Analysis of land use / land cover change dynamics and underlying driving forces in the Lake Hawassa Watershed, Ethiopia, based on satellite remote sensing, GIS and field investigations

Analyse av endringer i arealbruk/arealdekke og bakenforliggende mekanismer i nedslagsfeltet til Lake Hawassa i Etiopia, basert på satelittfjernmåling, GIS og feltundersøkelser

Philosophiae Doctor (PhD) Thesis

Nigatu Wondrade Tedo

Department of Mathematical Sciences and Technology
Faculty of Environmental Science and Technology
Norwegian University of Life Sciences

Ås 2015

Thesis number 2015:89
ISSN 1894-6402
ISBN 978-82-575-1323-8

Evaluation committee:

Dr. Thomas Schneider, Ecology and Ecosystem Management, Institute of Forest & Management
Chair for Aquatic System Biology, Technische Universität München (TUM)
Address: Hans-Carl-von-Carlowitz-Platz 2, D-85354 Freising, Germany
Phone: +49 8161 714666
E-mail: Tomi.Schneider@tum.de

Dr. Scient. Arnt-Børre Salberg, Norwegian Computing Center
Department of Statistical Analysis, Pattern Recognition and Image Analysis (SAMBA)
Address: Norsk Regnesentral, Postboks 114 Blindern, NO-0314 Oslo, Norway
Phone: +47 22 85 26 51
E-mail: Arnt-Borre.Salberg@nr.no

Associate Professor Ingunn Burud (committee coordinator)
Department of Mathematical Sciences and Technology, NMBU
Address: P.O. Box 5003 NMBU, N-1432 Ås, Norway
Phone: +4767231569 / +4740219286
E-mail: ingunn.burud@nmbu.no

Supervisors:

Prof. Øystein Bjarne Dick (main supervisor)
Geomatics section, Department of Mathematical Sciences & Technology
Faculty of Environmental Science & Technology
Norwegian University of Life Sciences, Norway

Assoc. Prof. Håvard Tveite (co-supervisor)
Geomatics section, Department of Mathematical Sciences & Technology
Faculty of Environmental Science & Technology
Norwegian University of Life Sciences, Norway

Acknowledgements

The studies reported in this thesis were carried out at the Department of Mathematical Sciences and Technology (IMT) of the Norwegian University of Life Sciences (NMBU), in the Lake Hawassa Watershed in Southern Ethiopia, and at the Department of Biosystems and Environmental Engineering of Hawassa University. The Norwegian Agency for Development Cooperation (NORAD) has financially supported this research work as part of capacity building at Hawassa University (HU), Ethiopia.

Writing a PhD thesis is a challenging task and in resolving the challenges, undoubtedly, I was not all alone. During the development of this thesis, obviously, there were many people from whom I have received advice and encouragement. In case I miss out your names, please understand that I am very grateful for your time and expertise. Let me take this opportunity to acknowledge those who were involved in the process of bringing this thesis to fruition. Most of all, I thank the Almighty God for His mercy, care and protection throughout the course of my study and for His provision of the wonderful learning and working environment at the Department of Mathematical Sciences and Technology of NMBU.

I would like to express my sincere gratitude and heartfelt thanks to my main supervisor Prof. Øystein B. Dick who gave me the opportunity to pursue my PhD study at NMBU, and then went through each step of my work: from the draft proposal to the thesis compilation, from office to the study site several thousand miles away from his working place, and from financial matters to the scientific methodologies. Without his continuous support and encouragement, it would not have been possible to reach this stage. I will always remember his words of encouragement that raised the level of my effort immensely and made my stay worthwhile. My sincere appreciation and thanks also goes to my co-supervisor, Prof. Håvard Tveite, for his dedication and time to exhaustively go through all chapters and forward critical and constructive comments. I would like to thank Josie Teurlings, PhD and Research Coordinator at NORAGRIC, for her inspiring capabilities to handle administrative matters during my entire stay in Norway. I would like to say thank you to all key informants for sharing their time and knowledge during the interviews.

I am thankful to Mr. Genene Assefa and Dr. Birhanu Abate from the sister institutions, Wondo Genet College of Forestry and Hawassa College of Agriculture, respectively for giving me the opportunity to use their equipment for the tree variable data collection. I wish to extend my sincere appreciation to Gemechu Koroso, Ababiya Geletu, and Wodamo Wodelo for their relentless assistance in the field measurement. I am personally grateful to forest guards for their support and company during the forest inventory.

I want to thank the entire IMT Department members who directly or indirectly contributed to this work. Worth mentioning are Ivar Maalen-Johansen, the first person whom I met when he came to pick me-up at the airport and drove me to Pentagon, Frode Hilmarsen, a person with an excellent integrity and always supportive in resolving challenges related to software packages used for data analysis, Mona Kristianson and Anita Habbestad who managed the financial matters during my stay at NMBU. I am also grateful to my employer, Hawassa University and

Department of Biosystems and Environmental Engineering, for granting me a study leave that enabled me to pursue the PhD program.

I would also like to acknowledge the support and encouragement of all my colleagues and friends. Special thanks go to Kennedy Were, Jan Potak, Kraniotis Dimitrios, and Karl Jacob. Life would have been difficult without the light moments I shared with you guys.

Finally, my greatest appreciation goes to my wife, Tenaye Mulatu, for her inspiration, constant support and encouragement all the way through. I find it difficult to express in words my wife's encouragement and support. Our children Senay and Luna were so special and I would like to thank them for their understanding. They all endured with cheer and patience the long hectic time I was away. I owe them more than a mere expression of thanks.

እግዝአብሔር ሆይ ለዚህ ስለአበቃኸኝ አመሰግንሀለሁ።
ኢትዮጵያንም የሚያስተምር ነቢይ፣
የሚያፅናና ካህን፣ እና
የሚመክር ሽማግሌ አታሳጣት።

Nigatu Wondrade

November, 2015

Ås

Table of contents

Summary

Lake Hawassa Watershed, in the Central Rift Valley, is one of the most environmentally vulnerable areas in Ethiopia. The rapidly increasing population and vegetation clearance in search of farming and grazing land, firewood, and construction materials have exerted pressure on the natural resources of the region. To understand the ongoing resource degradation and formulate mitigation strategies, accurate and timely information about land use land cover (LULC) changes and the driving forces is indispensable. Remote sensing and GIS are important tools for monitoring, mapping, and modelling of LULC changes at different spatial and temporal scales in order to assess the extent, direction and causes of the changes.

The present research aimed at filling the biophysical data gap in the area underrepresented by existing literature and thereby contribute knowledge to support informed decision making in sustainable resource management. Specifically, the study intended to:

(a) Classify multi-temporal image data to produce land cover (LC) maps and quantify changes that have occurred over the study period,

(b) Classify image data sets in the urban environment and extract the magnitude of built-up areas in order to quantify the rate of urban growth, test the relationship between observed and expected growth, and examine the degree of urban sprawl,

(c) Delineate forest cover using remotely sensed data for the base year 2011, estimate above ground biomass (AGB) and carbon stock using forest inventory data and allometric equations, and evaluate the diversity and dominance of species in the ecosystem, and

(d) Quantify the spatial and temporal dimensions of LULC conversions from the classified Landsat images extending over the period of 38 years, conduct key informant interviews and identify the most prominent underlying driving forces (UDFs) of LULC changes, and analyze the identified driving forces with a particular focus on LULC conversion and deforestation.

