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Ecological succession and land use changes in a lake retreat area (Main Ethiopian Rift Valley)

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Abstract

In the semi-arid Main Ethiopian Rift Valley, ecological succession is related to continuous lake retreat. Human activity, through its impact on land use and cover, affects this ecological succession at various degrees. Through a remote sensing study, we explored how the drivers for LUCC have changed over the last decades and which impact this has on ecological succession.

Remote sensing data used include a Landsat MSS from 1973, a Landsat TM from 1986 and Landsat ETM+ from 2000; a conventional type of classification was used whereby supervised classification of the 2000 image was supplemented by unsupervised classification of the older images. Due to decreased rainfall and water abstraction for intense irrigated agriculture in its catchment, Lake Abijata lost 46 % of its area between 2000 and 2006. On the emerged land, an ecological succession was observed along the environmental gradient of the retreating lake: emerged bare land, grassland, land with few scattered Acacia shrubs and open woodlands. Between 1986 and 2000, LUCC tendencies were totally reversed and woody vegetation decreased strongly, indicating increased human impact. This land degradation took place in a context of instable political situation, fuelwood extraction, higher population density and better communications.

Key words: Lake Abijata; remote sensing; Landsat imagery; lake retreat; successional trend; deforestation; Ethiopia

1. Introduction

Ecological succession is an orderly process of vegetation community development that involves change in species structure and community processes with time (Odum, 1971). In the Main Ethiopian Rift Valley (MERV), ecological succession is related to continuous lake retreat since some 5000 BP. Human activities, through their impact on land use and cover (LUC), also affect ecological succession at various degrees. LUC are continually changing owing to many factors. Whereas natural causes such as climatic variability (drought, heavy storms etc.), greenhouse impact and volcanic eruption may be important (Turner II et al., 1995; Serneels and Lambin, 2001), the majority of changes at contemporary time are however induced by human action

(Turner II et al., 1995). Empirical investigations in the highlands of Ethiopia (Zeleke, 2000) have shown that an increase in population density results in the conversion of the forest into cultivated land or of cultivated land into badlands. It is as important to consider the impact of land improvement practices and infrastructure development on land use and cover changes (LUCC) (Nyssen et al., 2009). According to Turner II et al. (1995), both direct and indirect effects of these practices must be included in research.

Individual earth-surface cover types are distinguishable in terms of their spectral reflection characteristics. Landsat TM, SPOT and Aster satellites imagery is frequently used for land resources assessment. The advantage with Landsat is that it has recorded data since 1970s and can provide a historical data set to study LUCC changes in temporal perspective.

Computer assisted digital image processing to extract information involves image classification and accuracy assessment. Digital image classification tends to fall into two operational classes: supervised and unsupervised classification (Lillesand and Kiefer, 2000). In general, it has been recognised that satellite datasets and GIS have due importance in LUCC detection and the outcomes have been used for planning and decision making activities (Howard, 1991; Walsh et al., 2006). The digital data processed from the satellite images is supplemented with data from field interviews and discussions with local people and key informants (Xu et al., 2005). Hence, the aims of this study are to (a) extricate ecological succession and human activity as causative factors for LUCC, and (b) explore how the drivers for LUCC have changed over the last decades and which impact this has on ecological succession in the MERV.

2. Research methods

2.1 Study area

2.1.1 Location

The study area (637 km²) is located in the MERV, about 200 km south of Addis Ababa (Fig. A1, in the online appendix), between 38° 24’ – 38° 42’E and 7° 30’- 7° 42’N. About 80 % of it is within Abijata Shala Lakes National Park (ASLNP). It is bounded by four lakes of tectonic or volcano-tectonic origin: Lake Ziway (1635 m a.s.l.), Lake Langano (1585 m a.s.l.), Lake Abijata (1580 m a.s.l.) and Lake Shala (1550 m a.s.l.) (Acocella et al., 2003). The elevation of the studied area ranges between 1580 and 1780 m a.s.l., with fairly level to gently sloping terrain.

2.1.2 Climate

The study area has a semi-arid climate (Umer and Bonnefille, 1991; Billi, 2002). Average annual rainfall in nearby Adamitullu station (half way between lakes Abijata and Ziway) is 768 mm (1980-2006). In most years, it is characterised by bimodal rainfall: very short and unreliable rain during the months April-May, while most of the rain occurs during three summer months (June-August) and sometimes up to September (Eshete, 1999). Temperatures are relatively high with mean monthly maximum and minimum of 28 °C and 13.8 °C (Billi, 2002).

