULCC study does not necessarily lead to improved understanding of the processes of land use change which researchers and policy makers would seek in order to establish effective conservation and management strategies for land resources. Understanding the fundamental processes of land transitions requires detection of dominant systematic land cover transitions (Pontius, 2004; Braimoh, 2006) and spatially explicit land use modeling (Serneels and Lambin, 2001; Veldkamp and Lambin, 2001).

Transitions in land use and land cover can be caused by negative socio-ecological feedbacks that arise from a severe degradation in ecosystem services or from socio-economic changes and innovations (Lambin and Meyfroidt, 2010). Furthermore, transitions can be random or systematic (Pontius, 2004; Braimoh, 2006). Conventionally, random transition refers to episodic processes of change, characterized by abrupt changes (Tucker et al., 1991; Lambin et al., 2003), whereas, systematic transition refers to more stable processes of change that evolve steadily or gradually in response to more permanent forces such as growing population pressure and market expansion (Lambin et al., 2003). From a statistical point of view, random transitions occur when a land cover replaces other land cover types in proportion to the size of other categories. A non-random gain or loss implies a systematic process of change in which land cover systematically targets other land covers for replacement (Pontius, 2004; Alo and Pontius, 2008).

Among the various LULCC modeling approaches, the binary logistic regression models have been used in order to identify the proximate causes and determinants of the most systematic transitions of LULCC (Schneider and Pontius, 2001; Serneels and Lambin, 2001; Verburg et al., 2004; Müller et al., 2011). The major advantages of binary logistic regression models are: (i) they allow testing the presence of links between LULCC and candidate explanatory variables, and (ii) they can predict the location of LULCC, if they are combined with spatially explicit data. Logistic regressions have been used to acquire an improved understanding of determinants of LULCC by previous studies (Schneider and Pontius, 2001; Serneels and Lambin, 2001; Verburg et al., 2004; Müller et al., 2011). In order to explain the spatial patterns of LULCC, the analysis was framed in the context of the Boserupian, Malthusian, Ricardian, and von Thunen's theories. The Boserupinan (Boserup, 1965) and Malthusian (Malthus, 1826) perspectives relate land use changes to population growth. The Ricardian land rent theory relates land use change to intrinsic land quality (e.g. soil quality, slope, elevation). The von Thunen's perspective links land use change mainly with location-specific characteristics such as cost of access to market centers (Chomitz and Gray, 1996).

In the Upper Blue Nile Basin, notwithstanding past research efforts on LULCC, there remains a knowledge gap in distinguishing systematic transitions and understanding the determinants of these transitions. This study aims at: (i) quantifying changes in land use/cover over the past 52 years, (ii) identifying the most systematic transitions, and (iii) identifying and quantifying the determinants of most systematic transitions in the rapidly changing environment of the Jedeb watershed in the Blue Nile Basin. The results of this study enable researchers and planners to focus on the most important signals of systematic landscape transitions and allow understanding of the proximate causes of changes. In other words, it is useful for investigating the possible drivers of transitions, and hence to propose site-specific and targeted preventative measures to avoid undesirable impacts of land cover changes (Pontius, 2004; Braimoh, 2006).

2. Data and methods

2.1. Study area

The study area, Jedeb watershed, lies between 10°23′ to 10°40′N and 37°33′ to 37°60′E. It covers an area of 296.6 km^2 and thus is meso-scale in size. It is situated in the southwestern part of Mount Choke, which is a headwater of the Upper Blue Nile in Ethiopia (Fig. 1). Administratively, the area belongs to two *weredas* (districts; *Machakel* and *Sinan*) of East *Gojam* Zone in *Amhara* Regional State of Ethiopia. The watershed is characterized by diverse topographic conditions with its elevation ranging from 2172 m to nearly 4001 m (Fig. 1), and slopes ranging from nearly flat (<2°) to very steep (>45°). Almost all of the farmers in the Jedeb watershed are engaged in small scale and subsistence mixed agriculture. Thus, land and livestock are the basic sources of livelihood. The livestock population density is higher in upper part of the watershed (*Sinan wereda*) than in the lower part (*Machakel wereda*) as shown in Table 11. The major source of water for both the human and livestock populations is the Jedeb river, with a mean annual stream flow of 716.6 mm a^{-1} (over the period 1973–2001). The mean annual rainfall varies between 1400 mm a^{-1} and 1600 mm a^{-1} based on data from 3 nearby stations (Debre Markos, Anjeni, and Rob Gebeya).

The headwater area as a whole, where the Jedeb river is one of the many tributaries, is a crucial water source area for the Upper Blue Nile. This important water supply zone, as some research results show, is presently one of the most soil erosion-affected parts of the Upper Blue Nile River Basin (Hurni et al., 2005; Bewket and Teferi, 2009). Therefore, the region has currently become a focal point of public concerns and received considerable research attention (Uhlenbrook et al., 2010; Tekleab et al., 2011).

2.2. Data used and image pre-processing

2.2.1. Data used

2.2.1.1. Aerial photographs and satellite images. The earliest known sources of land use and land cover data for the study area are black and white aerial photographs taken in 1957. Accordingly, 13 contact prints of aerial photos (Table 1) at a scale of 1:50,000 were obtained from the Ethiopian Mapping Agency (EMA) for the land use and land cover classification purpose. For ground truthing, 15 aerial photographs of the year 1982 at a scale of 1:40,000 were purchased and used (Table 1). For the recent years, Landsat images were used, which were selected based on: (i) availability, (ii) cloud cover percentage, and (iii) correspondence with years of major events in the study area (Table 1). All Landsat images were accessed free of charge from the US Geological Survey (USGS) Center for Earth Resources Observation and Science (EROS) via http://glovis.usgs.gov/. To assist the land cover classification, a high resolution data set of SPOT-5 2007 was also purchased from the EMA.

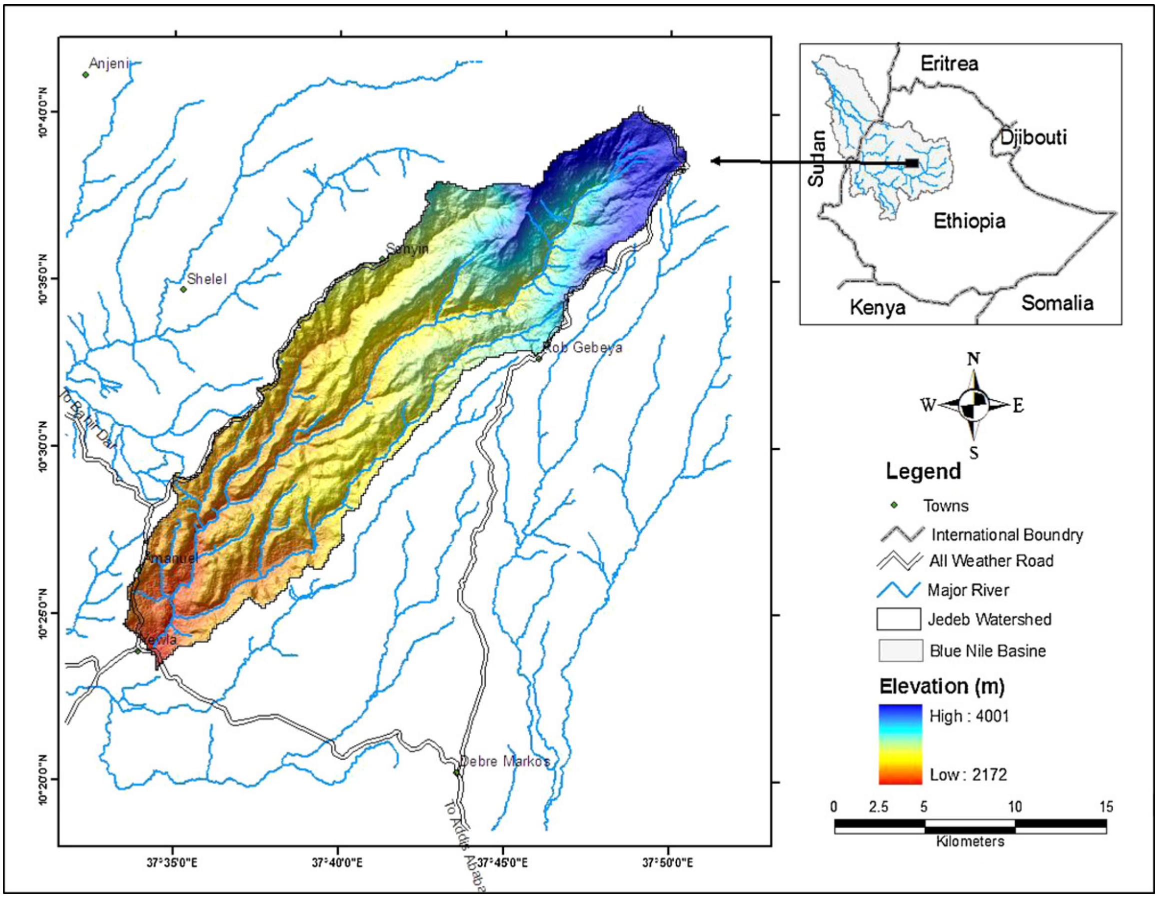

Fig. 1. Location and topography of the study area.

2.3. Ancillary data

Ancillary data were used to improve accuracy of the classification and to support the interpretation of land cover change. Digital Elevation Terrain Data (DTED-30 m) and its derived data sets such as slope supplemented the satellite data in mapping land cover since vegetation classes are often limited to specific agro-climatic conditions. Four topographic maps of the study area at a scale of 1:50,000 dated 1984 were purchased from EMA for the purpose of ground truth data collection. Population data (1984–2007) and vector overlays such as roads, and rivers were obtained from the Central Statistical Agency of Ethiopia (CSA). No national census of population and housing took place prior to 1984 in Ethiopia. Even after 1984 the censuses have been carried out based on

Table 1
Description of used aerial photographs and satellite images.

	1972	1986[a]	1994	2009[b]
Satellite (sensor)	Landsat MSS	Landsat TM	Landsat TM	Landsat TM
Path/Row	182/52&53	169/53	169/53	169/53
Acquisition date	09/12/1972	28/11/1986	02/11/1994	27/11/2009
Pixel spacing (m)	60	30	30	30
Sun Elevation	44.68	44.96	49.26	50.38
Sun Azimuth	138.94	134.35	127.01	142.25

Aerial photographs of 1957					Aerial photographs of 1982				
26/11/57	18/01/58	24/12/57	16/12/57	15/12/57	01/12/82	01/20/82	01/15/82	01/22/82	01/27/82
		9573	6949	6713			0209	0316	0407
		9572	6950	6712		0144	0208	0315	0406
	11630	9571	6951	6711		0143	0207	0314	
2383	11629	9571			0069	0142	0206		
					0068	0141			

[a]Aerial photographs of 1982 andfour topographic maps at a scale of 1:50,000 dated 1984 were used for ground truth data collection to classify the 1986 image.
[b]Since 4% of the 2009 image in the study area was covered by clouds. It was masked out and latter replaced by classification of ASTER (2007) AST_L1B_00303192007080348_17681and AST_L1B_00301302007080346_16466.

administrative boundaries. Hence, remote sensing techniques were used to estimate the population in the watershed, by counting the number of huts from aerial photographs (high resolution satellite image) and by multiplying it by mean occupants per hut derived from available secondary sources. The average family size for 1957 was 4.7 (USBR, 1964); 4.5 average family size for 1986 (Yoseph and Tadesse, 1984) and 4.5 average family size for 2007 (based on sample *kebelles*) (CSA, 2008) were used.

2.3.1. Aerial photograph pre-processing and interpretation

A total of 28 aerial photographs were scanned in A3 format to include the fiducial marks (which were used to establish the interior orientation) with a reasonable geometric (600 dpi) and radiometric resolution (8 bit, grey scale, uncompressed). All photos of a block were scanned in the orientation in which they form the block. To remove the distortion within aerial photographs, caused by terrain relief and the camera, the aerial photos were orthorectified using Digital Terrain Elevation Data (DTED-30 m), fiducial marks (mm), the camera's focal length (mm) and Ground Control Points (GCPs) as input in ERDAS IMAGINE software. Since there was no access to the camera calibration report, the fiducial coordinates were measured from the aerial photographs such that the origin of the coordinate system is the principal point of the aerial phtotograph. On each aerial photograph eight to twelve well-distributed X and Y coordinates of the GCPs were collected from digital orthorectified SPOT image (5 m) and Z coordinates were taken from (DTED-30 m). Rural churches were used as GCPs. The root mean-square error (RMS) of GCP locations was 0.4 pixels. The accuracy of the orthophotos was further assessed by overlaying the orthorectified photos over the available georefernced topographic map. The multiple orthophotos were then mosaiced to form a seamless image (Fig. 3a and b). Visual interpretation of various features on the mosaiced orthophotos was done based on shade, shape, size, texture and association of features to identify the features. Unrectified stereo-pairs of airphotos were used when a detailed 3D view was required to identify the features. After subsequent screen-digitizing of the user-defined land-cover units, GIS topology was employed to manage coincident geometry and ensure data quality (Fig. 2).

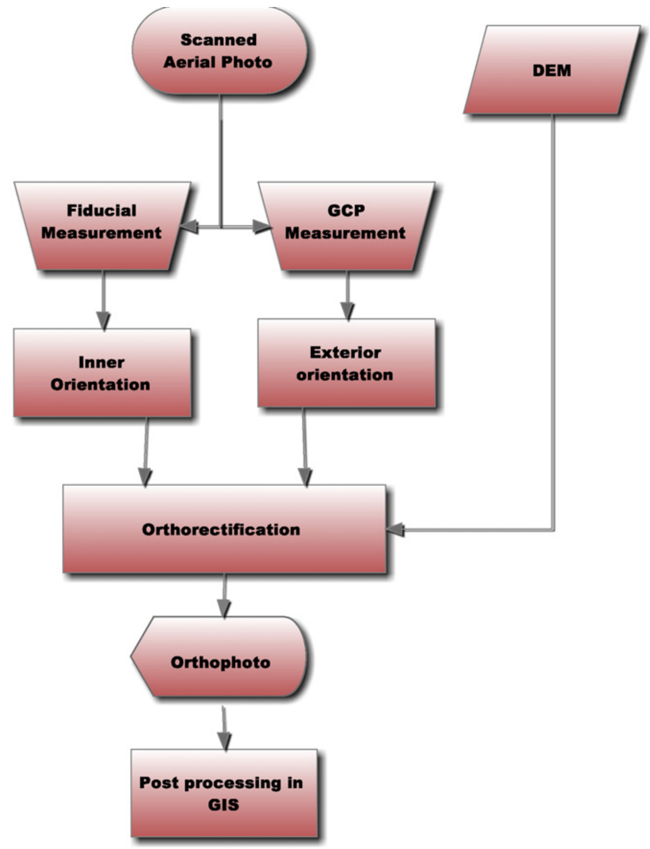

Fig. 2. Flowchart of the 1957 aerial photograph processing.