The integration of ancillary and field data, satellite remote sensing, and GIS methods enabled to derive the magnitudes and proportions of LULC types and the spatial patterns of changes over the study period (1973-2011). The results revealed that landscape transformation by humans was extensive. A set of anthropogenic biomes replaced large parts of the more recognized natural biomes offering a new view of the terrestrial biosphere. The dominant LC class was cropland, accounting for 43.6% in 1973 and 56.4% in 2011. The most affected LC classes over the study period were forest and woody vegetation, which declined by 45.3 and 35.3%, respectively. Lake Cheleleka with an area of 11.3km^2 in 1973 transformed into mud flat and grass dominated swamp, a change challenging the conservation of biodiversity. The increase in population and widespread clearance of vegetation cover, particularly in the western part, have led to severe land degradation and gully formation. More detailed information can be found in Paper I.

Monitoring, mapping, and modelling of the pattern and process of built-up areas in one of the regional capitals, Hawassa City, was performed utilizing remote sensing data and analytical models. The result of mapping exhibited that built-up area had increased by 234.5% with 9.8% annual rate of expansion between 1987 and 2011, and in absolute terms, the increase represents 8.8% of the total area. The rate of built-up area expansion more than doubled during the 1999-2011 temporal interval owing to the improvements in economic conditions. Most conversions to built-up area (33-47%) come from agricultural land. On the other hand, the output of analytical models produced higher degree-of-freedom and entropy values, indicating the disparity between observed and expected urban growth and a general tendency of sprawling of the city, respectively. In fact, a gradual improvement in the degree of sprawl was observed in the latter temporal interval as the result of infilling of open spaces that took place all over the city. Refer to Paper II for further description of the methods.

AGB and carbon stocks of forests in the Lake Hawassa Watershed were estimated using allometric models and remote sensing methods. The remote sensing analysis revealed that natural and plantation forests covered ca. 6% (8130.5ha) of the study area for the base year 2011, while the result of models indicated that the natural forest had lower mean AGB (200.9 Mg ha^{-1}) than the plantation forest (223.6 Mg ha^{-1}). The overall mean stand density was 785 stems ha^{-1} where the majority of trees belonged to the diameter at breast height class of 5–25cm, accounting for 79.1% and 73.3% in plantation and natural forests, respectively. The pantropic equations overestimated the AGB by about 13.0% and 20.5% for natural and plantation forests, correspondingly, compared to the local species-specific equations available. Importance value indices were also determined and *Cupressus lucitanica* (60.09%) was a species with the highest importance value followed by *Grevillea robusta* (28.65%) and *Eucalyptus citriodora* (20.87%). See Paper III for detailed information.

Moreover, the nature, extent, and rates of LULC conversions and UDFs of changes were derived using remote sensing methods and key informant interviews, respectively. Image analysis was extended to examine not only to differentiate changed from unchanged areas, but also to classify the changed areas according to the ''*from-to*'' identifiers using cross-tabulation matrices. The result indicated that LULC conversions were multi-directional and substantial in magnitude. Of the total area, ca. 38.2% has experienced change in LC over the study period. LC classes most affected by permanent conversions were woody vegetation, forest, and scrubland, while most conversions to cropland were from woody vegetation, forest, and grassland. The conversion of vegetation cover into other LC classes has led to environmental degradation exemplified by the desiccation of Lake Cheleleka, which is a great loss for biodiversity. Driven by the accelerating urban population, built-up area was the most dynamic process, which increased by 480.9% and grew at a rate of 12.7% per annum between 1973 and 2011. The largest proportion of land conversions to built-up area were from cropland in all temporal intervals. The assessment of key informant interviews identified demographic, low agricultural technology, institutional, economic, and biophysical factors as the major UDFs of LC conversions in the Lake Hawassa Watershed. The reader is directed to Paper IV for more information.

The current studies have generally indicated the excessive human use of the natural resources and had the biggest influence on the distribution patterns of the biophysical environment. The change mapping results achieved not only improved the understanding of the ongoing LULC change dynamics, but also gave an indication about actions to follow for sustainable management of natural resources.

Key words: Land use land cover change . urban sprawl . above ground biomass . allometric equations . importance value indices . underlying driving forces . remote sensing . GIS . Lake Hawassa Watershed

Sammendrag

Nedbørsfeltet til Lake Hawassa i Central Rift Valley, er et av de mest sårbare områdene med hensyn til miljø i Etiopia. Den raske befolkningsveksten som medfører avskoging for å dekke behovet for jordbruks- og beiteområder, ved, kull og bygningsmaterialer, har lagt press på naturressursene i regionen. For å forstå den pågående forringelsen av naturressursene og videre utforme strategier som kan begrense denne utviklingen, er det avgjørende å ha tilgang til korrekt og oppdatert informasjon om endringene i arealbruk/arealdekke (landuse/landcover-LULC) samt de faktorene som ligger til grunn for disse. Fjernmåling og GIS er viktige verktøy for overvåking, kartlegging og modellering av LULC-endringer med ulik oppløsning i rom og tid for å fastslå omfanget, retningen og årsaken til slike endringer.

Dette forskningsarbeidet har tatt sikte på å bøte på mangelen på biofysiske data slik den kommer til uttrykk gjennom det bortimot totale fravær av eksisterende litteratur relevant for det aktuelle området, for på denne måten å bidra med kunnskap til støtte for informasjonsbaserte beslutningsprosesser i en bærekraftig naturressursforvaltning. Mer spesifikt tok undersøkelsen sikte på å:

(a) Fremstille arealueknings(LC)-kart basert på klassifisering av multi-temporale bildedata, for på denne måten å kunne gi et kvantitativt uttrykk for de endringer som har skjedd i løpet av undersøkelsesperioden,

(b) (b) Klassifisere bildedatasett fra den urbane delen av området og bestemme omfanget av bebygde områder, for på denne måten å kunne kvantifisere graden av urban vekst, teste forholdet mellom observert og forventet vekst samt å undersøke graden av overdreven/ukontrollert byvekst (urban sprawl),

c) Avgrense områdene dekket av skog ved bruk av fjernmålte data for referanseåret 2011, anslå biomasse over bakken (Above Ground Biomass - AGB) og karbonlager (carbon stock) på grunnlag av feltmålinger kombinert med allometriske likninger og i tillegg vurdere biologisk mangfold og angi dominerende arter i økosystemet, og

(d) Ved hjelp av utvalgte klassifiserte Landsat satellittbilder tatt opp i løpet av et tidsrom på 38 år å gi en kvantitativ beskrivelse av de LULC endringer som har funnet sted, romlig så vel som over tid, gjennomføre intervjuer med nøkkelinformanter og finne de viktigste underliggende endringsmekanismene (underlying driving forces-UDFs) for LULC-endringer, samt å analysere de identifiserte endringsmekanismene med særlig vekt på LULC-endringer og avskoging.