2.1.3. Geology and hydrology

The Ethiopian rift valley is part of the Afro-Arabian rift system, bounded by the Arabian plate in the north, the African plate to the west and the east. It is a funnel-shaped endorheic depression that opens up in the northeast into the Gulf of Aden and the Red Sea and continues southwards through the East-African Rift up to Mozambique (Acocella et al., 2003). The lithology is dominated by basalt, ignimbrite, lava, gneiss, lapilli tuff, volcanic ash and pumice as well as riverine and lacustrine alluvium that gives rise to pale colour, coarse textured and well drained light soils (Makin et al., 1975; Dainelli et al., 2001; Billi, 2002). The study area lies in a part of the MERV called lakes district, encompasses seven lakes of tectonic or volcano-tectonic origin

(Coltorti et al., 2002). Lake Ziway is separated from Lake Langano by a dormant volcano mountain range. Ziway and Langano Lakes are outwardly linked to Lake Abijata by Bulbula and Horakelo rivers. Part of Jido River, normally draining to Lake Shala, overflows during the rainy season and also joins Lake Abijata through river Gogessa (Fig. A1, in the online appendix).

Lowering of lake levels had a strong effect on the exposure of parent material, and hence on soils, vegetation and land use. The abundant literature on late Quaternary rift lake level changes was systematised by Gasse and Fontes (1989) and later reviewed by Nyssen et al. (2004). They describe high lake levels before the Last Glacial Maximum (LGM – 30,000–27,000 ^{14}C years before present - BP), low levels during the LGM (22,000–12,000 BP), after which the lake levels rose again (Fig. 1). Since 5000 BP there is a nearly continuous lake level lowering which was only interrupted by high stands between 2500 and 1500 BP (Nyssen et al., 2004).

#Fig. 1 approximately here#

2.1.4. Soils

In most places in the study area, soils derived from volcanic ash are observed. Mostly the ash has been reworked and occurs as lacustrine sediment. Local outcrops of cemented lapilli tuff (as documented by Coltorti et al., 2002) have a preferred occurrence at an elevation of 1600-1610 m a.s.l. allowing to correlate this lacustrine terrace (Dainelli et al., 2001) with the last relatively high lake level (2200 to 1600 BP, see Fig. 1).

The lake deposits of different ages are interbedded with pumice and classified as Andosols. They are coarse textured (loamy sand to fine sand), highly alkaline (pH of 7.6-8.2) especially where high ionic strength has caused a precipitation of calcium carbonate. Their low bulk density and hence weaker structure render them vulnerable to wind and water erosion. The soils generally have low fertility and low organic matter with moderate nutrient retention capacity (Makin et al., 1975).

The extreme west of the study area (Alage campus) is however located on thick alluvium composed of reworked ignimbrites (Dainelli et al., 2001) that were deposited by Jido River. Its colour is more brownish than the lake sediment and it has a great susceptibility to gully erosion (visual observations).

2.1.5 Vegetation

The natural vegetation in most areas of this central part of the rift valley is sparse umbrella-shaped woodland, classified as Acacia-Balanites woodland (Umer and Bonnefille, 1991) (Fig. A2, in the online appendix). The woodlands surrounding the four lakes were formed as a result of lowering of the water level since 5000 BP. The main tree species include *Acacia Senegal* (L.) Willd., *A. tortilis* (Forsk.) Hay., *A. seyal* Del. and *Balanites aegyptica* (L.) Del. accompanied by some shrubs such as *Croton dichogamus* Pax., *Harisonia abyssinica* Oliv., *Terminalia brownii* Pers., *Sclerocarya birrea* (A.Rich.) Hochst. and *Acokanthera schimperi* (DC.) Oliv. with grass-dominated ground vegetation (Abdi, 1993; Eshete, 1999, Gebrekirstos et al., 2008). The woodland subsists mostly in a degraded state (Fig. A3, in the online appendix).

2.1.6. Land use and farming system

The study area is generally occupied by mostly pastoral Oromo people who came from around 100-km away highlands at both sides of the Rift Valley, as nowadays part of their dry season refuges in the better-watered highlands have been taken over for cultivation (Eshete and Ståhl, 1998). Formerly, cattle herding (sylvo-pastoralism) dominated the farming system of this area. These days, a mixed farming system that integrates cropping, fuel wood extraction and livestock (mostly cattle) is adopted in the area (agro-sylvo-pastoral system), but still herding is the main activity. Most grazing is free roaming on the vast communal grazing lands from which the lake retreated. In turn, crop production supplies crop residue as one of the basic feed sources for livestock. Farmers with no or less cattle rent out maize and sorghum fields immediately after harvest. The lessee will collect crop residues, pile it up on big trees between branches, and subsequently organize intensive grazing (Eshetu, 2003). As a consequence, it can be observed that topsoils of maize and sorghum fields are structurally destroyed and are composed of whitish fine dust.

Cattle manure is mainly used on gardens close to the homesteads, while the outfields, which will be considered in the present study, receive no manure. The major crop grown in the area is maize (*Zea mays*) which typically requires low labour input in cultivation. Other crops such as sorghum, green pepper, field pea and sweet potatoes do also occur in the area.