2.3.2. Satellite image pre-processing, classification and accuracy assessment

All the scenes obtained from the EROS Data Center were already georeferenced to the Universal Transverse Mercator (UTM) map projection (Zone 37), WGS 84 datum and ellipsoid. However, in some parts of the study area, there were significant discrepancies between these imageries, and the underlying GIS base layers which were extracted from high resolution SPOT-5 imagery. The nonaligned scenes were then georectified to the underlying base layers by using control points. Re-projection to the local projection system was made (UTM, map projection; Clarke 1880, Spheroid; and Adindan Datum) (Fig. 3c and d).

Since the Jedeb watershed is highly rugged and mountainous, all Landsat images were topographically corrected using C-correction (Teillet et al., 1982) to reduce effects that result from the differences in solar illumination (McDonald et al., 2000; Hale and Rock, 2003). A freely available IDL extension was used for the C-correction (http://mcanty.homepage.t-online.de/software.html). Atmospheric and radiometric correction of all Landsat images acquired for the different times were also made using a fully image-based technique developed by Chavez (1996) known as the COST model; this model derives its input parameters from the image itself. In a next step, temporal normalization of all the images was achieved by applying regression equations to the 1972, 1986, 1994, and 1998 imageries which predict what a given Brightness Value (BV) would be if it had been acquired under the same conditions as the 2009/11/29 TM reference scene. This pre-processing step reduces pixel brightness value variations caused by non-surface factors and enhances variations in pixel BV between dates related to actual changes in surface conditions. The 2009/11/29 TM image was selected as the reference scene to which the other images were normalized, because it was the only year for which quality in situ ground reference data were available.

A hierarchical land use classification was derived from the authors' prior knowledge of the study area and based on the most popular scheme of the U.S. Geological Survey Land Use/Cover System devised by Anderson et al. (1976). Table 2 contains a list of all land cover types present in the study area that could be clearly identified from the satellite images and aerial photographs. All classes have an unambiguous definition so that they are mutually exclusive.

A hybrid supervised/unsupervised classification approach was integrated with successive Geographic Information System (GIS) operations (spatial analysis) to classify the imageries of 1972 (MSS), 1986 (TM), 1994 (TM) and 2009 (TM). First, to determine the spectral classes Iterative Self-Organizing Data Analysis (ISODATA) clustering was performed. Ground truth (reference data) was collected to associate the spectral classes with the cover types of the already defined classification scheme for the 2009 (TM) imagery from field observations. Among other sources of information, reference data was collected from previous maps for the 1994 image (Zeleke and Hurni, 2001). Reference data for the 1986 image were based on aerial photo interpretation of 1982 as well as topographic maps (1:50,000 scale) of 1984. Reference data for the 1972 image classification were collected from already classified maps and in-depth interview of local elders. A total of 2277 reference data points for each year were obtained, of which 759 points were used for accuracy assessment and 1518 points were used for

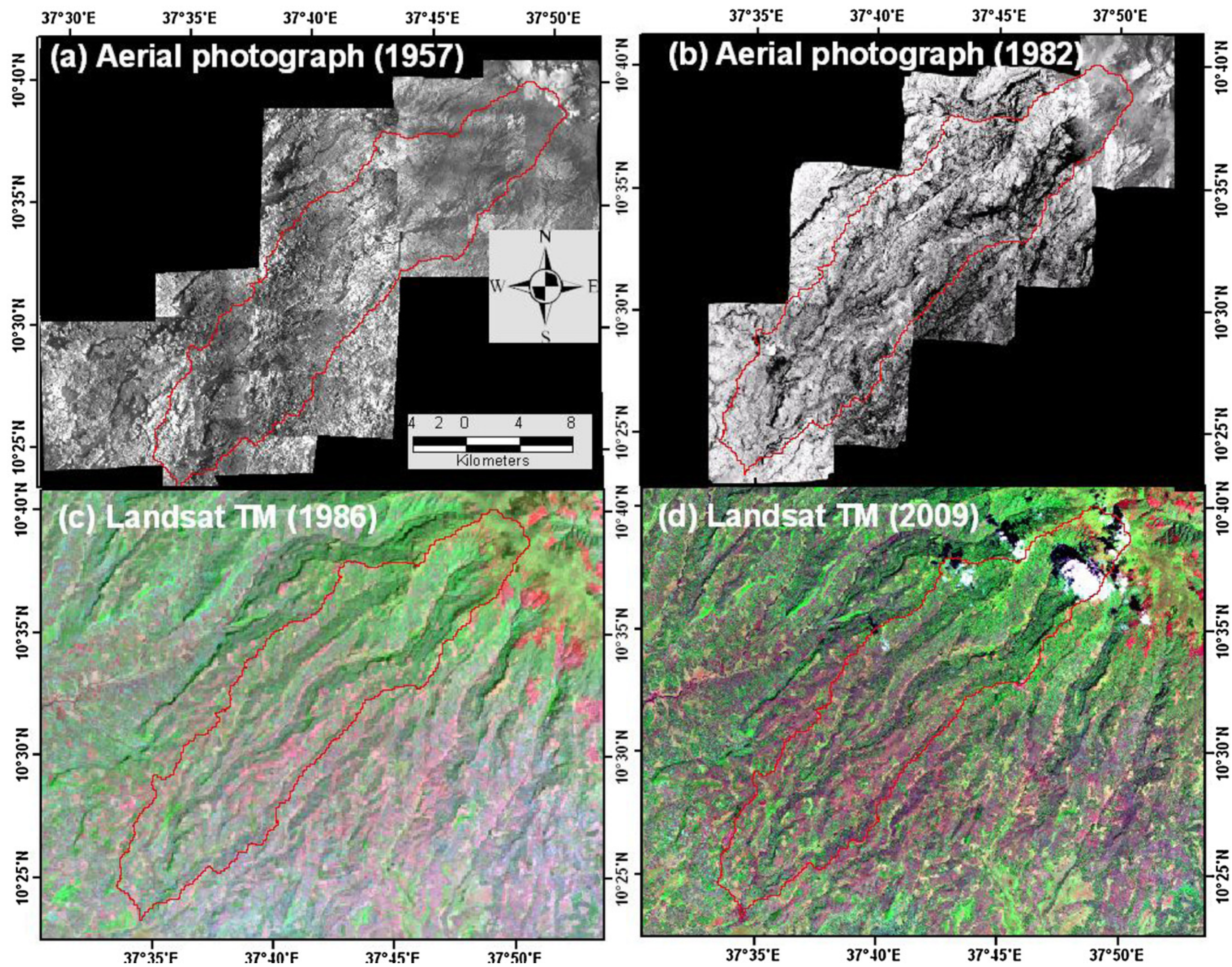

Fig. 3. Processed aerial photographs (a and b) and Landsat TM images of the study area with 742 band combination (c and d).

classification. Training sites were developed from the ground truth data collected to generate a signature for each land cover type. Signature separability was determined and it was found that the spectra of marshland were confused with grassland, urban land covers were confused with barren land and cultivated land during the preliminary classification. To tackle this problem, urban areas were digitized and masked out from the image. Similarly, marshlands were identified and masked out from the original image. The remaining part of the image was then classified using the Maximum Likelihood algorithm to identify grassland, cultivated land, shrubs and bushes, woodland, plantation forest and *Ericaceous* forest (Fig. 4).

To assess the accuracy of thematic information derived from 1972 (MSS), 1986 (TM), 1994 (TM) and 2009 (TM) imageries, the

Table 2
Description of land use and land cover classes.

No.	Land use and land cover classes	Description	Code
1	Grassland	Landscapes that have a ground story in which grasses are the dominant vegetation forms.	GL
2	Afroalpine grassland	High altitude (>3500 m asl) herbaceous vegetation typically consisting of *Lobeliaceae* (Hedberg, 1951).	AGL
3	Shrubs and bushes	This category includes low woody plants, generally less than three meters in height, usually with multiple stems, growing vertically.	SHB
4	Cultivated land	Areas covered with annual crops followed by harvest and bare soil period	CL
5	Riverine Forest	Trees and shrubs established along the banks of streams, rivers, and open bodies of water.	RF
6	Woodland	A continuous stand of a single storey trees with a crown density of between 20–80%.	WL
7	Plantation Forest	Areas composed of transplanted seedlings of *Eucalyptus globules* and *Cupresus spp.*	PF
8	Marshland	Periodically or continually flooded wetlands characterized by non-woody emergent plants	ML
9	Barren land	Areas with little or no vegetation cover consisting of exposed soil and/or bedrock	BL
10	Ericaceous Forest	*Ericaceae*, *Hypericum quartiniannm*	EF

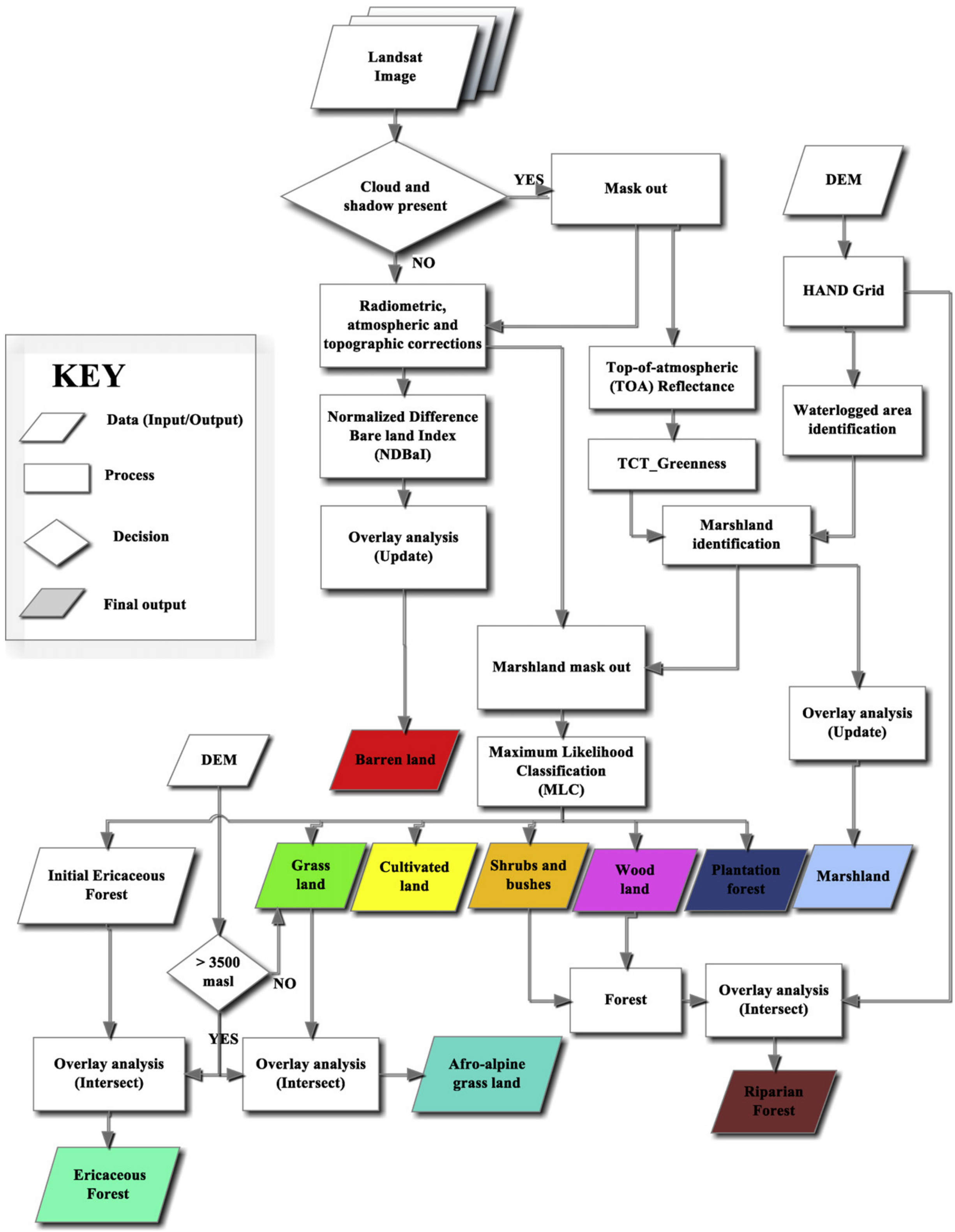

Fig. 4. Flow chart showing the steps for identifying land covers types from satellite images.

design-based statistical inference method was employed which provides unbiased map accuracy statistics (Jensen, 2005). The accuracy of the map interpreted from the 1957 aerial photographs was assessed using *confidence-building assessment* which involves the visual examination of the classified map by knowledgeable local people to identify any gross error. Stratified random sampling design was used to collect 759 reference data and to make careful observation during field visit of accessible areas. The number of samples required for each class was adjusted based on the proportion of the class and inherent variability within each category.

Discrete multivariate analytical techniques were used to statistically evaluate the accuracy of the classified maps (Foody, 2002).

As there is no single universally accepted measure of accuracy, a variety of indices were calculated (e.g. overall accuracy, producer's accuracy, user's accuracy and kappa analysis) (Stehman, 1997).