Sammenstillingen av feltdata og supplerende data, fra satellitt-fjernmåling og fra GIS-baserte metoder gjorde det mulig å bestemme LULC-endringer med hensyn til både størrelse og fordeling, og dermed også å kunne gi et bilde av det romlige endringsmønsteret i løpet av det aktuelle tidsrommet for undersøkelsen (1973-2011). Resultatene viste tydelig at menneskeskapte landskapsendringer var svært omfattende. Menneskeskapte biotoper erstattet store deler av biotopene ansett som mer naturlige, noe som gir et helt nytt inntrykk av den terrestriske biosfæren. Den dominerende LC klassen var dyrket mark, som utgjorde 43,6% av arealet i 1973 og 56,4% i 2011. De mest berørte LC klassene i løpet av undersøkelsesperioden var skog og skogaktig vegetasjon, som avtok med henholdsvis 45,3% og 35,3%. Lake Cheleleka, med et areal på 11.3 km^2 i 1973, gikk over til leirslette og gressdominert myr, en endring som utfordrer bevaringen av biologisk mangfold.

Befolkningsveksten og den utbredte fjerningen av vegetasjonsdekke, spesielt i den vestlige delen, har ført til alvorlig utarming av jorda og ravinedannelse.

Overvåking, kartlegging og modellering av de prosesser som lå til grunn for utviklingsmønsteret for den bymessige bebyggelsen i en av byene i regionen, Hawassa City, ble gjennomført ved å benytte fjernmålingsdata i kombinasjon med analytiske modeller. Resultatet av kartleggingen viste at området med bymessig bebyggelse hadde hatt en økning på 234,5%, med en årlig vekstrate på 9,8% mellom 1987 og 2011, en økning som utgjør 8,8 % av det totale arealet. Graden av vekst for områder med bymessig bebyggelse ble mer enn fordoblet i løpet av tidsintervallet 1999-2011, på grunn av bedring i de økonomiske forholdene. Hoveddelen av arealkategori-endringene til bymessig bebyggelse (33-47%) er fra dyrket mark. På den annen side viste de analytiske modellene høyere frihetsgrad og høyere entropiverdier, noe som indikerer et misforhold mellom henholdsvis observert og forventet urban vekst og en generell tendens til overdreven/ukontrollert byvekst. Faktisk ble en gradvis demping av den ukontrollerte byveksten observert i det siste intervallet av undersøkelses-perioden, som følge av at det over hele byen fant sted en fortetning i form av bygging i tidligere ikke-bebygde områder.

AGB og karbonlagre i skogsområdene innenfor nedslagsfeltet til Lake Hawassa ble estimert ved bruk av allometriske modeller og fjernmålingsmetoder. Analysen av de fjernmålte dataene viste at naturlig skog og plantasje-skog til sammen dekket ca. 6% (8130.5ha) av studieområdet i referanse-året 2011, mens de benyttede modellene indikerte at den naturlige skogen hadde en lavere gjennomsnittlig AGB (200,9 Mg ha^{-1}) enn plantasje-skogen (223,6 Mg ha^{-1}). Den samlede midlere bestandstettheten var 785 stammer per hektar der flertallet av treslag tilhørte klassen med diameter i brysthøyde på 5-25cm, noe som utgjorde 79,1% og 73,3% for henholdsvis plantasjeskog og naturskog. De pantropiske ligningene overestimerte på tilsvarende måte AGB med ca. 13,0% og 20,5% for naturskog og plantasjeskog, i forhold til de tilgjengelige lokale artsspesifikke ligningene. Betydningdsverdi-indekser ble også bestemt og *Cupressus lucitanica* (60.09%) var arten med høyest betydningverdi verdi etterfulgt av *Grevillea robusta* (28.65%).

I tillegg ble LULC-endringer med hensyn til type, omfang og endringstakt samt underliggende endringsmekanismer bestemt ved hjelp av henholdsvis fjernmålingsmetoder og intervjuer med nøkkelinformanter. Bildeanalysen ble utvidet til å omfatte, ikke bare det å skille endrede fra uendrede områder, men også å klassifisere de ulike formene for "*fra-til*" endringer basert på krysstabuleringsmatriser. Resultatet indikerte at LULC-overganger gikk i flere retninger og hadde et betydelig omfang. Omlag 38,2% av det totale arealet har vært utsatt for en endring av LC i løpet av undersøkelses-perioden. De LC-klassene som i størst grad var utsatt for varige endringer var skogaktig vegetasjon, skog og kratt, mens de fleste endringene til dyrket mark var fra skogaktig vegetasjon, skog og gressdekkede områder. Endringen av vegetasjonsdekke til andre LC-klasser har ført til en forringelse av miljøet, eksemplifisert ved uttørringen av Lake Cheleleka, noe som er et betydelig tap med hensyn til biologiske mangfold. Drevet av den stadig mer økende urbane befolkningen, var endringen av bebygd areal komponenten i prosessen med størst dynamikk, med en økning på 480,9% og med en endringsgrad på 12,7% per år mellom 1973 og 2011. Den største andelen av arealkategori-endring til bebygd areal var fra jordbruksområder i alle de aktuelle tidsintervallene. Demografiske, lav-landbruksteknologiske, institusjonelle, økonomiske og biofysiske faktorer ble på grunnlag av informasjonen hentet inn gjennom intervjuer med

nøkkelinformanter, vurdert som de dominerende bakenforliggende mekanismene for LC endringene i nedslagsfeltet til Lake Hawassa.

Disse undersøkelsene har stort sett påvist hvordan overdreven bruk av naturressursene fra menneskenes side har hatt en svært stor innvirkning på utformingen av det biofysiske miljøet. Resultatene fra endringskartleggingen førte, ikke bare til en bedre forståelse av dynamikken bak den pågående endringen av landskapet, men ga og en påvisning av tiltak det vil være nødvendig å gjennomføre for å oppnå en bærekraftig forvaltning av naturressursene.

Key words: Arealbruk/arealdekke . ukontrollert byvekst . anslå biomasse over bakken . allometriske likninger . Betydningsverdi-indekser . underliggende endringsmekanismene . Fjernmåling . GIS . Nedbørsfeltet til Lake Hawassa

List of papers

This thesis is made up of four individual but interrelated papers, which are referred to in the text by the Roman numerals (I-IV).

Paper I: Wondrade, N., Dick, Ø. B., & Tveite, H. (2014). GIS based mapping of land cover changes utilizing multi-temporal remotely sensed image data in Lake Hawassa Watershed, Ethiopia. *Environmental Monitoring and Assessment*, 186(3), 1765-1780.