2.2. *Remotely sensed data and maps used*

Remote sensing data used in the research include a Landsat Multi-Spectral Scanner (MSS) from 1973, a Landsat Thematic Mapper (TM) from 1986 and Enhanced Landsat Thematic Mapper Plus (ETM+) from 2000. Satellite imagery from the same period of the year (end January, begin February) was used in this change detection study because this minimises discrepancies in reflectance caused by seasonal vegetation fluxes and sun angle differences (Bottomley, 1998). Lowest possible seasonal moisture content and lowest percent monthly cloud cover were decisive factors considered during the selection of available dataset scenes (Table 1). In addition, a quick image, a very recent (at the time of use - 2006) satellite image displayed for preview by Global Land Cover ((http://glcfapp.umiacs.umd.edu:8080/esdi/index.jsp), was used for the purpose of delineation of the recent lake boundary. Supplementary data sources used include:

topographic maps, administrative map and map of the park. Topographic map sheets at scale of 1:50 000 and 1:250 000 (EMA, 1976a,b,c, 2004) were used for boundary delineation and navigation purpose, and supported ground truthing and training site establishment.

#Table 1 approximately here#

2.3. Image Processing

Ground control points were collected for each LUC type (Table 2) at the centre of uniform LUC units (radius >100 m). Recognition of patterns in the data (training — *sensu* Mather, 1999) was performed through a supervised method in which sets of signatures that define a training sample were recognised. The signatures on the recent image that correspond to a class, and a maximum likelihood decision rule were used to assign the pixels in the image to the respective class (Gallego, 2004) whereby seven LUC classes were considered in image classification. Training sites were established for the recent image (ETM+) being supplemented by dwellers' confirmations to fill the six years gap between time of image acquisition and training site establishment. The classification of older images (MSS and TM) was based on integration of unsupervised classification and visual signature editions (ERDAS, 1999), involving the spectral values of the recent image that led us to signature collection for supervised classification. Then a class separability test was performed to evaluate the significance of difference (degree of separability) between LUC classes (Bottomley, 1998). We used the supervised maximum likelihood classification algorithm for all the images, which is generally recognised as the best classifier technique (Verbyla, 1995; Mather, 1999; Gautam et al., 2003). Maximum likelihood classification assigns a pixel to a particular class based on the higher covariance information.

Before producing the final output, the classified images were sieved, clumped and filtered. Clumping of cultivated land with trees and without trees was undertaken based on the results of the spectral separability test of ERDAS Imagine signature editor and the classified images were corrected for their isolated pixels and spatial coherence.

#Table 2 approximately here#

An accuracy assessment, determining the quality of the information derived from the remotely sensed data, was done using a separate set of 45 testing sites. An error matrix compares the relationships between known reference data (ground truth) and the corresponding classification results (Lillesand and Kiefer, 2000) and comprises overall accuracy, users' accuracy (the probability that a LUC class identified on the map is classified into the same category on the ground), and producer's accuracy (the probability that a LUC class identified on the ground is classified into the same category on the map) (Campbell, 2002).

2.4. LUCC analysis and pattern detection

The classified images were vectorised and exported to Arc Info GIS software version 3.52, where change matrices among the three LUC maps were established. Based on the matrices, patterns of degradation or succession were thoroughly investigated and compared between the study periods.

3. Results and discussion

3.1 Land use and cover classification

On the basis of the temporal and spatial data sets acquired LUC maps of the study area were prepared for 1973, 1986 and 2000 (Fig. 2, Table 3).

#Fig. 2 approximately here#

#Table 3 approximately here#

The classification accuracy was assessed for the recent image (2000) with an overall accuracy level of 73.8 % (Table 4). The lowest user accuracy of 25 % was registered for the barren land class, which is attributed to the land emergence, since the lake showed a 46% reduction between 2000 and 2006.

 # Table 4 approximately here#

In 1973 the highest proportion was covered by the lake (31 %). About one fourth of the study area was covered by sparse and heavily grazed woodland which became the greatest cover in 1986 (31 %). The vast lake retreat area, which was subjected to long term ecological succession, had due contribution for grazing land accounting 20 % of the total area in 1973. The dense woodland including protected woodlands for various development activities was estimated at 12% in 1973 and increased by 5 % at 1986. In 2000, however, the dense woodland has decreased to one third of its 1986 area (7 %). The LUC classes with smaller area throughout the study period are broad-leaved forest and cultivated land. The cultivated land cover recorded for 1973 was only 3 %. This is mainly attributed to the farming system of the community which is more focused on cattle rearing than cropping (Eshetu, 2003). In addition, the impact of Lakes Abijata and Langano makes the large newly emerged areas of land salt affected and crusted by calcium sulphate (which could be visually inferred from Landsat MSS image whereby the lake retreat mark is conspicuously detected). Thereby, the soil is left with low organic carbon and hence low water holding capacity, infiltration and soil fertility. Furthermore, it is also possible that wooded cropland might have been classified to woodland and some very shiny and bright agricultural land could have been misclassified as barren land during image classification. This is suggested by the observation that, immediately after harvest, agricultural fields are subjected to intensive grazing and left exposed and dusty.