2.3.3. Extent, rate and trajectories of change

Gross gains, losses and persistence: Post-classification comparison change detection was made to determine the change in land use/cover between two independently classified maps from images of two different dates (Jensen, 2005). Although this technique has a few limitations, it is the most common approach to compare maps of different sources, as it provides detailed "from-to" change class information (Coppin et al., 2004; Jensen, 2005), and it does not require data normalization between two dates (Singh, 1989). The traditional cross-tabulation matrix (transition matrix) was computed using overlay functions in ArcGIS 9.3 software and Pivot Table function in Excel to analyze land use/cover transitions. Analysis of gains, losses, persistence, swap and net change were carried out for each of the periods: 1957–1972, 1972–1986, 1986–1994, 1994–2009 and 1957–2009. The computed transition matrix consists of rows that display categories at time 1 and columns that display categories at time 2 (Table 5). The notation P_{ij} is the proportion of the land that experiences transition from category i to category j. The diagonal elements (i.e. P_{jj}) indicate the proportion of the landscape that shows persistence of category j. Entries off the diagonal indicate a transition from category i to a different category j. According to Pontius (2004), the proportion of the landscape in category i in time 1 (P_{i+}) is the sum of P_{ij} over all j. Similarly the proportion of the landscape in category j in time 2 (P_{+j}) is the sum of P_{ij} over all i. The losses were calculated as the differences between row totals and persistence. The gains were calculated as the differences between the column totals and persistence. Persistence of land covers were also analyzed based on methods outlined in Braimoh (2006). The vulnerability of land cover classes to transition were assessed by calculating the loss-to-persistence ratio denoted by l_p. Higher tendency of land cover transition to other categories than persist is expressed by values of l_p greater than one. Similarly, values of gain-to-persistence ratio denoted by g_p greater than one indicate more gain than persistence.

Net change and swap: The difference between gain and loss is the net change (absolute value), denoted D_j. However, the net change underestimates the total change on the landscape since it fails to capture the "swap". Swap implies simultaneous gain and loss of a category on the landscape. The amount of swap of land class j, denoted S_j, was calculated as two times the minimum of the gain and loss because to create a pair of grid cells that swap each grid cell that gains is paired with a grid cell that loses. The total change for each land class, denoted C_j, was calculated as either the sum of the net change and the swap or the sum of the gains and losses.

$$D_j = |P_{+j} - P_{j+}| \quad (1)$$

$$S_j = 2 \times \mathrm{MIN}(P_{j+} - P_{jj}, P_{+j} - P_{jj}) \quad (2)$$

$$C_j = D_j + S_j = P_{j+} + P_{+j} - 2P_{jj} \quad (3)$$

Rate of change: The annual rate of change of land use/cover at different periods was computed using the formula derived from the Compound Interest Law due to its better estimation and biological meaning (Puyravaud, 2003).

$$r = \left(\frac{1}{t_2 - t_1}\right) \times \ln\left(\frac{A_2}{A_1}\right) \quad (4)$$

where r is annual rate of change, and A_1 and A_2 are the area coverage of a land cover at time t_1 and t_2, respectively. This equation provides a standard method for making land use and land cover change comparisons that are insensitive to the differing time periods between observation dates.

Trajectories of change: Trajectory analysis was made only for forest, non-forest, and plantation classes because of their ecological importance. Therefore, SHB, RF, EF and WL classes were reclassified as forest (e.g. F) category and GL, AGL, CL, ML and BL classes were reclassified as non-forest category (e.g. N). The number of permutations of three classes, taken five at a time when each can be repeated five times is given by: $NT = NC^d$, where NT is the number of trajectories, NC is the number of land cover classes and d is the number of observation dates. With three land cover classes (forest, non-forest, and plantation) and five temporal image dates (1957, 1972, 1986, 1994 and 2009), 114 out of 243 possible forest land cover change trajectories were found. Finally, similar trajectories were clustered to result in seven classes (Fig. 7 and Table 3).

2.3.4. Detecting the most systematic transitions (dominant signals of change)

The traditional way of identifying the most prominent types of transition is by ranking each conversion between classes after summing up the total area changed during each period. However, such a technique fails to consider the presence of the largest categories. Consequently, even the random process of land use/cover change would cause a large transition of dominant categories. Therefore, interpreting the transitions relative to the sizes of the categories is crucial in order to identify systematic transitions. This was carried out based on methods outlined by Pontius (2004). First expected gains (G_{ij}) and expected losses (L_{ij}) that would occur if random changes occurred were determined (Eqs. (5 and 6)). Values obtained were then used to compute the difference between the observed and expected transition under a random process of gain ($P_{ij} - G_{ij}$) or loss ($P_{ij} - L_{ij}$), denoted D_{ij} and the ratio, denoted R_{ij}. The values of D_{ij} indicate the tendency of category "j" to gain from category "i" (focus on gains) and the tendency of category "i" to lose to the category "j" (focus on losses). Large positive or negative deviations from zero indicate that systematic inter-category transitions, rather than random transitions occurred between two land classes. The magnitude of R_{ij} indicates the strength of the systematic transition. A large ratio means that the transition is systematic.

$$G_{ij} = (P_{+j} - P_{jj})\left(\frac{P_{i+}}{100 - P_{j+}}\right), \quad \forall i \neq j \quad (5)$$

$$L_{ij} = (P_{i+} - P_{ii})\left(\frac{P_{+j}}{100 - P_{+i}}\right), \quad \forall i \neq j \quad (6)$$

2.4. Logistic regression modeling of the most systematic transitions

Logistic regression was used to identify and quantify the relations between the locations of most systematic transitions and a set of explanatory variables. Two processes of systematic land use/cover transitions have been identified: (i) forest-to-grassland conversion, (ii) grassland-to-cultivated land. *Ericaceous* forest-to-grassland, shrubs and bushes-to-grassland, and riverine forest-to-grassland transitions were aggregated to form a forest-to-grassland dependent variable, as these transitions have been identified as most systematic. The dependent variable is a binary presence (specific land use conversion) or absence event (all other) for the period 1957–2009. The logistic function gives the probability of observing a given land use conversion as a function of the independent variables in Table 9. If p is a *probability* then $p/(1-p)$ is the corresponding *odds*, and the logit of the probability is the logarithm of the odds. The linear logistic model has the form:

$$\mathrm{logit}(p) = \log\left(\frac{p}{1-p}\right) = \alpha + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n \quad (7)$$

where α is the intercept and β_n are the logit coefficients.

Table 3
Land use and land cover change trajectories between 1957 and 2009.

No.	Description	Trajectories*
1	Stable forest	FFFFF
2	Afforestation/reforestation	FFFFP,FFFNP,FFFPF,FFFPP,FFNFP,FFNNP,FFNPP,FFPFP, FFPNP,FFPPP,FNFFP,FNFNP,FNFPF,FNFPP,FNNFP,FNNNP,FNNPF, FNNPP,FNPFP,FNPPP,FPPPP,NFFFP,NFFNP,NFFPF,NFFPP,NFNFP,NFNNP,NFNPP,NFPFP,NFPPP,NNFFP,NNFNP,NNFPP, NNNFP,NNNNP,NNNPF,NNPFP, NNPNP,NNPPF,NNPPP,NPPFP,NPPPP
3	Recent deforestation	FFFFN,FFFPN,FFNPN,FFPFN,FFPPN,FNFPN,FNNPN,FNPFN,FNPPN,FPPPN,NFFFN,NFFPN,NFNFN,NFNPN,NFPFN,NFPPN, NNFFN,NNFPN
4	Old deforestation	FFFNN,FFNNN,FFPNN,FNNNN,FNPNN,NFFNN,NFNNN, NFPNN,NNFNN,NNNPP,NNPNN,NPNNN,NPPNN
5	Regrowth	FFFNF,FFNFF,FFNNF,FFNPF,FFPFF,FFPNF,FFPPF,FNFFF, FNFNF,FNNFF,FNNNF,FNPFF,FNPNF,FNPNP,FNPPF,NFFFF, NFFNF
6	Regrowth with new clearing	FFNFN,FNFFN,FNFNN,FNNFN
7	Non forest	NNNNN

* The sequence represents the time periods 1957, 1972, 1986, 1994, and 2009. “F” stands for forest class, “N” stands for non-forest class, and “P” stands for plantation.

The probability can be expressed in terms of independent variables as:

$$p = \frac{\exp(\alpha + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n)}{1 + \exp(\alpha + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n)} \quad (8)$$

In order to assess the relative importance of the explanatory variables in determining most systematic conversions, the independent variables were standardized to zero mean and unit standard deviation, using the equation

$$X_i' = \frac{X_i - \bar{X}_i}{\sigma_X} \quad (9)$$

where $X_i{}'$ is the standardized variable, X_i original value of the independent variable, $\bar{X}_i$ the mean, and σ_X the standard deviation.

The goodness of fit of the logistic regression models was evaluated using the relative operating characteristics (ROC) (Pontius and Schneider, 2001). The ROC value above 0.5 is statistically better than random, while a ROC value greater than 0.7 is acceptable for land use change modeling (Lesschen et al., 2005).

2.4.1. Generation of spatially explicit independent variables

The variables *elevation, slope, aspect and Topographic Wetness Index* (*TWI*) were derived from Digital Elevation Terrain Data (DTED-30 m). Since the initially derived aspect variable was based on circular categorical values, it was again converted into a northness [cos(aspect)] and eastness [sin(aspect)] for the model input. In sin(aspect) map values close to 1 indicate east-facing slopes, while in cos(aspect) map values close to 1 represent north-facing slopes. Accessibility was calculated in terms of travel time to targets (roads and towns/markets). Anisotropic *Travel time to roads* and anisotropic *travel time to towns/markets* were calculated based on Tobler’s hiking function (Tobler, 1993), as the direction of slopes affects the efforts needed to cross an area especially in mountain environments. Euclidean *Distance from forest edges* was calculated using *center* versus *neighbor* measure of pattern on a 3 × 3 pixel window. The likelihood for agricultural use is dependent on proximity to rivers. Therefore, Euclidean distance of locations to permanent rivers was calculated. In order to account for the impact of the population pressure in determining the land use change, initial population density or population potential and change in population density or population potential between 1957 and 2007 were calculated. Population potential surfaces were generated based on population data collected at village (*Kebelle*) level for 2007 and 1957 (back-projected) using inverse distance weighting. However, population potential variables were found to be irrelevant variables because they had no explanatory power. In contrast, population density surfaces generated from aerial photos and satellite imagery were able to explain the logistic regression models. Hence, the population potential variables were removed from the analysis.

Prior to logistic regression modeling, violations of three major assumptions were tested: linearity of the logit, spatial dependence, and multi-collinearity. In order to minimize the effect of spatial auto-correlation, an initial random sampling of 6595 observations (i.e. 4% out of 329,729 observations) was carried out for each model. Subsequently, 1876 observations for grassland-to-cultivated land conversion and 764 observations for forest-to-grassland conversion model were sampled with an equal number of 0 and 1 observations of the dependent variable. Since logistic regression assumes a linear relationship between the logit of the independent and the dependent variable, linearity of the logit was tested using Box-Tidwell transformation (Menard, 2009). Variables with Spearman rank correlation coefficients of 0.8 or higher were removed as recommended by Menard (2001) to remove multi-collinearity effect. Besides, outliers were detected and removed by observing very large Cook’s distance scores (Cook, 1977) from a scatter plot of Cook’s distance scores versus sample codes.

3. Results and discussion

3.1. Accuracy assessment

Fig. 5 depicts the classified maps for 1957, 1972, 1986, 1994, and 2009. According to the confusion matrix report (Table 4) 95.65% overall accuracy and a Kappa Coefficient (*khat*) value of 0.94 were attained for the 2009 classified map. Similarly, overall classification accuracies achieved were 89.25% (with a *khat* of 0.84) for the 1957, 87.67% (with *khat* of 0.81) for the 1972, 91.47% (with *khat* of 0.89) for the 1986, and 94.17% (with *khat* of 0.91) for the 1994 image classifications. Applying the methods of Congalton and Green (2009) the above results represent strong agreement between the ground truth and the classified classes. In general, the maps met the minimum accuracy requirements to be used for the subsequent post-classification operations such as change detection (Anderson et al., 1976).