Paper II: Wondrade, N., Dick, Ø. B., & Tveite, H. (2014). Landscape mapping to quantify degree-of-freedom, degree-of-sprawl, and degree-of-goodness of urban growth in Hawassa, Ethiopia. *Environment and Natural Resources Research*, 4(4), 223-237.

Paper III: Wondrade, N., Dick, Ø. B., & Tveite, H. (2015). Estimating above ground biomass and carbon stock in Lake Hawassa Watershed, Ethiopia by integrating remote sensing and allometric equations. *Forest Research*, 4, 151, doi: 10.4172/2168-9776.1000151.

Paper IV: Wondrade, N., Dick, Ø. B., & Tveite, H. (2015). Analysis of land use land cover conversions and underlying driving forces: The case in the Lake Hawassa Watershed, Ethiopia. Submitted to *Kart og Plan* (under review).

List of abbreviations

AGB	Above ground biomass
AGC	Above ground carbon
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BA	Basal area
BEF	Biomass expansion factor
BoFED	Bureau of Finance and Economic Development
CORINE	Coordination of Information on the Environment
CSA	Central Statistical Agency
DBH	Diameter at breast height
DEM	Digital Elevation Model
DSH	Diameter at stump height
EMA	Ethiopian Mapping Agency
EOSDG	Earth Observing System Data Gateway
ESDI	Earth Science Data Interface
FAO	Food and Agricultural Organization of the United Nations
FCSG	Forest Cover Shrinkage Globally
FDRE	Federal Democratic Republic of Ethiopia
FF	Form factor
GCP	Ground control points
GDP	Gross Domestic Product
GIS	Geographical Information System
GLOVIS	Global Visualization
GPS	Global Positioning System
GTP	Growth and Transformation Plan
HDP	Human Dimensions Program
IGAD	Intergovernmental Authority on Development in East Africa
IGBP	International Geosphere-Biosphere Programme
IHDP	International Human Dimensions Programme
IPCC	Intergovernmental Panel on Climate Change
IRS	Indian Remote Sensing (satellite)
ISODATA	Iterative self-organizing data analysis technique
IVI	Importance value index
LC	Land Cover
LULC	Land Use and Land Cover
MP	Map Library
MEA	Millennium Ecosystem Assessment
MODIS	Moderate Resolution Imaging Spectrometer
MoRAD	Ministry of Agriculture and Rural Development

MSS	Multispectral scanner
MWUD	Ministry of Works and Urban Development
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
NORAD	Norwegian Agency for Development Cooperation
ORS	Oromiya Regional State
PLEC	People, land management and ecosystem conservation
RMSE	Root mean square error
SNNPRS	Southern Nations Nationalities and People's Regional State
SPOT	Satellite Pour l'Observation de la Terre (Satellite for Observation of Earth)
SRTM	Shuttle Radar Topographic Mission
SWB	Stem wood biomass
SWIR	Short wave infrared
TAGB	Total above ground biomass
TIR	Thermal infrared
TM	Thematic mapper
TRFIC	Tropical Rain Forest Information Center
UDF	Underlying Driving Forces
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
VOB	Volume over bark
WCED	World Commission on Environment and Development
WD	Wood density
WGCF	Wondo Genet College of Forestry
WGEORC	Wondo Genet Essential Oils Research Center
WGS	World Geodetic System
WGWSH	Wondo Genet Wabishebele Hotel
WGYPED	Wondo Genet Yanasse Participatory Forest Development
WR	World Resources
WRI	World Resources Institute
WWDSE	Water Works Design and Supervision Enterprise

1 General introduction

1.1 Land use and land cover changes

Land use and land cover (LULC) is a composite term, which includes both categories of land cover and land use. Land cover refers to the physical attributes of earth's surface, captured in the distribution of vegetation, water, soil and/or artificial structures (Moran et al. 2004; Ioannis and Meliadis 2011). It is a fundamental variable that has impact on and links many parts of the human and physical environments (Foody 2002). Land use is quite different and it expresses the purpose to which those attributes are transformed by humans; for instance, cropping, ranching, and recreation. Land use dynamics are more subtle, with a critical element in it - the human agent. Humans have always depended on nature to derive valuable resources, such as food, fuel, timber, and fresh water. Individuals, households, and firms take specific actions according to their own decision rules, driving land cover change (IGBP-IHDP 1999). However, over the last four decades, the rising human population and increasing per capita consumption of resources has resulted in widespread alteration of the earth's biosphere and atmospheric composition (Ramankutty and Foley 1999). Agricultural activities and settlements have expanded into vegetated areas (forests, woodlands, and grasslands) following the increasing demand for more resources, and this alters the native ecosystems. More land was converted to cropland in the 30 years between 1950 and 1980 than in the 150 years between 1700 and 1850 (MEA 2005), and much of this conversion occurred at the expense of forests and woodlands. Since the middle of the 20th century, land-cover change has become truly global in scale and is now occurring at rates that are unprecedented (IGBP-HDP 1993). Land cover change involves the full spectrum of alterations, from subtle changes that affect the character of the land cover without changing its overall classification (land cover modification), to complete replacement of one cover type by another (land cover conversion) (IGBP-HDP 1993; Turner II et al. 1994; Lambin and Ehrlich 1997; Lambin 1999; Lambin et al. 2003).

Change trends in the area are usually shaped by causes that may be described as episodic (changes due to fire, drought and famine), gradual (population growth and agricultural expansion), and recurring causes (regime changes) that appear intermittently and often alter the course of previous trends (Dessie and Kleman 2007). The combination of proximate causes (agricultural expansion, excessive extraction of biomass, urbanization, and overgrazing) and underlying drivers (population growth, policies, and biophysical conditions) triggers processes of habitat destruction (conversion), degradation (modification) and fragmentation which are the most important chains of events leading to worldwide species decline and extinction (Geist and Lambin 2002; Chhabra et al. 2006). Land cover change varies in space and time and does not affect all places equally. Past actions to reduce the degradation of ecosystems have yielded benefits, but the results were not comparable with growing pressures and demands. Thus, knowing the status of land cover, the rates at which the changes occur, and consequently, the way we prepare ourselves to respond to the growing land cover conversions and ecosystem degradation will create winners and losers in the change process.

1.2 Impacts of land use and land cover changes

Land use and land cover changes have been attracting increasing attention globally from both the environmental and socio-economic points of view (Rembold et al. 2000; Petit et al. 2001; Dewidar 2004; Symeonakis et al. 2006; Zak et al. 2008; Gashaw et al. 2014). Such changes have been occurring rapidly and involve large areas, especially in developing countries, and their impact on environment and welfare of people is severe. Land cover change is one of the challenges which strongly affect the process of agricultural development and food security in Ethiopia. This is a major concern, particularly in highlands which support the overwhelming majority of the population in the country.