The second part of the study period shows a pattern of land use changes that is very different from the first period (Table 3, last columns). In 1973-1986, increases in woodland and decrease of barren land are indicators of ecological succession, whereas in 1986, LUCC tendencies are totally reversed, indicating increased human impact.

Changes in soil organic carbon (SOC) stock in the study area follow a similar trend: on average, it was assessed that there was 3966 (±1799) g m^{-2} SOC in 2000, against 4319 (±1835) g m^{-2} in 1986 and 4199 (±1866) g m^{-2} in 1973 (Nyssen et al., 2008).

3.3. Current lake retreat

Although LUC maps show that Lake Abijata's area decreased by 5.6 % between 1973 and 1986, no change was registered from 1986-2000. This interruption in the general trend of lake level lowering could be due to the increased runoff coefficient resulting from decreased vegetation cover between 1986 and 2000. Supplemental information extracted from a quick image shows however a dramatic reduction by 46.5% between 2000 and 2006 (Fig. 3). Similar figures are mentioned in a separate study by Jansen et al. (2007).

#Fig. 3 approximately here#

#Fig. 4 approximately here#

A study of old maps by Billi (2002) concluded that, at current retreat rate, within less than 100 years L. Abijata will be totally dry. This projection could be reduced by more than half based on the retreat rate observed between 2000 and 2006. Legesse et al. (2004) modelled explanatory factors for lake retreat. Sometimes the Soda Ash factory is blamed for pumping an excessive amount of water (Gebre-mariam, 1998). Nevertheless, factory officials pointed to two basic reasons: the decreased discharge of Bulbula River (overflow of Lake Ziway into Lake Abijata) as Lake Ziway's water is increasingly used for irrigation, and underground flow to Lake Shala.

Although it calls for investigation and is not new to this period, the probability of Lake Abijata infiltrating to the less elevated Lake Shala is also supported by Billi (2002). Discussions with farmers again point to the decreased discharge of Bulbula River, which is in accordance with observed large expansion of irrigated agriculture including vastly expanding floriculture on Lake Ziway's shore.

Observed rainfall reduction (Fig. 4), water pumping for soda ash production and especially abstraction for irrigation in the upper catchment around Lake Ziway are three recent developments that concur in lowering the lake level.

#Table 5 approximately here#

3.3. Land use and cover changes

The change matrix (Table 5) shows that broad-leaved forest increased by 0.6 % during the first period (1973- 1986) and decreased by 0.7 % during the second period (1986-2000) when it was basically changed to protected woodland (40 %), grazed woodland (35 %) and cultivated land (11 %). Field observations and discussions with local people showed that the change of broad-leaved forest to protected woodland by 40% is due to the thinning of the broadleaved forest through removal of some of the big ficus trees for lumber that created a woodland structure and species composition similar to that of the protected woodland class. This land cover class mainly exists around Alage. Own observations and informal discussions with elders of the surroundings reveal that there was a good protection and conservation of the natural vegetation after the establishment of the "Children Amba" institution in 1980 (Alage) and it continued until the change of the government of Ethiopia in 1991. The reduction of this broad leaved forest is thus attributed to the encroachment exerted by the communities since 1991. Chuluun and Ojima

(2002) also showed that increased human population and political reforms are most outstanding basic causes of LUC change in arid and semi-arid areas of Asia.

More importantly, protected and grazed woodlands increased by 5.2 % and 4.1 % during the first period and dramatically decreased by 10.6 % and 5.8 % during the second period. The change matrix analysis shows (Table 5) that protected woodland in 1986 was mainly converted to grazed woodland (41 %), grazing land (28 %) and some to cultivated land (7 %). Likewise, grazed woodland reduction is attributed to its conversion to grazing land (33 %) and cultivated land (9 %). This implies that overgrazing and charcoal production are efficient anthropogenic agents for wood cover reduction.

Among the major land use groups, a cumulative increment of 8.6 % was registered for grazing land. An increase in the three woodland covers during the first period reduced the grazing land but this tendency was reversed in the second period (1986-2000). In the same way, cultivated land showed a net increment of 4 %. According to the informants and change matrix analysis, this was obviously due to the conversion of woodland (34 %) and grazing lands (39 %) to cultivated land.

In both periods, the apparently random conversion of most of the cultivated land to other land uses should not surprise, as shifting cultivation is a common practice in the area, whereby established fields are abandoned for longer periods during which ecological succession is allowed to take over.