3.2. Extent, rate and trajectories of land use/cover change

3.2.1. Gross gains, gross losses and persistence

Table 5 depicts the proportion of each land use/cover class that made a transition from one category to another for each of the study periods. During the whole period 1957–2009, cultivated land and grassland were the major proportions as compared to the other land use/cover classes. Both the highest gain (21.9%) and the highest loss (13.5%) in cultivated land occurred during the period 1957–1972. The highest gain in grassland (14.1%) was experienced during the period 1957–1972, while the highest loss (7.2%) was experienced during the period 1994–2009. In the period 1957–1972, a decrease in the following natural woody vegetation covers was observed: shrubs and bushes (declined by 53.7%); riverine forest (declined by 47.5%); wood land (declined by 27.5%); and *Ericaceous* forest (declined by 22.2%) from the initial states. Although a decline in natural woody vegetation was observed in all periods, the highest declines in percentage changes of shrubs and bushes, riverine

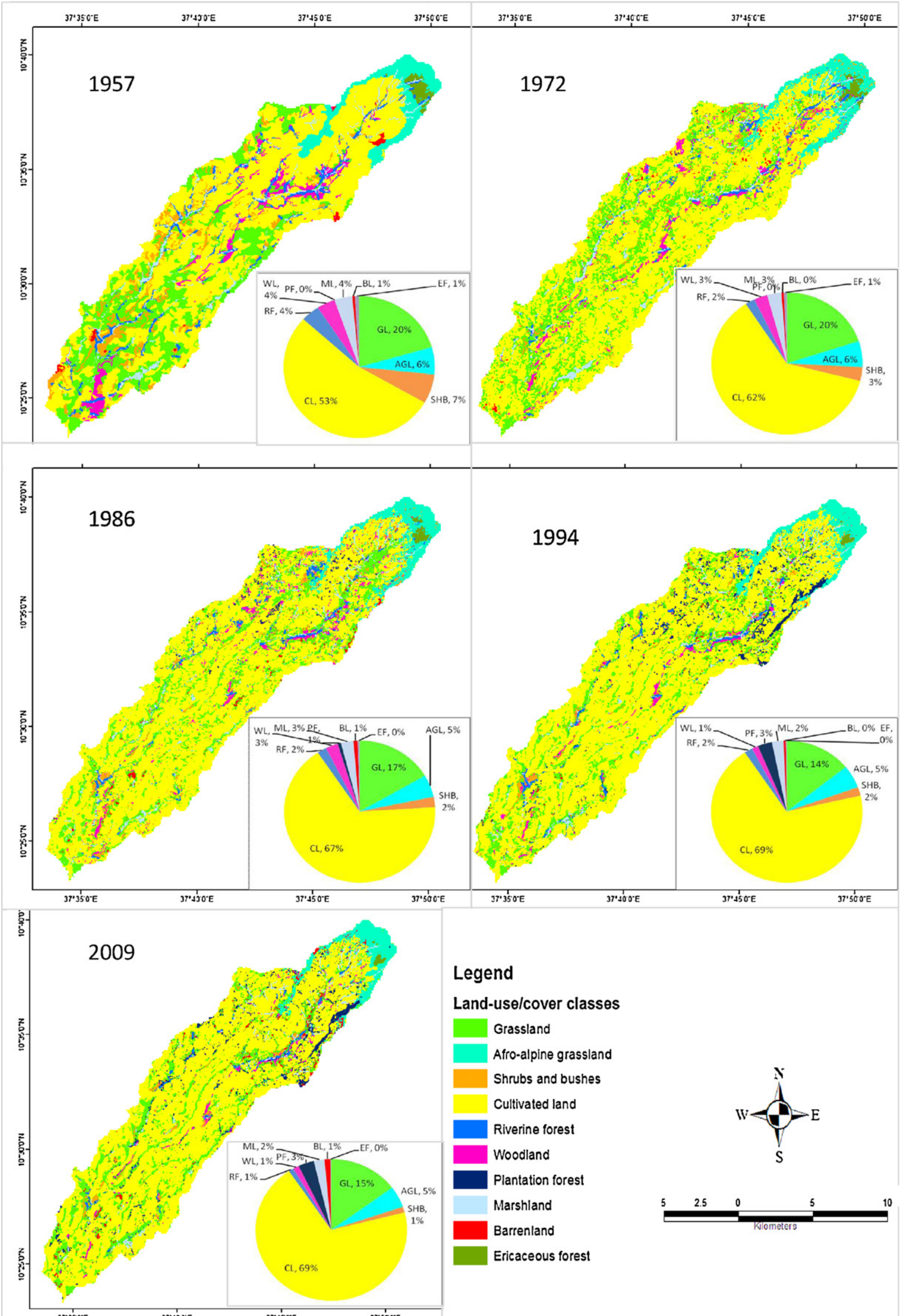

Fig. 5. Land use and land cover map of Jedeb watershed in 1957, 1972, 1986, 1994 and 2009.

Table 4
Confusion matrix (error matrix) for the 2009 classification map.

Classified data	Reference data											User's accuracy
	GL	AGL	SHB	CL	RF	WL	PF	ML	BL	EF	Row total	
GL	190	1	1	1	2	0	0	0	1	0	196	97%
AGL	0	67	0	1	0	0	0	0	0	1	69	97%
SHB	0	0	18	0	1	3	3	0	0	0	25	72%
CL	2	0	0	323	0	0	0	0	1	0	326	99%
RF	0	0	0	0	13	0	1	1	0	0	15	87%
WL	0	0	0	0	1	16	2	0	0	0	19	84%
PF	0	0	0	0	0	1	45	0	0	0	46	98%
ML	1	1	2	0	0	0	0	34	0	0	38	89%
BL	2	2	0	1	0	0	0	0	17	0	22	77%
EF	0	0	0	0	0	0	0	0	0	3	3	100%
Column total	195	71	21	326	17	20	51	35	19	4	759	
Producer's accuracy	97%	94%	86%	99%	76%	80%	88%	97%	89%	75%		

Overall accuracy = 95.65%, Khat = 94%.

forest and woodland were observed during the period 1957–1972. In contrast, cultivated land showed a relative growth of 15.7% from the original state. During the period 1972–1986, cultivated land experienced more gain (17.7%), whereas grassland experienced more loss (17.4%). Cultivated land, plantation forest, and barren land showed relative growths of 7.6%, 600% and 80%, respectively, whilst the other categories showed relative declines from their initial states; i.e. 1972 (Fig. 9). During the period 1986–1994, plantation forest and cultivated land showed relative increase by 342.9% and 4.2%, respectively, while the remaining categories showed declines. During the periods of 1972–1986 and 1986–1994 *Eucalyptus globules* plantation expanded significantly. The decrease in percentage change of barren land only in the period 1986–1994 indicates that the environment was recovering from the devastating drought of 1984/1985. In the period 1994–2009, the percentage of bare land, plantation forest and grassland showed increase by 140%, 9.7% and 4.9%, respectively, while riverine forest declined by 38.9%, shrubs & bushes declined by 35%, marshland declined by 8%, afro-alpine grassland declined by 7.7%, and wood land declined by 7.1% (Fig. 9). The increase in percentage change of cultivated land has stopped since 1994. This is likely because of lack of suitable lands for further expansion, or perhaps there are more strict local government rules and regulations with respect to land tenure and land use rights, prohibiting expansion of cultivation at one's own will. This finding accords with Tegene (2002) who concluded that there was no significant expansion of cropland in one of the

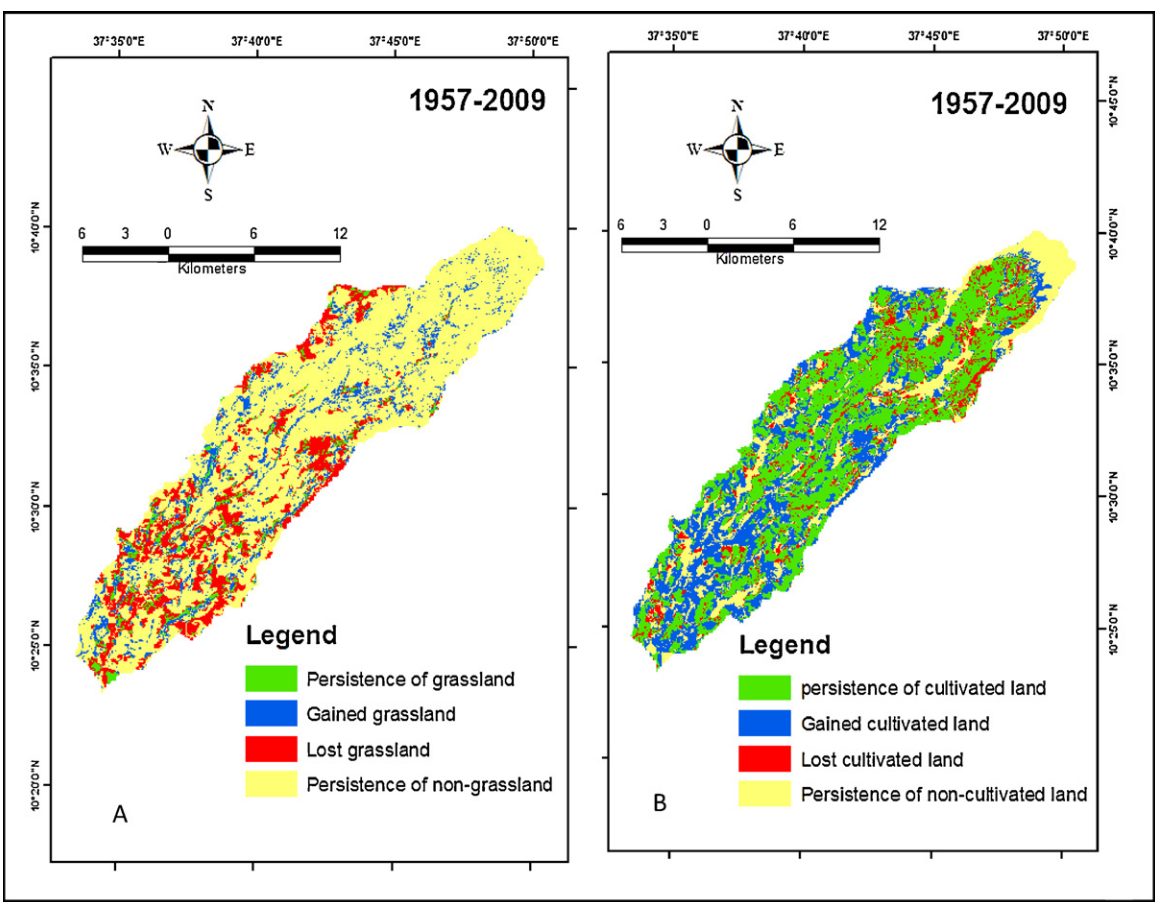

Fig. 6. Spatial representation of the gains, losses, and persistence experienced in (a) grassland and (b) cultivated land.

Table 5
Land use and land cover change flow matrices for each period (percentage).

	GL	AGL	SHB	CL	RF	WL	PF	ML	BL	EF	P_{i+}	Loss	C_j	S_j	D_j	l_p	g_p
1957/1972																	
GL	5.8	0.0	0.3	13.7	0.2	0.2	0.0	0.1	0.1	0.0	20.5	14.7	28.8	28.2	0.6	2.5	2.4
AGL	0.2	4.2	0.3	1.0	0.2	0.1	0.0	0.0	0.0	0.2	6.2	2.0	3.7	3.4	0.3	0.5	0.4
SHB	2.3	0.0	0.6	3.3	0.0	0.4	0.0	0.0	0.0	0.0	6.7	6.1	8.6	5.0	3.6	10.2	4.2
CL	8.9	1.1	1.4	39.9	0.7	0.9	0.0	0.1	0.3	0.0	53.4	13.5	35.4	27.0	8.4	0.3	0.5
RF	1.2	0.1	0.0	1.6	1.0	0.1	0.0	0.0	0.0	0.0	4.0	3.0	4.1	2.2	1.9	3.0	1.1
WL	1.0	0.0	0.4	1.5	0.0	1.0	0.0	0.0	0.0	0.0	3.9	2.9	4.8	3.8	1.0	2.9	1.9
PF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0			0.0		
ML	0.4	0.0	0.1	0.4	0.1	0.0	0.0	2.8	0.0	0.0	3.9	1.1	1.4	0.6	0.8	0.4	0.1
BL	0.1	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	1.0	1.0	0.0		
EF	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.9	0.4	0.6	0.4	0.2	0.8	0.4
P_{+j}	19.9	5.9	3.1	61.8	2.1	2.9	0.1	3.1	0.5	0.7	100	44.2	44.2	35.8	8.4		
Gain	14.1	1.7	2.5	21.9	1.1	1.9	0.1	0.3	0.5	0.2	44.3						
1972/1986																	
GL	5.2	0.0	0.7	12.5	0.4	0.4	0.2	0.4	0.1		19.9	14.7	26.0	22.6	3.4	2.8	2.2
AGL	0.1	4.0	0.2	1.2	0.0	0.1	0.0	0.1	0.0	0.1	5.9	1.9	3.1	2.5	0.6	0.5	0.3
SHB	0.6	0.2	0.6	1.3	0.1	0.3	0.0	0.0	0.0		3.1	2.6	4.4	3.6	0.8	4.5	3.2
CL	8.8	0.5	0.6	48.8	0.4	0.9	0.4	0.8	0.7	0.0	61.8	13.0	30.7	26.0	4.7	0.3	0.4
RF	0.4	0.1	0.0	0.7	0.8	0.0	0.0	0.0	0.0	0.0	2.1	1.3	2.5	2.4	0.1	1.7	1.6
WL	0.5	0.1	0.2	1.0	0.0	0.9	0.0	0.0	0.0	0.0	2.9	2.0	3.8	3.5	0.2	2.2	2.0
PF							0.1				0.1	0.0	0.7	0.0	0.7	0.0	11.0
ML	0.7	0.1	0.1	0.5	0.2	0.1	0.0	1.3	0.0	0.0	3.1	1.8	3.2	2.8	0.4	1.4	1.1
BL	0.1	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0		0.5	0.4	1.3	0.9	0.4	15.7	30.6
EF	0.0	0.3	0.0	0.1		0.0		0.0	0.0	0.3	0.7	0.3	0.4	0.2	0.2	1.0	0.3
P_{+j}	16.5	5.3	2.4	66.5	2.0	2.7	0.7	2.7	0.9	0.4	100	38.0	38.0	32.3	5.7		
Gain	11.3	1.3	1.8	17.7	1.2	1.8	0.7	1.4	0.9	0.1	38.0						
1986/1994																	
GL	6.5	0.0	0.5	8.1	0.3	0.1	0.4	0.5	0.1		16.5	10.0	17.8	15.4	2.3	1.5	1.2
AGL	0.0	3.8	0.0	1.1	0.0	0.0	0.2	0.1	0.0	0.0	5.2	1.4	2.8	2.7	0.1	0.4	0.4
SHB	0.4	0.1	0.7	0.7	0.0	0.2	0.2	0.0	0.0	0.0	2.4	1.7	3.0	2.6	0.4	2.6	2.0
CL	6.1	0.9	0.6	56.5	0.4	0.3	1.3	0.4	0.1	0.0	66.5	10.0	22.7	19.9	2.8	0.2	0.2
RF	0.2	0.1		0.5	0.9		0.2	0.1	0.0		2.0	1.1	2.0	1.8	0.2	1.2	1.0
WL	0.2	0.0	0.2	0.9	0.0	0.7	0.5	0.0	0.0	0.0	2.6	2.0	2.7	1.4	1.3	3.0	1.1
PF	0.0	0.0	0.0	0.6	0.0	0.0	0.1	0.0	0.0		0.7	0.6	3.6	1.2	2.4	5.7	27.8
ML	0.4	0.0	0.0	0.7	0.1	0.0	0.1	1.4	0.0		2.7	1.3	2.3	2.1	0.2	0.9	0.8
BL	0.4	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.2		0.9	0.7	1.0	0.6	0.4	3.9	1.6
EF		0.2	0.0	0.0	0.0	0.0	0.0	0.0		0.2	0.4	0.2	0.2	0.0	0.2	1.1	0.0
P_{+j}	14.2	5.2	2.0	69.3	1.8	1.4	3.1	2.5	0.5	0.2	100	29.1	29.1	23.9	5.2		
Gain	7.7	1.4	1.3	12.8	0.9	0.7	3.0	1.1	0.3	0.0	29.1						
1994/2009																	
GL	7.0		0.2	5.5	0.0	0.0	0.4	0.4	0.6		14.2	7.2	15.0	14.4	0.6	1.0	1.1
AGL	0.3	3.8		0.6	0.0	0.0	0.1	0.1	0.2	0.0	5.2	1.4	2.4	2.1	0.3	0.4	0.3
SHB	0.3	0.0	0.9	0.4		0.1	0.2	0.1	0.0	0.0	2.0	1.0	1.4	0.8	0.7	1.1	0.4
CL	5.8	0.8	0.0	60.1	0.1	0.2	1.1	1.0	0.1		69.3	9.1	18.5	18.3	0.3	0.2	0.2
RF	0.2	0.0		0.3	0.9	0.0	0.2	0.1	0.0	0.0	1.8	0.8	1.0	0.3	0.7	0.9	0.1
WL	0.2	0.0	0.1	0.2		0.6	0.2	0.1	0.0	0.0	1.4	0.8	1.4	1.4	0.1	1.3	1.1
PF	0.2	0.0	0.0	1.3	0.0	0.2	1.1	0.1	0.0		3.1	2.0	4.2	3.9	2.0	1.8	2.0
ML	0.8	0.1	0.0	1.0	0.0	0.0	0.1	0.4	0.0		2.5	2.1	3.9	3.8	0.2	4.9	4.5
BL	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.2		0.5	0.2	1.2	0.5	0.8	0.9	4.0
EF	0.0	0.0		0.0		0.0	0.0			0.2	0.2	0.0	0.1	0.0	0.0	0.2	0.1
P_{+j}	14.9	4.8	1.3	69.5	1.1	1.3	3.4	2.3	1.2	0.2	100	24.6	24.6	22.7	2.8		
Gain	7.8	1.0	0.4	9.4	0.1	0.7	2.2	1.9	1.0	0.0	24.6						
1957/2009																	
GL	4.4	0.0	0.2	14.8	0.1	0.1	0.3	0.3	0.4	0.0	20.6	16.2	26.7	21.0	5.7	4.7	2.4
AGL	0.5	3.6	0.0	1.3	0.0	0.1	0.4	0.1	0.2	0.0	6.2	2.6	3.9	2.6	1.3	0.7	0.4
SHB	1.6	0.0	0.5	4.1	0.0	0.2	0.2	0.1	0.0	0.0	6.7	6.2	7.1	1.8	5.3	12.4	0.5
CL	5.4	0.4	0.2	43.8	0.2	0.3	1.4	1.2	0.5	0.0	53.4	9.6	35.3	19.2	16.1	0.2	0.6
RF	1.0	0.1	0.0	1.9	0.6	0.0	0.3	0.1	0.0	0.0	4.0	3.4	3.9	1.0	2.9	5.7	0.8
WL	0.6	0.0	0.4	2.0	0.0	0.5	0.3	0.1	0.0	0.0	3.9	3.4	4.2	1.6	2.6	6.8	1.6
PF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.3	0.0	3.3		
ML	1.3	0.1	0.1	1.4	0.2	0.1	0.3	0.4	0.0	0.0	3.9	3.5	5.4	3.8	1.6	8.8	4.8
BL	0.1	0.0	0.0	0.2	0.0	0.0	0.1	0.0	0.0	0.0	0.4	0.4	1.5	0.8	0.7		
EF	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.9	0.7	0.7	0.0	0.7	3.5	0.0
P_{+j}	14.9	4.9	1.4	69.5	1.1	1.3	3.3	2.3	1.1	0.2	100	46.0	46.0	25.9	20.1		
Gain	10.5	1.3	0.9	25.7	0.5	0.8	3.3	1.9	1.1	0.0	46.0						