Ethiopia is a highland country. 65% of its total area has an elevation of more than 1400 m above sea level and a substantial area is also over 3000 m (Birhanu 2014). The altitude ranges from 4620 m above sea level at the peak of Mountain Ras Dashen down to the Dallol Depression about 120 m below sea level. Major rivers, such as Blue Nile (*Abay*), Omo, and Wabi Shebele are gushing out of the country eroding top soil exacerbated by poor land use systems. The upstream land degradation is also costing downstream countries (Sudan and Egypt) from ca. USD 280 to 480 million to clear sediments every year (Selassie and Amede 2014). The Ethiopian highlands are home to more than 88-90% of Ethiopia's population, 60% of the livestock, and 90% of the agriculturally suitable area (Tefera 2006; Hurni et al. 2010). The highlands, including the current study area, are affected by land cover conversions and characterized by land degradation, erosion, and low agricultural productivity. The population growth rate of the country, about 3%, is above the rate of increase in agricultural production, resulting in a decline of food production per capita even though the gross agricultural production is actually improving (WRI 2003 cited in Hurni et al. 2007) (Fig. 1). It is estimated that over 1.9 billion tons of soil are lost from the highlands of Ethiopia per annum, the loss ranging between 5 and 300 t/ha/year depending on the land use (Selassie and Amede 2014). Deforestation is taking place at an alarming rate and accelerating LULC change. The forest cover of Ethiopia declined from 40% in 1900 to 16% in 1954, 8% in 1961, 4% in 1975, 3.2% in 1980 and now it is estimated to be less than 3% (Bekele and Berhanu 2001; Bishaw 2001; FAO 2003; Ango and Bewket 2007; Mengistu 2008; Bekele 2011; Eshetu 2013). The forest cover in the highlands of Ethiopia in 1980 was ca. 5.6%, nearly twice of the forest cover at country level (3.2%) for the same period (Yirdaw 2002). Impacts of land use and land cover change include:

- Shortage of wood and wood products for fuel and construction material
- Shortage of land, compelling the farming community to cultivate marginal and ecologically vulnerable areas such as steep hillsides and sensitive wetlands
- Potential effects on biomass burning, increasing CO_2 concentration, environmental pollution, and biodiversity loss
- Disappearance of perennial rivers and deepening of the water table
- Irregular rainfall pattern and suppression of vegetation regrowth, and
- Land degradation through erosion, nutrient loss, low agricultural productivity, and food insecurity

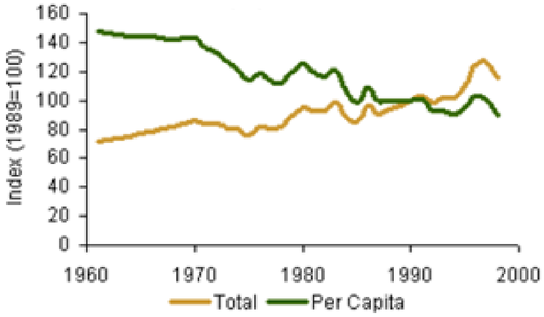


Fig. 1. Index of total and per capita food production, 1961-1998, calculated based on rising population growth rate, widespread poverty, inappropriate allocation of property rights, and government policy. (*Source: World Resource Institute 2003 cited in Hurni et al. 2007*).

In recent years, land cover changes have become a top priority research topic (Moran et al. 2004; Jianzhong et al. 2005; Imam 2011) both at national and international levels. This is manifested by the emergence of LULC change as an independent theme in global change, climate change, earth systems, and sustainability research programs (Moran et al. 2004). For example, the establishment of LULC change as a separate element of the United States Climate Change Program and the NASA-LULC change program; International Geosphere-Biosphere Program (IGBP) and International Human Dimension Program (IHDP) to understand land cover dynamics and the human dimensions on land cover, respectively. As the impacts of land cover changes increased, land cover change programs continued to gain support from international research efforts, such as DIVERSITAS (dealing with the loss of biodiversity, ecosystem services, and human well-being), Millennium Ecosystem Assessment (ecosystem changes, their causes, and their effect on human well-being), and People, Land Management and Ecosystem Conservation (PLEC) - a United Nations University Project which combines traditional knowledge and new technologies to manage land and enhance livelihoods.

1.3 Remote sensing and land cover change detection

Information about changes in a landscape can be obtained either by conventional ground observation methods or by extracting it from remotely sensed data. The conventional method, for example, the gridded mirror technique for evaluating the temporal change in forest crown density (IPCC 2003; Hussain et al. 2008; Imam 2011) is time consuming and do not provide a holistic picture. In contrast, remote sensing which is broadly defined as ''*the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation*'' (Lillesand et al. 2008), with its synoptic overview, allows independent, fast, area-wide, and relatively cost-effective transformation of image data into information (Taubenboch and Esch 2011). Here, it should be noted that extraction of the required information from remotely sensed data should be supported by field observation. Monitoring land cover from space or airborne platforms can permit repetitive observations at the required temporal interval, which makes it possible to detect changes more efficiently. The possibility of obtaining land cover information for an area that is difficult to access or totally inaccessible is an added advantage of remote sensing technology. Many studies (Nemani and Running 1995; Petit et al. 2001; Guler et al. 2007; Imam 2011; Ioannis and Meliadis 2011) have demonstrated that remote sensing is a powerful tool to detect LULC change for critical environmental areas, vegetation dynamics, and urban expansion. The first Earth observation using a captive balloon in the 1860s is regarded as an important benchmark in the history of remote sensing (Jensen 2007). Since then platforms have evolved to space stations, sensors have evolved from cameras to sophisticated scanning devices and the user base has grown from specialized cartographers to all-round disciplines (Bedru 2006). The first civilian remote sensing of the earth's surface from space at medium spatial resolutions (<250 m) began in 1972 with the launch of the Earth Resources Technology Satellite1 (Landsat) and was followed by several others, such as SPOT, IRS, EOS Terra-ASTER, among others (Campbell 1996; Rogan and Chen 2004). And since the advent of remote sensing technology, different sensors aboard aerial and space-borne platforms have detected and recorded land cover features from electromagnetic reflection and radiation from the earth's surface through advanced sensors. The recorded signals are processed to produce remotely sensed imagery. Certainly, the way data is collected, the improved data quality, the ease to access important spatial information in areas that are difficult to access, the possibility of acquiring repeated coverage of the same area that enables to observe periodical changes, and the availability of affordable computing devices that can handle large data, have prompted experts in the field to explore the use of remotely sensed data for natural resource management. The image data are further processed in a standardized fashion to ensure spatial, temporal, and spectral compatibility between scenes before being used for change detection. The increased application of remote sensing data has also contributed to the improvement of spatial resolution and radiometric sensitivity.

Although the leading remote sensing data product vendors are commercial in nature, there are several online and on request image data suppliers that provide access to imagery at a relatively low cost (Bedru 2006). These include, *inter alia*: (1) The Earth Science Data Interface (ESDI) at the Global Land Cover Facility, which provides Landsat (with the longest history and widest use for LULC change), MODIS and other derived products such as Normalized Difference Vegetation Index (NDVI); (2) Tropical Rain Forest Information Center (TRFIC), that provides Landsat and other high-resolution satellite data and digital deforestation maps; (3) The USGS Global Visualization (GLOVIS) viewer at http://glovis.usgs.gov/, which provides Landsat data, as well as ASTER and some MODIS satellite images; (4) Earth Observing System Data Gateway (EOSDG) at http://edcimswww.cr.usgs.gov/pub/-imswelcome/, provides satellite products such as AVHRR, MODIS, and ASTER; and (5) SPOT Vegetation, whose primary products are commercial, but 1km ground resolution SPOT5 products can be accessed by users at http://free.vgt.vito.be/.