Generally, a net area reduction is observed for woodland. This is thought to be due to: (1) the failure of the strength of institutions in the study area in conserving the protected woodlands which started during the transition period (1991/92) of “Derg” regime to the present government, (2) an increase in human and subsequently in cattle population and (3) charcoal extraction (Eshetu, 2003). Investigations by Muttitanon and Tripathi (2005) in the coastal zone of Ban Don

Bay (Thailand) show that institutional and political change greatly affects sustainable resources management. In the study area, intense conflicts over boundaries between the Oromo people and bordering diverse ethnic groups of the Southern Peoples' Regional state have also resulted in weak implementation of land management policies by authorities at different levels.

3.4 Patterns of land use and cover change (ecological succession versus land degradation)

Two different patterns of change were distinguished in the study period: (1) increased areas of woody vegetation land classes and decreased barren land areas during the first study period, implying that there was an ecological succession during that period, and (2) a reduction in area of woody vegetation and an increase in barren land were observed in the second study period. Ecological succession, which is an orderly process of vegetation development, is reasonably directional and, therefore, predictable (Odum, 1971). In this perspective, the grass community development on the barren lake retreat area can easily be visualised from false colour composite displays of 1973 to 1986. Similarly, statistics of change analysis between 1973 and 1986 reveal that barren land coverage shrunk from 7 % in 1973 to 4 % in 1986 and succeeding sparse wood and shrubland consumed 41 % of the grazing land (Fig. A4, in the online appendix).

The ecological succession that took place on emerged lands (in a horizontal dimension, from old to recent images: emerged bare land, grassland, land with few scattered Acacia shrubs and open woodland) corresponds to a situation where the ecosystem is strongly zoned along an environmental gradient (Watt, 1947; Shugart et al., 1988), in this case the retreating lake.

The incidental increasing successional trend from 1973 to 1986 was shown to be hampered during the next period and even up to date (1986-2000/2006). As a result of LUCC indicated above, the three wood based classes significantly decreased during this period implying that deforestation had substantial contribution to land degradation (Haile and Gebre-Hiwot, 2002).

More evidently, substantial proportions of grazing land gain were observed at the expense of woody vegetation through deforestation. Secondly, at constant lake size, 2.5 % gain was registered for barren land which is most certainly attributed to the impact of overgrazing whereby grazing land is reconverted to barren land. Third, although it was less important during 1973-1986, throughout the study period, cultivated land was increased; by 3.2 % during 1986-2000. Thus, agricultural expansion has an obvious contribution for hampering ecological succession. Informants around ASLNP headquarters confirmed that besides agricultural expansion, woodland deforestation is due to increased fuelwood (firewood and charcoal) sale to the nearby towns, which is spurred by the increasing consumption of fuelwood to produce "katikala", a local alcohol, in view of its demanding market at Arisi Negele and other towns including Addis Ababa.

3.5 Drivers of land use and cover changes

As the summarised results show (Table 5), during the period between 1973 and 1986, woody vegetation cover and grazing land increased with subsequent reduction of barren land. This implies that there was an ecological succession following lake retreat. Discussions with elders showed that the major underlying cause for the observed succession during the aforementioned period was attributed to the better environmental protection and sparse population density during the "Derg" regime period, as also demonstrated by Reid et al. (2000).

In contrast, a reduction of woody vegetation cover and an increase in cultivated land and barren land were observed between 1986 and 2000 (Table 3). Discussions with elders and experts of three institutions in the study area (Alage Agricultural Vocational Training College, Abernosa Cattle Ranch and Abijata Shala Lakes National Park) confirmed that the basic underlying causes of the changes are anthropogenic, particularly deforestation and overgrazing rather than climatic catastrophe.

Technological progress of the recent period which adopted improved agricultural inputs attracted the community to practice agriculture more widely and to extensively work with irrigated agriculture which exacerbated the lowering of Lake Abijata, as was also found by Jansen et al. (2007). These could result from accessibility of the area and betterment of infrastructure as modelled by Serneels and Lambin (2001) in Kenya, Narok District. Their model explained that spatial determinants (driving forces) prevail to explain the spatial distribution of different LUCC processes.

4. Conclusions

The LUCC observed are the cumulative effect of the interactions between social and environmental factors conditioned by the prevailing subsequent socio-economic changes that took place in the area. The pattern of changes notably differs between 1973-1986 and 1986-2000, being governed by the intensity of protection exerted before and after 1991, which marks the change in government in Ethiopia. Ecological succession took place between 1973 and 1986 on emerged lands in a horizontal dimension from old to recent image: emerged bare land, grassland, land with few scattered Acacia shrubs and open woodlands., However, overgrazing and deforestation for fuelwood production and cultivation have contributed to the degradation of vegetated areas since 1986. The continued deforestation of the vegetated areas in the study area, like other areas in the country, adversely affects the LUC and biodiversity resources. In light of the findings of this study the following issues are recommended for further investigation and also to be noted by policy makers and land use planners:

1. Despite their significance for sustainable land resources management and planning, LUCC detections of Ethiopia have only been performed in a patchy form in space and time. Thus, sustainable development planning entails the spatial and temporal LUCC detection of the country.