*The highlighted entries indicate persistence. P_{i+} = total time 1, P_{+j} = total time 2, C_j = total change, S_j = the amount of swap, D_j = the absolute value of the net change, l_p = loss-to-persistence ratio, and g_p = gain-to-persistence.

watersheds (Derekolli watershed). The diagonal entries in Table 5 show the percentage of landscape that remained unchanged. About 56%, 62%, 71%, and 75% of the landscape persisted or 44%, 38%, 29% and 25% of the landscape has changed during the period 1957–1972, 1972–1986, 1986–1994, and 1994–2009, respectively, indicating that persistence dominates in all periods. Cultivated land, grassland, afro-alpine grassland together accounted for 50%, 58%, 67%, and 71% of the persistence of the landscape in the respective periods. Both the loss-to-persistence ratio (l_p) and gain-to-persistence ratio (g_p) for grassland, wood land, and marshland are greater than 1 during the period 1957–2009 suggesting that these classes have a tendency to lose or gain rather than to persist. Fig. 5a depicts this pattern for grassland. The loss-to-persistence ratio is greater than 1 for riverine forest and shrubs and bushes, indicating that they experienced a higher tendency to lose than persist in the period 1957–2009. Cultivated land showed a tendency to persist or gain rather than lose (Fig. 6b) suggesting more intensive as well as extensive cultivation. Moreover, the persistence of cultivated land is widespread in areas where population density is highest. Afro-alpine grassland tends to persist rather than lose or gain; riverine forest and shrubs and bushes tend to lose rather than gain/persist; and grassland, woodland and marshland tend to rather gain or lose than persist.

3.2.2. Net change and swap

Swap land change dynamics accounted for 81%, 85%, 82%, and 92% of total landscape change for periods 1957–1972, 1972–1986, 1986–1994, and 1994–2009, respectively. During the whole period 1957–2009, changes in plantation forest and *Ericaceous* forest consist of only a net change, whereas changes in all other categories consist of both net and swap type of changes. In the Jedeb watershed as a whole during this period the change attributable to location (swap = 25.9%) is larger than the change attributable to quantity (net change = 20.1%). During the period 1957–1972, changes in shrubs and bushes, cultivated land, riverine forest, wood land, marshland and *Ericaceous* forest consisted of both net and swap type changes, whereas changes in grassland, afro-alpine grassland and bare land consisted mainly of swap type of change. For example, the net change of grassland (0.6%) perhaps indicates as if there was a lack of change in the landscape because it fails to capture the swapping component of change (28.2%). The change attributable to the net change is highest for marshland (58% of total change for marshland); whereas the change attributable to swap is highest for grassland (98% of the total change for grassland). During the period 1972–1986, all categories consisted of both net and swap types of change with the exceptions for riverine forest and wood land which consisted of mainly swap type of change. In the period 1986–1994, the change in *Ericaceous* forest consisted of almost pure net change, while the change in the rest categories, with the exceptions for afro-alpine grassland and marshland, consisted of both swap and net changes. During the period 1994–2009, changes in grassland, cultivated land, wood land, plantation forest, and marshland experienced swapping change dynamics, whereas the changes in all other categories consisted of both swap and net changes.

3.2.3. Rate of land use and land cover change and trajectories of forest cover

The rate of land use and land cover change throughout the 52 years studied showed periodic fluctuations (Table 6). The annual rate of increase of cultivated land slowed down from 1.2% a^{-1} in 1957 to 0.1% a^{-1} in 2009, suggesting a decrease in agricultural extensification over time. Higher annual rates of decline of grassland were observed during the periods 1972–1986 (−1.7% a^{-1}) and 1986–1994 (−1.9% a^{-1}). The succession of droughts during those periods could be the major factor for those changes.

Higher annual rate of de-vegetation of shrubs and bushes (−6.3% a^{-1}) was observed during the period 1957–1972. *Ericaceous* forest was deforested at a higher annual rate during the periods 1972–1986 (−3.9% a^{-1}) and 1986–1994 (−9.7% a^{-1}) as compared to other classes. The annual average rates of deforestation of shrubs and bushes, riverine forest, wood land, and *Ericaceous* forest were 3.3%, 3%, 3%, and 4.1%, respectively, indicating *Ericaceous* forest was de-vegetated at a faster rate. The annual rate of afforestation/reforestation (of plantation) increased during the periods 1972–1986 (21.4% a^{-1}) and 1986–1994 (18.3% a^{-1}). The recent (1994–2009) rates of deforestation of riverine forest (−4.44% a^{-1}) and shrubs and bushes (−3.69% a^{-1}) exceeded the rate of increase of recent (1994–2009) plantation forest (0.88% a^{-1}). This indicates that recent efforts of establishment of plantations are not balanced with recent deforestation. Therefore, in order to increase the environmental benefits from plantation forest, it is important to give due attention to plantation of selected forests. Fig. 7 depicts the area affected by old deforestation (38.3 km^2) is much greater than that of the recent deforestation (7.4 km^2). The extent of stable forest (i.e. natural forest that remained unchanged over the past 52 years) accounted for only 2.2 km^2 (∼1% of the landscape), which calls for a strong attention to conserve the remaining patches (Fig. 7).

3.3. Detection of most systematic transitions

The difference between observed and expected gains under a random process of change for grassland–cultivated land transition is 3.5% (Tables 7 and 8). Thus, the transition of 15% of the landscape from grassland to cultivated land was due to systematic processes of change. The difference between observed and expected gains for afro-alpine grassland-cultivated land (−2.1%) is relatively large and the negative value suggesting that when cropland gains, a higher tendency of cultivated land to avoid gaining systematically from afro-alpine grassland. When grassland gains it tends to systematically gain from shrubs and bushes, riverine forest, and marshland but not from cultivated land. The difference between observed and expected losses under a random process of loss for grassland-cultivated land was 1.7%. Thus, there is a systematic transition from grassland to cultivated land as cultivated land was systematically gaining from grassland and at the same time grassland was also systematically losing to cultivated land. However, a systematic transition was not observed in the cultivated land to grassland change. Even though cultivated land was systematically losing to grassland (0.7%), grassland rather systematically avoided gaining from cultivated land (−1.6%). One of the implications of cultivated land expansion at the expense of grassland is scarcity of grazing land. Grazing land scarcity could induce resource use conflicts and stimulate unsustainable resource use practices such as overstocking that leads to overgrazing. On the one hand, grazing land scarcity will consequently bring increased land degradation due to overgrazing, and on the other hand it will lead to the decline in livestock population due to shortage of pastures. Therefore, a systematic transition of grassland to cultivated land contributes to the increase in poverty levels among agro-pastoral farmers of the Jedeb watershed.

The difference between observed and expected losses for grassland-plantation forest, afro-alpine grassland-plantation forest, riverine forest-plantation forest, wood land-plantation forest and marshland-plantation forest transitions were −0.3%, 0.3%, 0.2%, 0.2%, and 0.2%, respectively (Tables 7 and 8). These results indicate that plantation forest avoided gaining from grassland systematically but it tended to replace afro-alpine grassland, riverine forest, wood land and marshland systematically. This pattern is attributable to the establishment of *Eucalyptus globules* and *Eucalyptus camaldulensis* plantations mainly for wood for fuel and construction uses (Getahun, 2002). During the military regime

Table 6
Rate of change for different land use and land cover classes.

Land use/cover	1957–1972		1972–1986		1986–1994		1994–2009		Mean	
	$km^2\,a^{-1}$	$\%\,a^{-1}$	$km^2\,a^{-1}$	$\%\,a^{-1}$	$km^2\,a^{-1}$	$\%\,a^{-1}$	$km^2\,a^{-1}$	$\%\,a^{-1}$	$km^2\,a^{-1}$	$\%\,a^{-1}$
GL	0.00	−0.2	−0.02	−1.7	−0.02	−1.9	0.00	0.45	−0.01	−0.8
AGL	0.00	−0.4	−0.01	−1.0	0.00	−0.2	−0.01	−0.55	−0.01	−0.5
SHB	−0.06	−6.3	−0.03	−2.6	−0.02	−2.1	−0.04	−3.69	−0.04	−3.7
CL	0.01	1.2	0.01	0.7	0.01	0.5	0.00	0.06	0.01	0.6
RF	−0.05	−5.5	0.00	−0.5	−0.02	−1.6	−0.04	−4.44	−0.03	−3.0
WL	−0.03	−2.6	−0.01	−0.7	−0.08	−8.3	−0.01	−0.51	−0.03	−3.0
PF	–	–	0.21	21.4	0.18	18.3	0.01	0.88	0.10	10.1
ML	−0.02	−1.8	−0.01	−1.3	−0.01	−1.0	−0.01	−0.63	−0.01	−1.2
BL	−0.01	−0.7	0.06	5.6	−0.08	−7.7	0.09	8.69	0.02	1.5
EF	−0.03	−2.7	−0.04	−3.9	−0.10	−9.7	0.00	0.00	−0.04	−4.1

(1974–1991) *Eucalyptus globules* plantations were established through government supported afforestation programs, funded in some areas partly by international organizations (Zeleke and Hurni, 2001). During the current regime (1991- to date) increased market demand and attractive price of eucalyptus poles that resulted from urbanization, road development and human population pressure have acted as driving forces to the establishment of *Eucalyptus* forest plantations. Bewket (2003) demonstrates the fact that the major factor in increased area coverage of forests has since recently been planting of trees at the household level.

When cultivated land gains, it is inclined to gain only from grassland systematically and disinclined to gain from the other categories. This result indicates that farmers in the Jedeb watershed are inclined to convert grassland rather than natural forest into cultivation, partly because of the ease with which grasslands could be converted to cultivated lands in terms of the required land clearing and the fact that forests are generally located in rough terrain and steep slopes that are unsuitable for cultivation. Therefore, the widely held view that expansion of agriculture is the primary cause for the loss of natural woody vegetation was not found to hold true in the case of Jedeb watershed. The loss of natural woody vegetation is largely attributed to increased demand for wood for fuel, farm implements, construction and other uses. The observed pattern, in the case of Jedeb watershed, was conversion of natural woody vegetation initially to grassland and subsequently grassland into cultivated land. These findings agree with those of Tegene (2002) who indicated for his study area that expansion of cultivation is not the primary cause for disappearance of woody vegetation.