The development of different algorithms (Coppin et al. 2004; Lu and Weng 2007; Chen et al. 2012; Xie et al. 2012; Hussain et al. 2013) to classify land cover types and detect changes on remotely sensed images has by and large increased the application of remote sensing techniques in LULC change research. However, given the complex nature of the land cover types and uneven occurrence of changes on the surface of the earth, searching for improved classification algorithms that could better discern thematic features is still a hot research topic. Change detection using digital imagery is complex, but attainable if quality images, appropriate classification schemes and algorithms are used.

1.4 Land use and land cover changes in the Lake Hawassa Watershed

The Lake Hawassa Watershed had undergone profound LULC change. This area and its hinterland are home for a large human population engaged in various activities which are directly or indirectly related to the well-being of the ecosystem. The Lake Hawassa Watershed has come under unprecedented pressure, ever since the beginning of 1950s (Lemma 2005). In the process, together with population growth, changes in LULC have occurred mainly due to subsistence agriculture, large-scale state farms, clearing of forests and woodlands for different purposes. Before the foundation of Hawassa town, the area was covered by forest housing a variety of wild animals (MWUD 2006; Reynolds et al. 2010). The first settlers of the area were the pastoral Sidama people. The settlers gradually became sedentary farmers for which the importance of farming increased and that exerted pressure on the immediate native ecosystem. However, accelerated LULC change began after Hawassa Town was founded in 1960 by the order of Emperor Hailesilassie (Zeleke and serkalem 2006). Commissioned soldiers and their families from various parts of the country were brought to Hawassa and were provided the first plots of land in a newly set-up village to settle on (ibid), which is believed to have given an impetus to the growth and development of the town. The rationale for the settlement of ex-soldiers and their families was to tighten security of the region and supply labor force for the new state farm which replaced the ‘Adaare’ jungle, the native ecosystem. Studies conducted in Lake Hawassa Watershed for 1965 and 1998 indicated that cultivated fields and urban areas have shown a spatial increases of 50.7 and 185.7%, respectively, while dense and open woodlands decreased by 55 and 73.8%, respectively (Ayenew and Gebreegziabher 2006).

Significant economic growth has been observed since 1994, when Hawassa became the capital of the multi-ethnic region of the SNNPRS and the Sidama Zone. This enabled Hawassa to become a major center of commerce, transportation, and information, which attracted people not only within the region, but also all over the country. As a result, the number of people living in the watershed in 1973 was estimated at 44 086 (CSA 1975), a number which increased to 1 103 507 by the year 2014 (BoFED 2014). Under the increasing pressure by human population through intensified cultivation, overgrazing, and deforestation, vegetation cover had declined and indigenous species such as ‘Weira’ (*Olea spp.*), ‘Zigba’ (*Podocarpus gracilior*), ‘Kerero’ (*Anningeria adolfi fredricii*), ‘Wanza’ (*Cordia africana*), and ‘Kawoot’ (*Celtis africana*) in the Wondo Genet escarpments are threatened. Deforestation and subsequent land degradation have expedited soil erosion causing siltation, deepening of water level, and desiccation of Lake Cheleleka. The population increase is continuing not only in urban areas, but also in peasant associations in the area. It was reported that the highest ratio of rural population to cropland in Ethiopia, 1 488 per km^2, is found in Wosha peasant association within the current study area (Yibeltal 1995).

The overstocking of saw mill and joinery enterprises and excessive extraction of timber by illegal loggers coupled with weak law enforcement have aggravated the rate of deforestation and natural resource degradation in the area. A survey result indicated that about 410 formal and 226 informal small and medium forest enterprises exist in Hawassa area (Gebremariam et al. 2009). Though several attempts have been made by the government to address natural resource degradation and forest destruction, some peasants showed a covert resistance against conservation policies/schemes manifested by deep encroachment into protected dense forests (Fig. 2c). This is because farmers, who give more priority to access to the land than to environmental protection (Nishizaki 2004; Bogale et al. 2006; Eshetu 2013), were poorly informed and/or excluded from planning and decision making processes.

Wood, wood products, bamboo, and other biomass are the major construction materials and energy sources in Ethiopia including the study area. The response of the community as the demand increases leads to biomass depletion and environmental degradation. About 74% of the housing units in the rural and 72% in the urban areas were reported to be houses with walls made of wooden materials (Wells 1995; Birhanu 2014). The excessive extraction of fuelwood (charcoal and firewood), (Fig. 2b) are the primary drivers of deforestation and subsequent land degradation, which in turn lead to soil erosion and loss of fertility. Ethiopia is one of the world’s most fuel wood reliant nations. This is because fuel wood is the dominant household energy source and it accounts for about 92-97% of the total energy consumption (FAO 2003; Sima 2011; Asfaw and Demissie 2012; Brink et al. 2014; She 2014). The consumption of fuel wood for household energy in the study area is estimated at 54, 61, 72, and 96% in Arsi, East Shewa, Bale, and Sidama Zones, respectively, where the eight districts are situated (SNNPRS 2001; ORS 2002). The first three have the lowest proportion of energy deriving from fuel wood, as these are large animal dung and crop residue consuming zones of the Oromiya Region.

Fig. 2. Anthropogenic activities: (a) large bundles of firewood collected from the forest (Photo by Scottsdale 2013), (b) charcoal put into sacks for sale after burning (Photo by Eshete 2014), (c) deep encroachment into forests to expand agricultural land (Photo by the author, 2012), (d) widespread selective cutting of trees (Photo by the author 2012), (e) crop residue transported for cattle feed (Yigrem et al. 2008), and (f) urban expansion at the expense of native ecosystem (Photo by the author 2013).

The introduction and prioritization of cash crops, such as Khat (*Catha edulis*), Sugarcane (*Saccharum officinarum*), and Coffee (*Coffea arabica*) that fetch more income than other crops per unit area (Dessie and Christiansson 2008), together with uncontrolled mining of building and road filling materials are factors that have adversely affected LULC in the area. The current status of LULC and its change patterns are, in general, the outcome of many highly-interlinked drivers including natural, socio-economic, policy, unsustainable farming practices, among others (Tefera et al. 2002; Meshesha et al. 2010). In many instances, one becomes a cause for the other and vice versa, creating a kind of vicious circle. Figure 3 illustrates this conceptualization of the links between LULC change and the major drivers.

2 What is the problem and why bother?

The increase in human and livestock population and their interaction with natural ecosystem have caused landscape changes in the lake Hawassa Watershed. Most changes to the ecosystem have been made to meet a dramatic growth in the demand for food, water, timber, fiber, and fuel (MEA 2005).