2. Both ecological succession and land degradation are pointed out in this study as being governed by human activities and political reformation. However, ecological succession in the MERV has been overtaken by land degradation since 1986, which obliges for rehabilitation interventions.

3. Succession progress on lake retreat areas involves stunted *Acacia* plants (Fig. A4, in the online appendix), which are accompanied by aeolian deposits on the leeward side (Kocurek and Nielson, 1986; Bristow et al., 2000). Ways of using vegetation to decrease the prevailing wind erosion in the area need to be investigated.

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Tables

Table 1. Satellite images used in LUCC detection

Satellite instrument	No. of bands	Ground resolution	Acquisition date	path/row
Landsat MSS	4	57 m * 57 m	31/01/1973	181/055
Landsat TM	7	28.5 m * 28.5 m	21/01/1986	168/055
Landsat Enhanced TM+	7	28.5 m * 28.5 m	05/02/2000	168/055

Table 2. LUC categories with number of GCPs used to establish the signature on the 2000 image

Land cover/ land use	General description	No. of GCPs
Broad-leaved forest	Areas dominated by broad-leaved trees including artificial plantation areas (mainly in and around Alage TVET college).	4
Protected / dense woodland	Areas covered by woody plants (*Acacia*-dominated), with an undergrowth of grasses and shrubs. It may have a status of closed to semi-open canopy (mainly in Abernosa cattle ranch, ASLNP headquarter and Alage TVET college)	6
Grazed woodland and shrubland	Areas covered with sparse woody plants (*Acacia*-dominated), whose undergrowth is heavily grazed. It includes also shrubland covered with small trees, bushes and shrubs	6
Cultivated land	Areas of land prepared for growing rainfed crops. This category includes areas currently under crop, fallow, and recently cleared land for cultivation; broadly spaced trees may occur	8
Grazing land	Areas covered with natural pasture dominated by grasses; this class may also include small shrubs	6
Barren land	Areas of land without vegetation, either due to erosion and overgrazing or due to recent emergence	3
Water bodies and wetlands	Includes the lake, intermittent ponds, and other areas with shallow water	3

Table 3. Distribution of LUC in 1973, 1986 and 2000

LUC type	1973		1986		2000		LUCC (%)		
	Area (ha)	(%)	Area (ha)	(%)	Area (ha)	(%)	1973-1986	1986-2000	1973-2000
Broad-leaved forest	379	0.6	755	1.2	302	0.5	+0.6	-0.7	-0.1
Protected / dense woodland	7696	12	10962	17	4183	7	+5.2	-10.6	-5.5
Grazed woodland and shrubland	16906	26	19488	31	15822	25	+4.1	-5.8	-1.7
Cultivated land	2023	3	2538	4	4602	7	+0.8	+3.2	+4.1
Grazing land	12713	20	11210	18	18156	28	-2.3	+10.9	+8.6
Barren land	4293	7	2560	4	4180	7	-2.7	+2.5	-0.2
Water bodies and wetlands	19855	31	16232	25	16506	26[a]	-5.6	+0.4	-5.2

[a] Including three small reservoirs existing at Alage

Table 4. Summary of the accuracy assessment

Classified data	Producer accuracy (%)	Users' accuracy (%)	Overall accuracy (%)
Unclassified	-	-	73.8
Broad-leaved forest	75.0	100	
Protected/dense woodland	66.6	80.0	
Grazed woodland	66.7	66.6	
Cultivated land	77.7	100	
Grazing land	71.4	62.5	
Barren land	50.0	25.0	
Water bodies and wetlands	100	83..3	

Table 5. LUCC matrix between the three LUC maps (1973, 1986 and 2000) (in %)

1986 1973	Broad-leaved forest	Protected/ dense woodland	Grazed woodland	Cultivated land	Grazing land	Barren land	Lake and wetlands
Broad-leaved forest	34	39	17	4	1	0	5
Protected/ dense woodland	3	56	36	3	1	0	0
Grazed woodland	0	30	61	4	4	0	0
Cultivated land	1	11	53	16	16	3	0
Grazing land	0	6	41	7	45	1	0
Barren land	0	0	4	6	78	13	0
Lake and wetlands	1	2	0	0	6	9	81

2000 1986	Broad-leaved forest	Protected/ dense woodland	Grazed woodland	Cultivated land	Grazing land	Barren land	Lake and wetlands
Broad-leaved forest	10	40	35	11	3	1	0
Protected/ dense woodland	1	22	41	7	28	1	0
Grazed woodland	0	6	51	9	33	1	0
Cultivated land	1	6	22	27	32	11	0
Grazing land	0	1	3	10	69	16	1
Barren land	0	3	2	12	9	72	3
Lake and wetlands	0	0	0	0	0	0	100