Based on the above analyses, the most dominant signals of changes in the Jedeb watershed during the period 1957–2009 were:

- conversion of about 14.8% of grassland to cultivated land, and
- the conversion of shrubs and bushes, riverine forest, and marshland to grassland which accounts for about 3.9% of the landscape.
- the conversion of *Ericaceous* forest to afro-alpine grassland which accounts for 0.7% of the landscape.
- the conversion of wood land to shrubs and bushes which accounts for 0.4% of the landscape (Fig. 8).

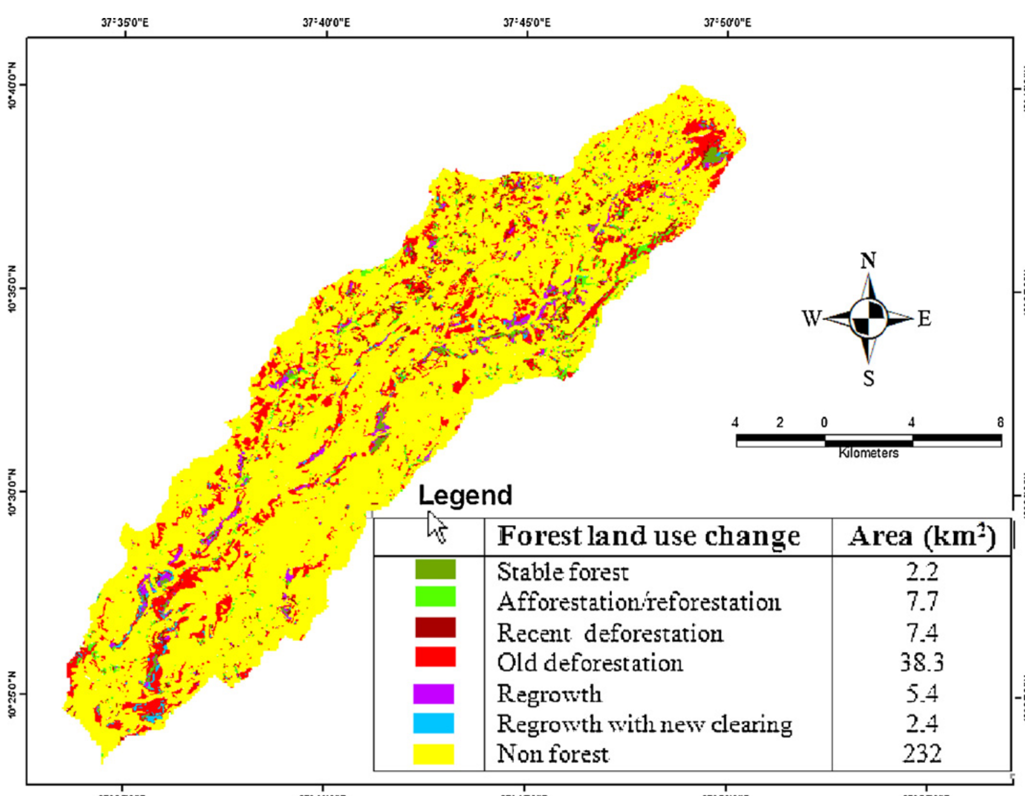

Fig. 7. Forest land use and land cover change trajectory map.

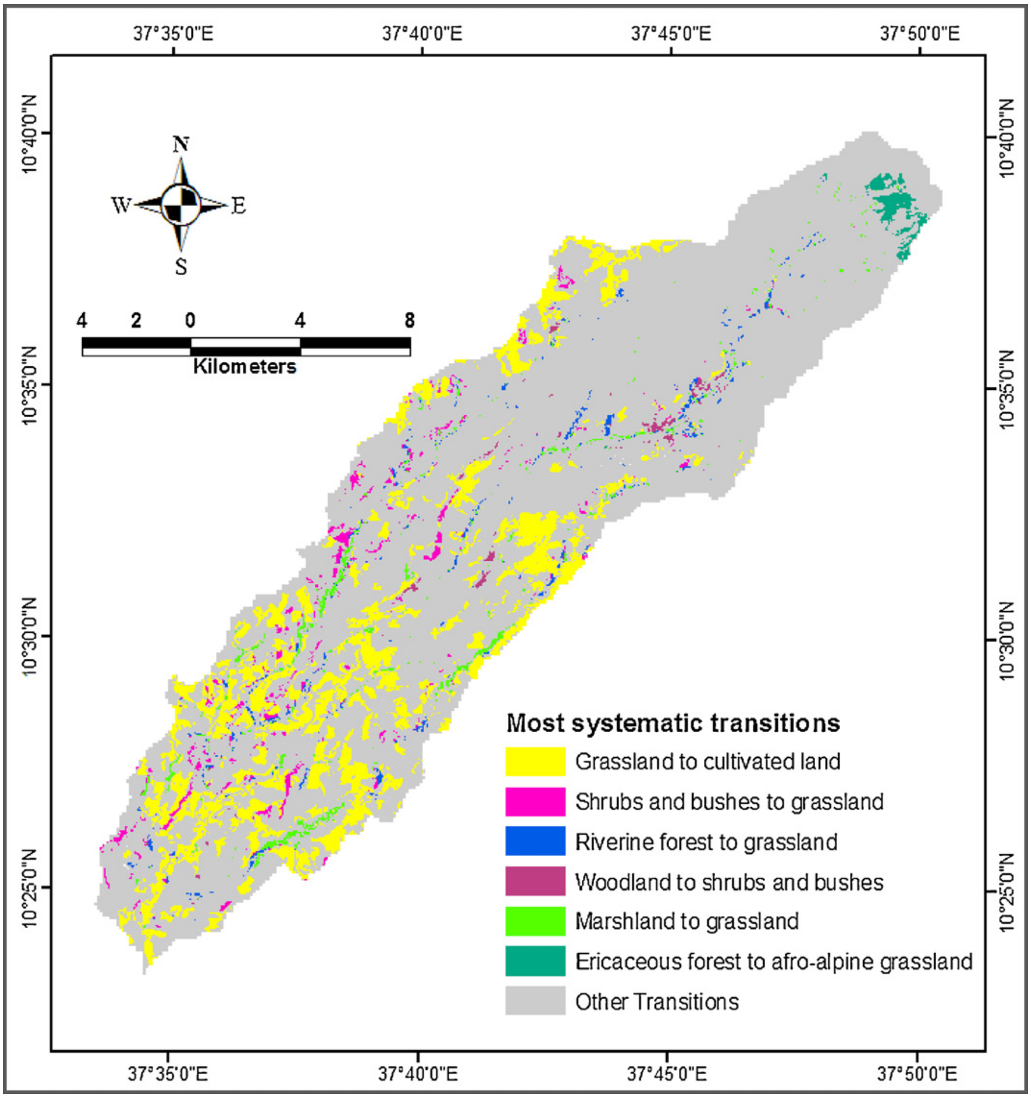

Fig. 8. Map of the most systematic land use and land cover transitions for the period 1957–2009.

3.4. Determinants of locations of the most systematic transitions

3.4.1. Forest-to-grassland conversion

A binary logistic regression analysis was conducted to analyze the factors determining the patterns of forest-to-grassland conversion using 11 predictors (Table 9) for the period 1957–2009. A test of the full model against a constant only model was statistically significant, indicating that the predictors as a set reliably distinguished forest to grassland conversation against all other conversions (χ^2 (11, N = 764) = 500.47, p < 0.000). The model as a whole explained 64.1% (Nagelkerke pseudo R^2) of the variance, and correctly classified 86.8% of the cases. The ROC value of this model is 0.91 (Table 10), indicating that the goodness of fit of the model is excellent according to the rating explained by Hosmer and Lemeshow (2000). The result of this spatially explicit logistic regression model is illustrated in Fig. 10d. As shown in Table 10, *travel time to town* (*market*) and *north-facing slope* (*cosine of aspect*) did not have any statistically significant contribution to forest-to-grassland conversion.

3.4.1.1. Topographic variables. The variables elevation, sine of aspect (eastness), topographic wetness index and slope appear to be positively related with forest-to-grassland conversion. Thus, the likelihood of forest-to-grassland conversion increases with increasing elevation, eastness, soil wetness, and steepness of a location. A unit standard deviation increase in elevation (488 m) is associated with a 0.971 standard deviation increase in the logit of forest-to-grassland conversion. This is to be explained by the existence of high livestock density in the high elevation areas (e.g. *Sinan* wereda = 138 #/km^2) than in the lower elevation areas (e.g. *Mchakel* wereda = 108 #/km^2) of Jedeb watershed (Table 11). Thus, cattle grazing could be the immediate cause for forest-to-grassland conversion. A unit standard deviation increase in slope (6.4°) is associated with a 0.302 standard deviation increase in the logit of forest-to-grassland conversion, suggesting forest areas with steep slopes are more likely to be converted to grassland.

3.4.1.2. Distance variables. All statistically significant distance variables are negatively correlated with forest-to-grassland conversion. Thus, deforestation decreases with increasing *distance from forest edges*, *rivers* and *roads*. *Distance from forest edge* appears to have the strongest effect (−4.484 in Table 10) in explaining forest-to-grassland conversion, followed by elevation, slope aspect, wetness, population density, proximity to river, proximity to road, and then slope. The probability of forest-to-grassland conversion decreases from 0.68 to 0.31 for an increase in *distance from*

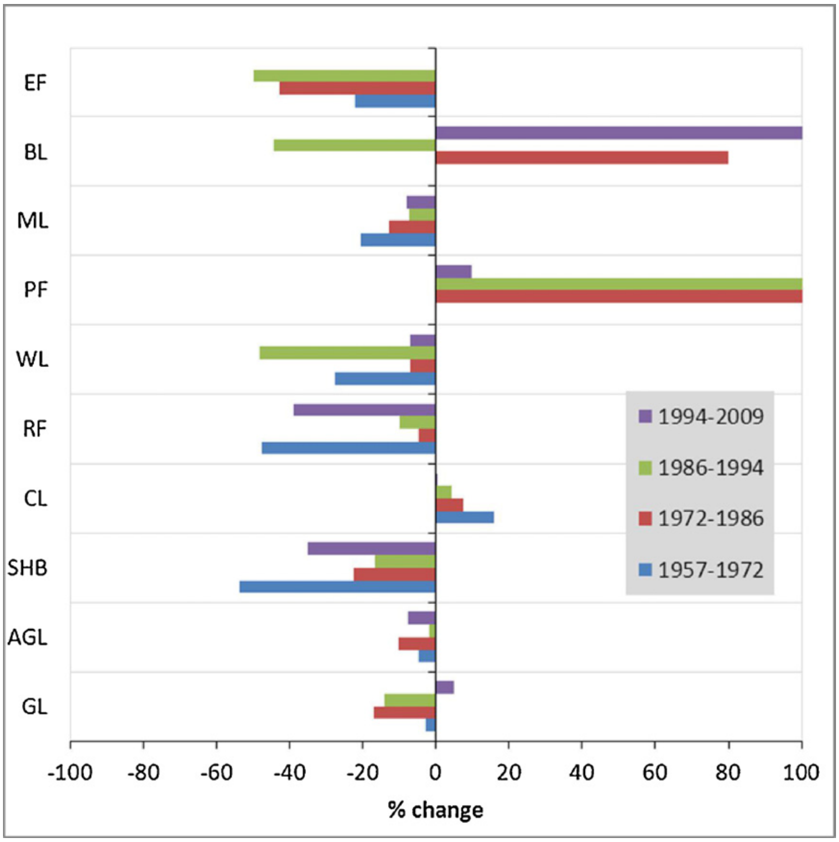

Fig. 9. Percentage of change of each category; see Table 2 for the definition of the abbreviations.

forest edge of 0–120 m. Even at a distance of 60 m from forest edges, the predicted probability is 0.49. This suggests that not only at the edges of forest but also at a distance of 60 m from the edge there is a moderately higher probability of deforestation. Therefore, a 240 m-buffer of existing forest can protect it from conversion to grassland, because the predicted probability at this distance is 0.08 (Fig. 11e). A unit standard deviation decrease in *distance from river* (537 m) is associated with a 0.408 standard deviation increase in

Table 7
Transitions in percentage of total landscape under random process of gain (G_{ij}), and random process of loss (L_{ij}) for the period 1957–2009.

1957/2009	Variable	GL	AGL	SHB	CL	RF	WL	PF	ML	BL	EF	P_{i+}	Loss
GL	G_{ij}	4.4	0.3	0.2	11.4	0.1	0.2	0.7	0.4	0.2	0.0	17.8	13.4
	L_{ij}	4.4	0.9	0.3	13.2	0.2	0.2	0.6	0.4	0.2	0.0	20.6	16.2
AGL	G_{ij}	0.8	3.6	0.1	3.4	0.0	0.1	0.2	0.1	0.1	0.0	8.4	4.8
	L_{ij}	0.4	3.6	0.0	1.9	0.0	0.0	0.1	0.1	0.0	0.0	6.2	2.6
SHB	G_{ij}	0.9	0.1	0.5	3.7	0.0	0.1	0.2	0.1	0.1	0.0	5.7	5.2
	L_{ij}	0.9	0.3	0.5	4.4	0.1	0.1	0.2	0.1	0.1	0.0	6.7	6.2
CL	G_{ij}	7.1	0.7	0.5	43.8	0.3	0.4	1.8	1.1	0.6	0.0	56.2	12.4
	L_{ij}	4.7	1.5	0.4	43.8	0.3	0.4	1.0	0.7	0.3	0.1	53.4	9.6
RF	G_{ij}	0.5	0.1	0.0	2.2	0.6	0.0	0.1	0.1	0.0	0.0	3.7	3.1
	L_{ij}	0.5	0.2	0.0	2.4	0.6	0.0	0.1	0.1	0.0	0.0	4.0	3.4
WL	G_{ij}	0.5	0.1	0.0	2.2	0.0	0.5	0.1	0.1	0.0	0.0	3.5	3.0
	L_{ij}	0.5	0.2	0.0	2.4	0.0	0.5	0.1	0.1	0.0	0.0	3.9	3.4
PF	G_{ij}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	L_{ij}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ML	G_{ij}	0.5	0.1	0.0	2.2	0.0	0.0	0.1	0.4	0.0	0.0	3.4	3.0
	L_{ij}	0.5	0.2	0.1	2.5	0.0	0.0	0.1	0.4	0.0	0.0	3.9	3.5
BL	G_{ij}	0.1	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3
	L_{ij}	0.1	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.4
EF	G_{ij}	0.1	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.2	0.9	0.7
	L_{ij}	0.1	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.2	0.9	0.7
P_{i+}	G_{ij}	14.9	4.9	1.4	69.5	1.1	1.3	3.3	2.3	1.1	0.2	100	46.0
	L_{ij}	12.2	7.0	1.4	71.3	1.3	1.4	2.3	2.0	0.8	0.3	100	46.0
Gain	G_{ij}	10.5	1.3	0.9	25.7	0.5	0.8	3.3	1.9	1.1	0.0	46.0	
	L_{ij}	7.8	3.4	0.9	27.5	0.7	0.9	2.3	1.6	0.8	0.1	46.0	

Table 8
Percent of land use and land cover changes in terms of gains and losses for the period 1957–2009*.