Several studies undertaken in the area have indicated that the landscape has undergone significant transformations. For instance, natural resource degradation and decline in agricultural productivity (Gashaw et al. 2014; Ango and Bewket 2007), deforestation and high conversion of vegetation cover to agricultural land (Girma and Mosandl 2012; Rembold et al. 2000), water pollution and wet land destruction (Meshesha et al. 2010; Wondafrash and Tessema 2011), and overgrazing and reduction in grassland cover (DELTA 2005). Though the growth of built-up areas could play an important role in alleviating housing problems for a rapidly growing population, urbanization has stepped-up informal settlements, the extraction of biomass, and destruction of ecological structure. If all these problems continue unabated, the life of millions of people will be at risk. Therefore, addressing these multi-faceted problems of land cover changes is essential to sustainably manage natural resources and achieve the Growth and Transformation Plan (GTP) of the country. To understanding the consequences and develop effective mitigation strategies, accurate and up-to-date data about the magnitude and rates of land cover conversions and biomass depletion is required. Such background data are poorly archived or totally lacking in the study area. We, therefore, opted for remote sensing which provides a realistic and cost-effective means of detecting land cover conversions as well as for estimating AGB and modelling urban growth status.

The current study has provided estimates of land cover change dynamics and AGB/AGC storage in the Lake Hawassa Watershed together with urban growth status in Hawassa City. This fills the data gap in an area under-represented by existing literature and contributes knowledge towards planning and natural resource management.

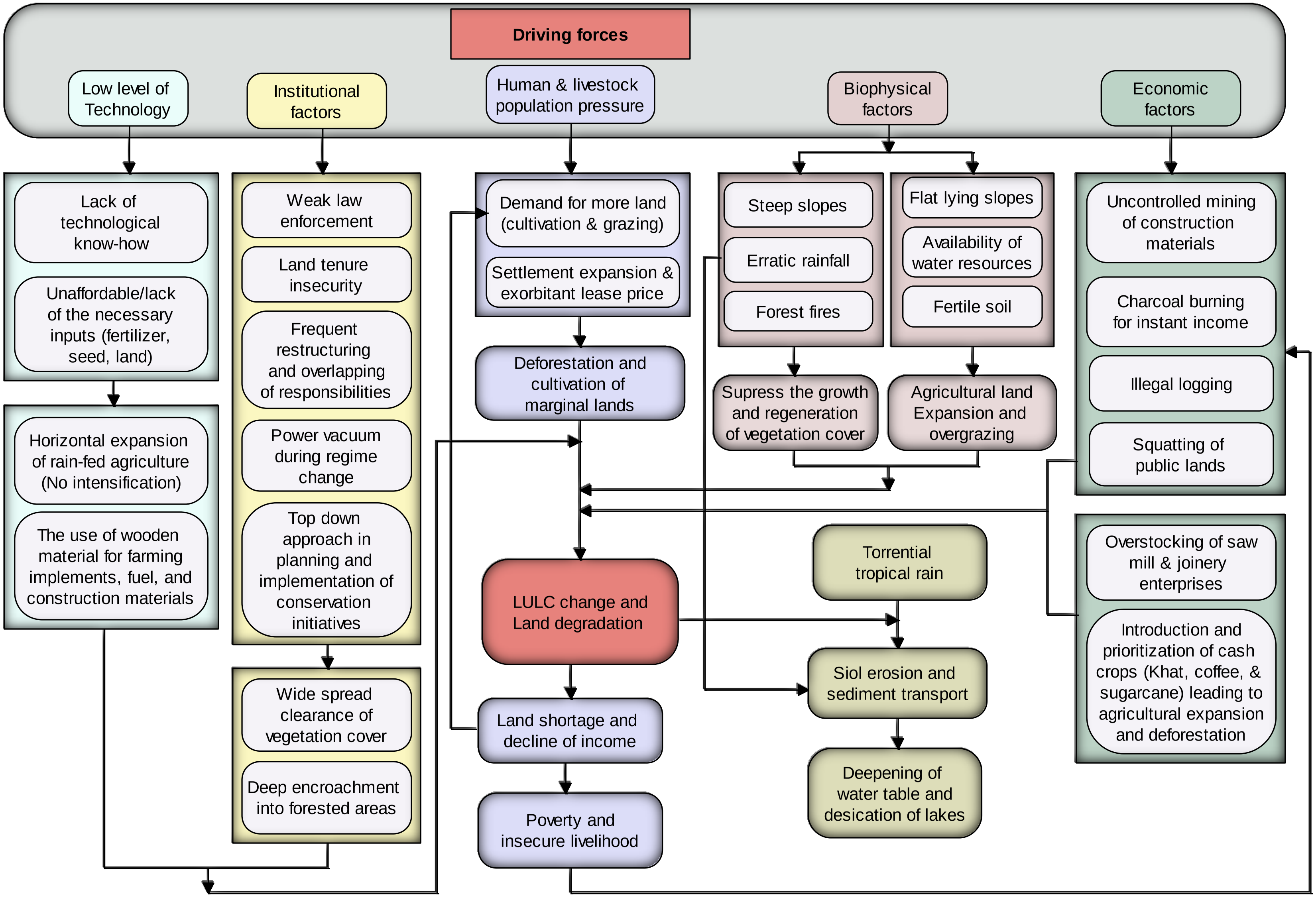


Fig. 3. Simplified representation of interaction between LULC change and the major driving forces.

2.1 Research objectives

This study aims at mapping and analyzing LULC change dynamics and underlying driving forces as the impacts of these changes are critical in the context of environmental change and consequently improve resource management planning. The specific objectives are:

1. To classify the selected image data, produce land cover maps, and quantify changes that have occurred during the study period, and disseminate the findings for further use (Paper I),
2. To analyze the classified image data and extract the proportion and magnitude of built-up areas; quantify the rate of urban growth, test the relationship between observed and expected growth, and examine the degree to which the city was sprawled using Shannon entropy (Paper II),
3. To estimate the potential AGB-Carbon in the lake Hawassa Watershed using forest cover derived from satellite image for the base year 2011, forest inventory data, and pantropic allometric equations, and to evaluate the diversity and dominance of species in the ecosystem (Paper III),
4. To quantify the spatial and temporal dimensions of LC conversions from the classified Landsat images, conduct key informant interviews and identify the most prominent Underlying Driving Forces (UDFs) of LC changes, and analyze the identified driving forces with a particular focus on LC conversions and deforestation (Paper IV).

2.2 Research questions

The research that resulted in this thesis was initiated to deal with the rapidly accelerating landscape transformations in the Lake Hawassa Watershed, raising the following research questions:

i. What are the spatial and temporal patterns, magnitudes, and rates of land cover changes that have taken place over the study period?

ii. Can remote sensing and GIS techniques detect, classify, and map land cover features using freely available multi-temporal image data sets from space-borne platforms with above 80% overall accuracy?

iii. Can a combination of coarse resolution remote sensing data from different sensors and analytical models quantify spatio-temporal urban growth and sprawl in the urban environment between 1987 and 2011?

iv. What is the AGB/AGC stock of the forest cover in the Lake Hawassa Watershed? Can we integrate remote sensing technique and pantropic allometric equations to relate tree variables obtained by non-destructive measurements to the oven dry biomass?

v. What are the prominent underlying driving forces of land cover changes in the study area? Can interviews with key informants identify the underlying driving forces?