2000 1973	Broad-leaved forest	Protected/ dense woodland	Grazed woodland	Cultivated land	Grazing land	Barren land	Lake and wetlands
Broad-leaved forest	23	64	23	11	4	2	1
Protected/ dense woodland	2	22	59	9	14	1	0
Grazed woodland	0	9	51	9	30	1	0
Cultivated land	0	7	27	19	40	7	0
Grazing land	0	2	10	9	71	5	0
Barren land	0	3	2	10	42	33	0
Lake and wetlands	0	1	1	2	4	8	83

Figure captions

Fig. 1. Levels of Ziway-Shala lakes during the Holocene. The x-axis represents the age (in 10^3 years BP); the y-axis is the elevation of the lake level (in m above the present level of Lake Shala). Reprinted from Gasse (1998), with permission from IAHS Press.

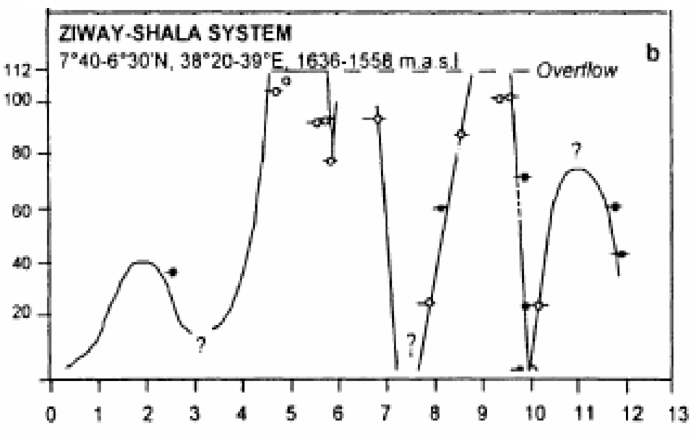
Fig. 2. LUCC in the study area between 1973 and 2000. Numerous linear features, more or less parallel to the shore of Lake Abijata correspond to successive shore lines during the lake's regression.

Fig. 3. Area of Lake Abijata as obtained from satellite imagery. Data for 2006 are from a quick image of January 2006 (*http://glcfapp.umiacs.umd.edu:8080/esdi/index.jsp*)

Fig. 4. Correspondence between lake area (lower curve) and yearly rainfall (Adamitullu station) with trendline (bold)

Figures

Figure 1.