1957/2009	GL		AGL		SHB		CL		RF		WL		PF		ML		BL		EF	
	D_{ij}	R_{ij}	D_{ij}	R_{ij}	D_{ij}	R_{ij}	D_{ij}	R_{ij}	D_{ij}	R_{ij}	D_{ij}	R_{ij}	D_{ij}	R_{ij}	D_{ij}	R_{ij}	D_{ij}	R_{ij}	D_{ij}	R_{ij}
GL	**0.0**	**0.0**	**-0.3**	**-1.0**	**0.0**	**0.0**	**3.4**	**0.3**	**0.0**	**-0.1**	**-0.1**	**-0.4**	**-0.4**	**-0.6**	**-0.1**	**-0.3**	**0.2**	**0.8**	**0.0**	
	0.0	0.0	-0.9	-1.0	-0.1	-0.2	1.6	0.1	-0.1	-0.5	-0.1	-0.6	-0.3	-0.5	-0.1	-0.3	0.2	0.9	0.0	-1.0
AGL	**-0.3**	**-0.4**	**0.0**	**0.0**	**-0.1**	**-1.0**	**-2.1**	**-0.6**	**0.0**	**-1.0**	**0.0**	**0.9**	**0.2**	**1.0**	**0.0**	**-0.2**	**0.1**	**1.9**	**0.0**	
	0.1	0.2	0.0	0.0	0.0	-1.0	-0.6	-0.3	0.0	-1.0	0.1	1.8	0.3	3.4	0.0	0.6	0.2	5.7	0.0	-1.0
SHB	**0.7**	**0.8**	**-0.1**	**-1.0**	**0.0**	**0.0**	**0.4**	**0.1**	**0.0**	**-1.0**	**0.1**	**2.6**	**0.0**	**-0.1**	**0.0**	**-0.2**	**-0.1**	**-1.0**	**0.0**	
	0.7	0.7	-0.3	-1.0	0.0	0.0	-0.3	-0.1	-0.1	-1.0	0.1	1.4	0.0	0.0	0.0	-0.3	-0.1	-1.0	0.0	-1.0
CL	**-1.7**	**-0.2**	**-0.3**	**-0.5**	**-0.3**	**-0.6**	**0.0**	**0.0**	**-0.1**	**-0.3**	**-0.1**	**-0.3**	**-0.4**	**-0.2**	**0.1**	**0.1**	**-0.1**	**-0.2**	**0.0**	
	0.7	0.2	-1.1	-0.7	-0.2	-0.5	0.0	0.0	-0.1	-0.4	-0.1	-0.3	0.4	0.3	0.5	0.7	0.2	0.4	-0.1	-1.0
RF	**0.5**	**0.9**	**0.0**	**0.8**	**0.0**	**-1.0**	**-0.3**	**-0.1**	**0.0**	**0.0**	**0.0**	**-1.0**	**0.2**	**1.3**	**0.0**	**0.3**	**0.0**	**-1.0**	**0.0**	
	0.5	1.0	-0.1	-0.4	0.0	-1.0	-0.5	-0.2	0.0	0.0	0.0	-1.0	0.2	1.6	0.0	0.3	0.0	-1.0	0.0	-1.0
WL	**0.1**	**0.2**	**-0.1**	**-1.0**	**0.4**	**9.6**	**-0.2**	**-0.1**	**0.0**	**-1.0**	**0.0**	**0.0**	**0.2**	**1.3**	**0.0**	**0.3**	**0.0**	**-1.0**	**0.0**	
	0.1	0.2	-0.2	-1.0	0.4	7.3	-0.4	-0.2	0.0	-1.0	0.0	0.0	0.2	1.6	0.0	0.3	0.0	-1.0	0.0	-1.0
PF	**0.0**		**0.0**		**0.0**		**0.0**		**0.0**		**0.0**		**0.0**		**0.0**		**0.0**		**0.0**	
	0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0	
ML	**0.8**	**1.5**	**0.0**	**0.9**	**0.1**	**1.7**	**-0.8**	**-0.3**	**0.2**	**8.8**	**0.1**	**2.1**	**0.2**	**1.3**	**0.0**	**0.0**	**0.0**	**-1.0**	**0.0**	
	0.8	1.4	-0.1	-0.4	0.0	1.0	-1.1	-0.4	0.2	4.1	0.1	1.1	0.2	1.5	0.0	0.0	0.0	-1.0	0.0	-1.0
BL	**0.0**	**0.9**	**0.0**	**-1.0**	**0.0**	**-1.0**	**0.0**	**-0.1**	**0.0**	**-1.0**	**0.0**	**-1.0**	**0.1**	**6.6**	**0.0**	**-1.0**	**0.0**		**0.0**	
	0.0	0.7	0.0	-1.0	0.0	-1.0	-0.1	-0.3	0.0	-1.0	0.0	-1.0	0.1	6.5	0.0	-1.0	0.0		0.0	-1.0
EF	**-0.1**	**-1.0**	**0.7**	**55.1**	**0.0**	**-1.0**	**-0.5**	**-1.0**	**0.0**	**-1.0**	**0.0**	**-1.0**	**0.0**	**-1.0**	**0.0**	**-1.0**	**0.0**	**-1.0**	**0.0**	**0.0**
	-0.1	-1.0	0.7	19.4	0.0	-1.0	-0.5	-1.0	0.0	-1.0	0.0	-1.0	0.0	-1.0	0.0	-1.0	0.0	-1.0	0.0	0.0

* D_{ij} = the difference between the observed and the expected value, R_{ij} = the difference between the observed and the expected value, relative to the expected value. The numbers in bold are values for the gains (%) and the numbers in normal font are values for the losses (%). The most systematic transitions are highlighted.

the logit of forest-to-grassland conversion. Forests located near rivers and on wet soils (higher *topographic wetness index*) seem to have higher likelihood of being converted to grassland. This indicates the susceptibility of riverine forest to deforestation than any other forest types in the Jedeb watershed. This finding is in line with results reported from elsewhere at local scale analysis of deforestation (e.g.Wyman and Stein, 2010). *Travel time to town* (*market*) is not a statistically significant predictor of the location of forest-to-grassland conversion. This implies that the local market is not influencing forest-to-grassland conversion as most of the forest products are instead transported to other larger towns including the capital city, Addis Ababa. The model predicted that a unit standard deviation decrease in *travel time to road* (31.7 min) is associated with a 0.353 standard deviation increase in the logit of forest-to-grassland conversion, indicating that forests located near roads are more likely to be deforested as lower travel costs increase returns from forests. At zero *travel time to road* the model predicted a 0.28 likelihood of deforestation. This indicates *travel time to road* has a moderate power in explaining forest-to-grassland conversion. If forest conservation planners want to minimize the effect of roads on deforestation it is possible to delineate areas for afforestation at beyond 80 min *travel time from roads* (Fig. 11b).

3.4.1.3. Population density. The Jedeb watershed was inhabited by a total population of about 47,448 in 2007, growing at a rate of 2.02% per annum. Assuming that this rate of growth has remained constant, the total population of the watershed would have been around 17,281 in 1957. Similarly, the estimated population for the year 2012 would be 52,490 and the population will be double within 35 years from now (Table 12). Despite the rise in population pressure over the past 50 years, an increase in population density between 1957 and 2007 was not a significant determinant of forest-to-grassland conversion (Table 10). The population potential surface derived from *kebelle* population acquired from CSA (2008) was not found to be a significant predictor of forest-to-grassland conversion. The model predicts that a unit standard deviation increase in *initial population density* (32 persons/km^2) is associated with a 0.41 standard deviation decrease in the logit of forest-to-grassland conversion. This could raise several hypotheses, as it is difficult to determine causal relationships. This could be related to the establishment of eucalyptus plantations around homesteads in place of deforested riverine forest and woodland as a result of population pressure. This result accords with some earlier analysis (e.g. Leach and Fairhead, 2000; Bewket, 2003) who explored neo-Boserupian perspective of population-forest dynamics.

Table 9
List of variables included in the binary logistic regression.

Independent variables	Abbreviation	Units	Proxy for
Topography related variables			
Slope	SLP	degrees	Diffuse solar radiation
Elevation	ELEV	m	Mean annual air temperature
Sine of aspect	SIN_ASP	−1 to 1	Eastness
Cosine of aspect	COS_ASP	−1 to 1	Northness
Topographic wetness index	TWI	Index	Moisture accumulation
Distance variables			
Distance to forest edge	D_FOREDGE57	m	Likelihood for forest loss
Distance to river	D_RIV	m	Likelihood for agriculture use
Travel time to roads	TT_ROAD	min	Accessibility*
Travel time to towns (market)	TT_TOWN	Min	Accessibility*
Demographic variables			
Population density in 1957	PD_57	Inha./km^2	Likelihood of forest loss
Change in population density (2007–1957)	PD07_57	Inha./km^2	Likelihood of forest loss

* Measure of accessibility is defined as the ability for contact with sites of economic or social opportunities (Deichmann, 1997)

Table 10
Binary logistic regression results for grassland-to-cultivated land conversion and forest-to-grassland conversion.

Dependent variable	Model evaluation	Independent variables	Unstandardized logit coefficient (β)	Standard error of β	Standardized logit coefficient (β^*)
GL-CL Conversion (1957/2009)	LR χ^2 = 389.29 (p = 0.000) Nagelkerke R^2 = 0.25 ROC = 0.72	SLP	−0.0613	0.0113	−0.3420
		ELEV	−0.0032	0.0003	−1.0180
		SIN_ASP	*	*	*
		COS_ASP	*	*	*
		TWI	−0.1135	0.0279	−0.2370
		D_RIVER	*	*	*
		TT_ROAD	0.0065	0.0020	0.2130
		TT_TOWN	−0.0037	0.0015	−0.1730
		PD57	−0.0071	0.0021	−0.2300
		PD07_57	−0.0088	0.0020	−0.2590
		Intercept	10.6446	0.8178	−0.1750
F-GL Conversion (1957/2009)	LR χ^2 = 500.47 (p = 0.000) Nagelkerke R^2 = 0.64 ROC = 0.91	SLP	0.0475	0.0187	0.302
		ELEV	0.0019	0.0005	0.971
		SIN_ASP	0.8679	0.1647	0.624
		COS_ASP	*	*	*
		TWI	0.2680	0.0607	0.572
		D_FOREDGE57	−0.0163	0.0016	−4.484
		D_RIVER	−0.0007	0.0003	−0.408
		TT_ROAD	−0.0111	0.0043	−0.353
		TT_TOWN	*	*	*
		PD57	−0.0123	0.0041	−0.410
		PD07_57	*	*	*
		Intercept	−5.6701	1.3102	−1.231

* Not significant, all other values are significant at 0.05 level.
Note: The standardized logit coefficient is the unstandardized logit coefficient multiplied by the parameter's standard deviation.
LR χ^2: Likelihood Ratio or Model Chi-square. ROC: Relative Operating Characteristics.