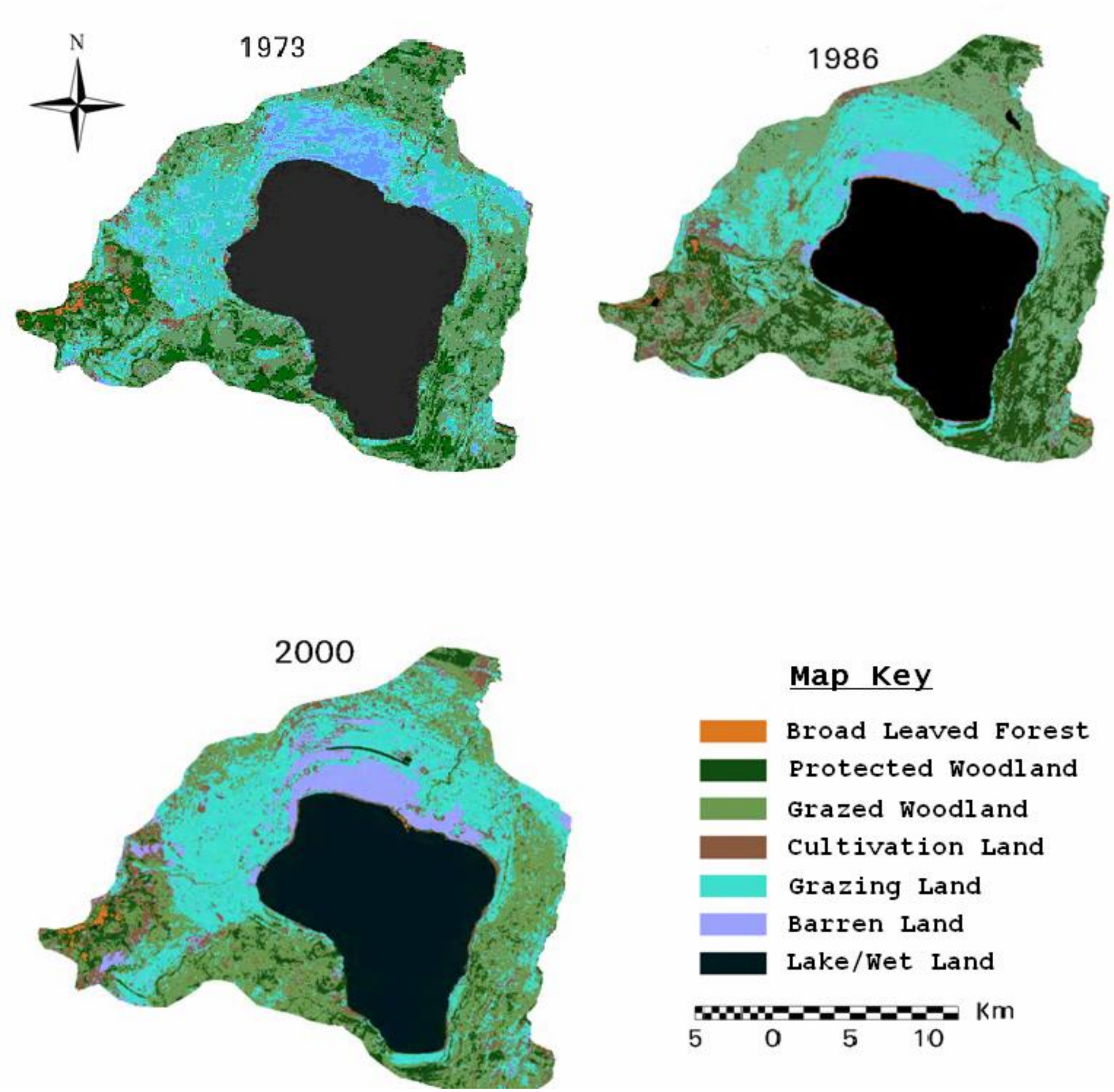

N
1973
1986
2000
Map Key
Broad Leaved Forest
Protected Woodland
Grazed Woodland
Cultivation Land
Grazing Land
Barren Land
Lake/Wet Land
Km
5
0
5
10

Figure 2.

Figure 3.

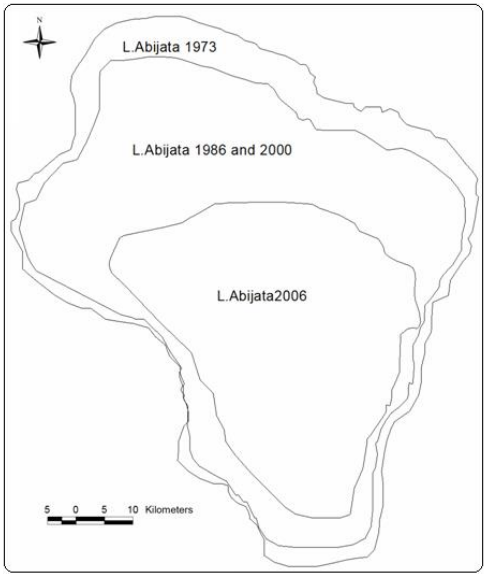
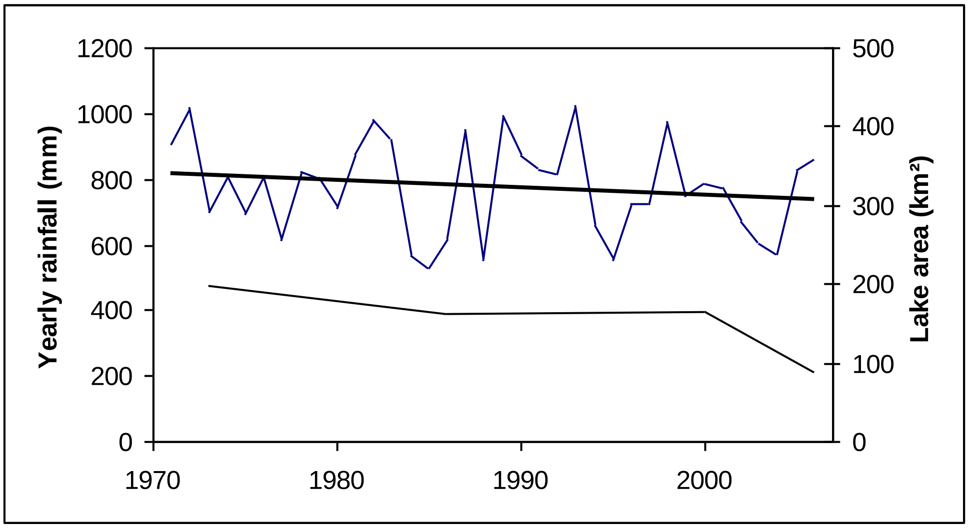

N
L.Abijata 1973
L.Abijata 1986 and 2000
L.Abijata2006
5 0 5 10 Kilometers

Figure 4.


Yearly rainfall (mm)
1200
1000
800
600
400
200
0
Lake area (km²)
500
400
300
200
100
0
1970
1980
1990
2000