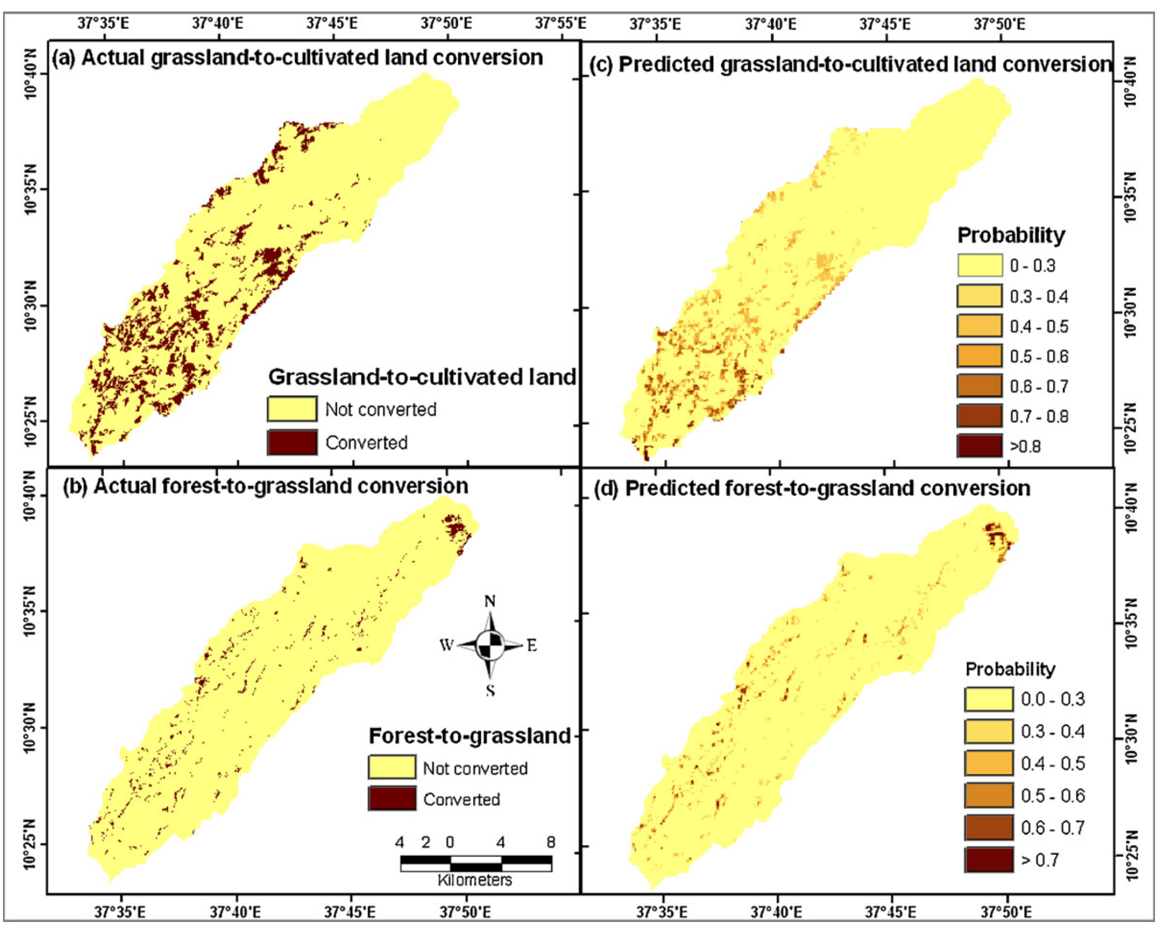

Fig. 10. (a and b) actual conversions between 1957 and 2009 and (c and d) predicted conversions based on the logistic regression models in Table 10.

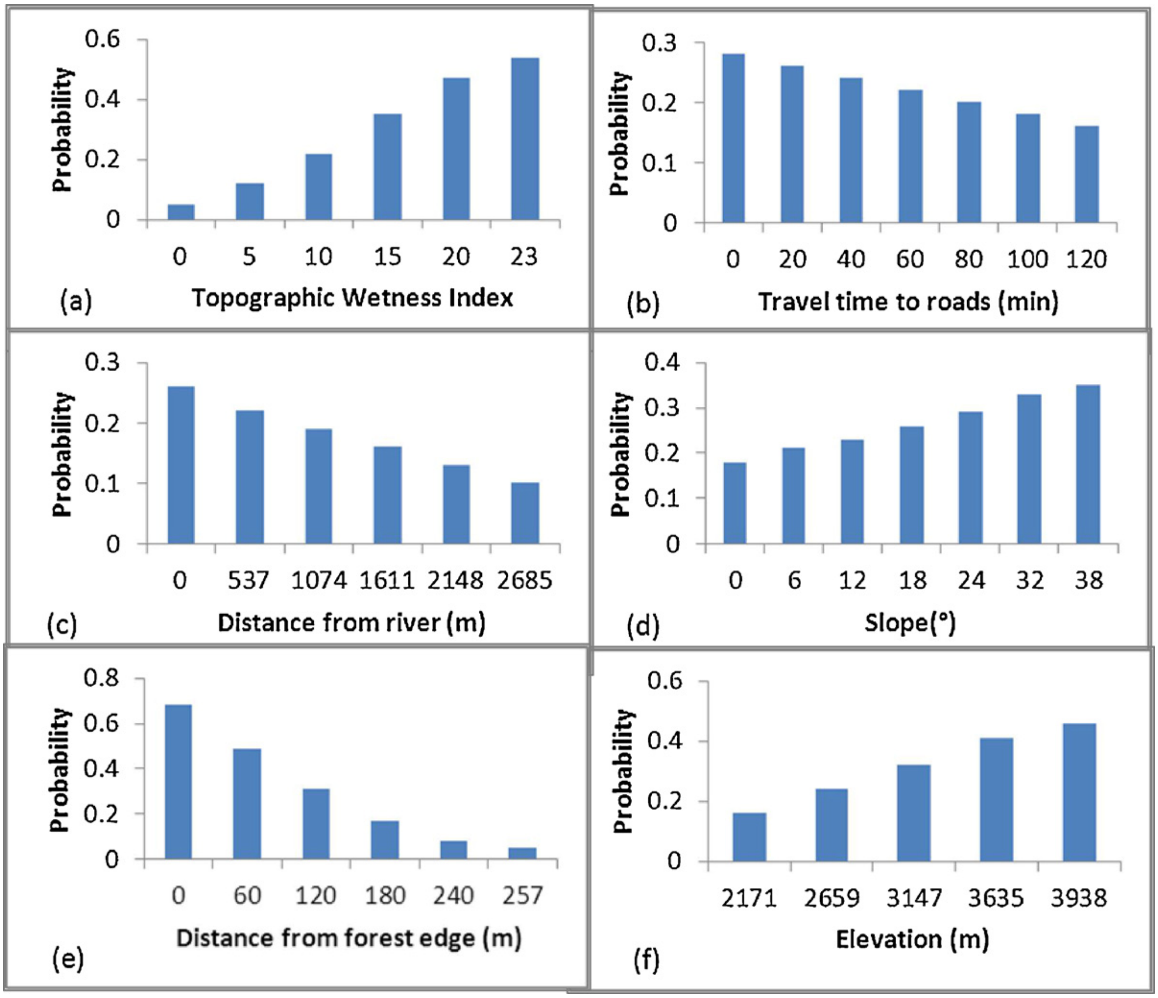

Fig. 11. Probability of forest-to-grassland conversion according to different explanatory variables.

Table 11
Human (rural) and livestock population density in the two *Kebelles* (districts) of Jedeb watershed.

Wereda (district)	Mean elevation (m)[*]	Population density (#/km^2)	
		Human (Rural)[**]	Livestock[***]
Machakel	2284	148.48	107.62
Sinan	2900	216.24	137.49

Source: [*]SRTM90; [**]CSA, 2007; [***]Office East Gojam Zone Agriculture and Rural Development (unpublished report, 2010).

3.4.2. Grassland-to-cultivated land conversion

Another binary logistic regression analysis was conducted to predict grassland-to-cropland conversion using ten predictors for the period 1957–2009. A test of the full model against a constant only model was statistically significant, indicating that the predictors as a set reliably distinguished grassland-to-cropland conversion against all other conversions (χ^2 (10, N = 1876) = 389.29, p < 0.000). The model as a whole explained 25% (Nagelkerke pseudo R^2) of the variance, and correctly classified 71.2% of the cases. The result of this spatially explicit logistic regression model is illustrated in Fig. 10c. The ROC value of 0.72 (Table 10) suggests that the model fit is generally good. Proximity to river and slope aspect did not have any statistically significant contribution to grassland-to-cropland conversion (Table 10). Grassland located near rivers seems to have little likelihood of being converted to cultivated land even though there is a good possibility of getting water for irrigation.

Table 12
Demographic characteristics of Jedeb Watershed.[*]

Demographic variables	1957[a]	2007[b]
Total population size	1721 (15,909)	47,448 (29,115)
Number of households	3677 (3387)	10,612 (6470)
Average population density (Persons/km^2)	58 (50)	160 (91)

[*] Numbers in parentheses are estimations based on counting the number of huts (“tukul”) using 4.7 and 4.5 average inhabitants for 1957 and 2007, respectively.
[a] The projection is based on the assumption of exponential increase: $P_n = P_o e^{r^*n}$.
[b] Source: CSA, 2008.

3.4.2.1. Topographic variables.

Based on the standardized logistic regression coefficients, *elevation* appears to have the strongest explanatory power, followed by *slope*. A unit standard deviation decrease in elevation (312 m) is associated with a 1.018 standard deviation increase in the logit of grassland-cultivated land conversion. Similarly, a unit standard deviation decrease in slope (5.4°) is associated with a 0.342 standard deviation increase in the logit of grassland-to-cropland conversion. Topographic wetness index has a statistically significant negative relationship with grassland-cultivated land conversion. A unit standard deviation decrease in *topographic wetness index* is associated with a 0.237 standard deviation increase in the logit of grassland-cultivated land conversion. This indicates that farmers do not take soil wetness into consideration when they tend to convert grassland to cultivated land. The above results indicate only two of the geo-physical determinants of agricultural potential (elevation and slope) reinforce the Ricardian land change theory.

3.4.2.2. Distance variable. *Travel time to market* (*towns*) is another important determinant of the location of grassland-to-cropland conversion. A unit standard deviation decrease in travel time (46.6 min) is associated with a 0.173 standard deviation increase in the logit of grassland-to-cropland conversion, suggesting that the shorter the travel time to markets the higher is the likelihood of grassland-to-cropland conversion. This is because the reduced cost to transport inputs and outputs to the market as a result of shorter travel time may stimulate increases in agricultural production. This finding very well agrees with that of Dercon and Hoddinott (2005), who explained the more remote households are from towns, the less likely they are to purchase inputs or sell a variety of products in Ethiopia. This result clearly indicates the land use pattern in the Jedeb watershed is shaped by von Thunen's theory. However, *travel time to road* is positively correlated with the grassland-to-cultivated land conversion, suggesting that local people do not use existing roads intensively to come to markets/towns. This could be explained by poor access to and/or high cost of transportation for the local people.

3.4.2.3. Population pressure. Low population density in 1957 increased the likelihood of observing grassland-to-cultivated land conversion, suggesting that low population density is an important determinant of agricultural extensification. The model predicts that a unit standard deviation decrease in *initial population density* (32 persons/km^2) is associated with a 0.23 standard deviation increase in the logit of grassland-to-cultivated land conversion (Table 10). This finding is in line with that of Braimoh and Vlek (2005) who indicated that population density is important determinant where the dominant change process is extensification. An increase in population density between 1957 and 2007 significantly decreased the probability of observing the grassland-to-cultivated land conversion. This result suggests that an increasing population pressure could rather lead to intensified cultivation of land as a land use change process than an agricultural extensification.

4. Conclusions

Analysis of multi-temporal LULCC through enhanced transition matrix and spatial statistical modeling improved the identification, quantification and understanding of determinants of most systematic transitions in the Jedeb watershed, a headwater tributary of the Blue Nile River in Ethiopia. The study found that the watershed has undergone significant land use/cover alterations since 1957. In all of the time spans considered (1957–1972, 1972–1986, 1986–1994, 1994–2009), cultivated land and grassland constituted the predominant types of land cover, although the former has been by far the largest coverage. Of the total area of the watershed, cropland accounted for 53.4% in 1957, 61.8% in 1972, 66.5% in 1986, 69.3% in 1994 and 69.5% in 2009. A clear trend of growth in cultivated land until 1994 was found. The absence of a significant increase in the cultivated land since 1994 suggests that all the area that is suitable for cultivation has most likely been used, or the land tenure system has effectively controlled spontaneous expansion of cultivation by local people.

About 46% of the watershed area experienced transition from one category to a different category of land use/cover over the 52 years considered. Out of the 46%, about 20% of the changed area was a net change while 25.9% was a swap change. Swap change is greater than net change suggesting the importance of the swapping component and common methods of land use/cover change study would miss this dynamics. Cultivated land and afro-alpine grassland tend to persist; riverine forest and shrubs and bushes tend to lose; and grassland, woodland and marshland tend to gain or lose rather than persist. The type of change that each land use/cover experienced differs from period to period. For example, when the difference between gains and losses experienced by grassland is small (1957–1972 and 1994–2009), grassland experienced mainly swap type of change. Otherwise, it experienced both net and swap types of change. Identification of swapping change dynamics is important especially in the absence of the net change which may otherwise be interpreted as absence of change because the net change fails to capture the swapping component of the change.

The rate of afforestation/reforestation (plantation) far outpaced that of deforestation in the periods 1972–1986 and 1986–1994, whereas recent (1994–2009) rates of deforestation of riverine forest ($-4.44\%\,a^{-1}$) and shrubs and bushes ($-3.69\%\,a^{-1}$) exceeded the rate of increase of recent (1994–2009) rate plantation forest ($0.88\%\,a^{-1}$). Plantation forest grew at the expense of afro-alpine grassland, riverine forest, wood land and marshland systematically. Increasing demands and attractive prices of *Eucalyptus* poles resulting from urbanization, road development and human population pressure are the main driving forces for the recent expansion of forest plantations.

Lower elevations, gentle slopes, less populated areas, locations near to markets/towns, and locations farther from roads increase the likelihood of grassland-to-cultivated land conversion in the Jedeb watershed. Farmers of the Jedeb watershed are inclined to convert grassland rather than natural forest for cultivation. The observed overall pattern has been conversion of natural woody vegetations to grassland and then grassland was subsequently converted to cultivated land. Therefore, the widely held view that expansion of agriculture is the primary cause for the loss of natural woody vegetation in Ethiopia was not found to hold true in the case of the Jedeb watershed. Forest edges, higher elevations, east-facing and steeper slopes, less populated areas, locations near roads and rivers, and locations with high soil wetness increase the likelihood of forest-to-grassland conversion. A 240 m-buffer of existing forest is likely to protect forest edges from conversion to grassland. Forests located near rivers and on wet soil (i.e. riverine forests) seem to have higher susceptibility to deforestation than the other forest types. Forests located near roads are more likely to be deforested, as lower travel costs increase returns from forests. Thus, the loss of forest could be largely due to increased demand for wood for fuel, construction, farm implements and other uses. The spatial statistical modeling of most systematic transitions in this study suggests that spatial determinants of LULCC can be related to the well-established land change theories. The determinants of grassland-to-cultivated conversion model such as *travel time to market* reinforce evidence of von Thunen's model, whilst the geo-physical determinants of agricultural potential (elevation and slope) reinforce the Ricardian land change theory.

Finally, this study has highlighted that integrated use of Remote Sensing and GIS technologies improves quantification, statistical modeling and therefore improved understanding of the process of land use/cover change. Thus, identifying most systematic transitions and its spatial statistical modeling under GIS environment provides essential planning tools for sustainable watershed management.

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