3 Materials and methods

3.1 The study area

The Lake Hawassa Watershed is located at the border between two regional states, namely Southern Nations, Nationalities and People's Regional State and Oromiya Regional State in Ethiopia. It is situated in the Ethiopian Rift Valley floor on the main highway from Addis Ababa to Nairobi via Moyale. Its extreme coordinates are $6^{o}49'$ and $7^{o}14'$ N latitude and $38^{o}16'$ and $38^{o}44'$ E longitude (Fig. 4), covering about 1435 km^2. The topographical characteristics include *inter alia*, flat plains, gentle slopes to dissected escarpments, mountainous regions, and hilly surfaces with the altitudes ranging from 1678 to 2970 m above sea level. The mean annual rainfall is estimated at 1060 mm (Wondrade et al. 2014), but varies both spatially and temporally, ranging from 821 mm in the low land area to 1307 mm in the highlands (see Fig. 1 in paper IV). The climate of the research area is characterized by a high variation in mean minimum and maximum temperature (12.5 to 27.2^{o}C).

Lake Hawassa is a vital source of livelihood for over five million people (Ayenew and Gebreegziabher 2006) and it is one of the biggest bird sanctuaries in Ethiopia. Wondo Genet is a home to remnant montane forest and harbors a number of wild animals.

Lake Hawassa and Senkelle Swayne's Hartebeest Sanctuary located at the north-western part of the Watershed are major sources of income through tourism both at the local and national level. Most of the flat rift plains around the lakes are covered with thick lacustrine sediments and volcanoclastic quaternary deposits (Ayenew 2004). Agriculture at subsistence level is the main stay of the farming community which dictates the major land use. The western part of the areas near Lake Hawassa are highly degraded due to repeated cultivation and exposure to gully erosion. The eastern and north eastern part of the area are more stable and covered with forests and woodlands. In Ethiopia, the land is owned by the state and people cannot sell the land, but have the right to use (Crewett and Korf 2008; Garedew et al. 2009). Thus, the jurisdiction to manage forested areas is given to four institutions: Wondo Genet Yanasse Participatory Forest Development (WGYPFD) project, Wondo Genet College of Forestry (WGCF), Wondo Genet Essential Oils Research Center (WGEORC), and Wondo Genet Wabishebele Hotel (WGWSH), but all of them have not been successful in protecting the forests from destruction (Ango and Bewket 2007). The study area is one of the most densely populated regions in the country, ranging from 255.0 in the Kokosa district to 1 330 persons/km^2 in the Shebedino district for the base year 2011 (CSA 2011). The population density of the Hawassa and Shashemene cities were estimated at 1 994.5 and 11 064.7 persons /km^2, respectively for the same year (ibid). Because of the increasing population and unsustainable resource management practices, the area is experiencing rapid land cover conversion and associated problems.

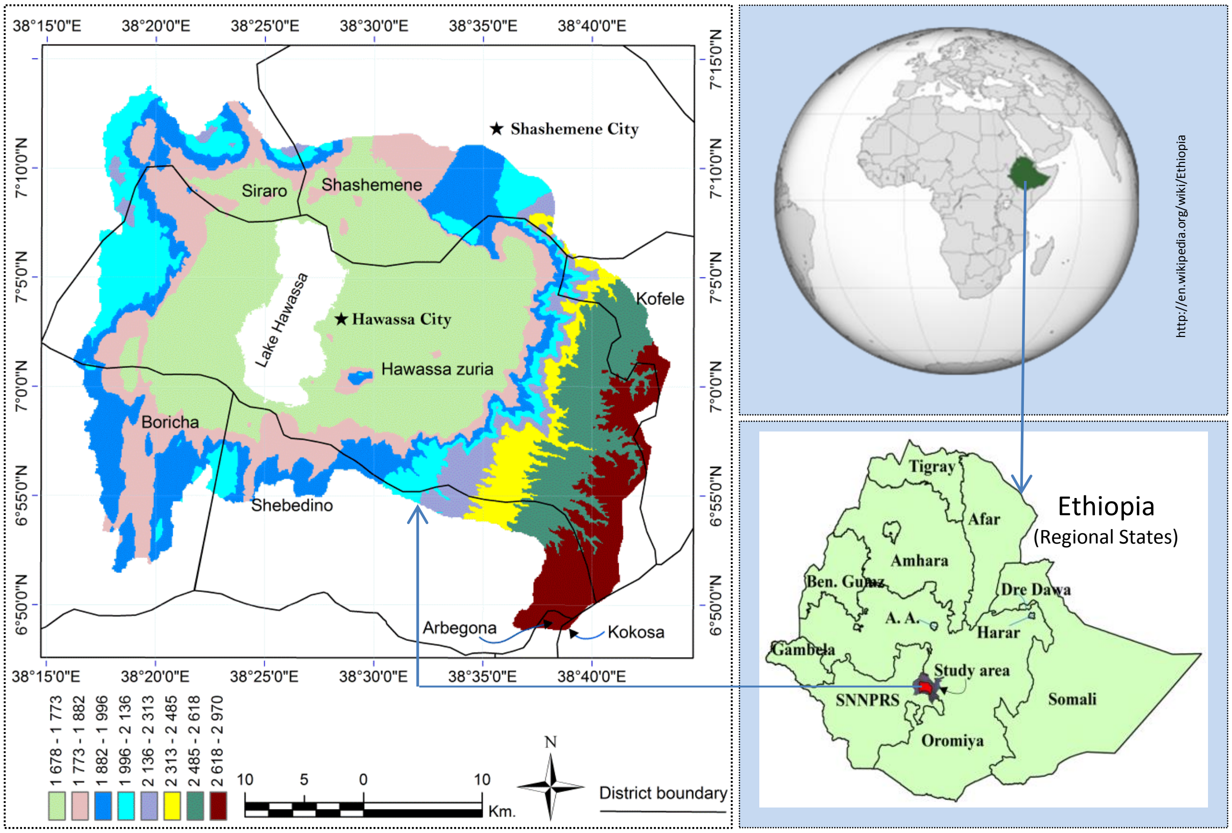


Fig. 4. Map of the study area and location of the eight districts. Graduated colors in the legend refers to elevation ranges.

3.2 Framework of the research design and input resources

Several types of input resources have been used for this research work. The data used can be subdivided into field data, remotely sensed data, and ancillary data. The data used are presented in Fig. 5.

3.2.1 Field data

Fieldwork was undertaken during the dry months of January and February 2012 to collect field data. The data collected can be grouped into three sections: (1) data for the assessment of LULC types, (2) data for the estimation of AGB, and (3) key informant interviews to identify underlying driving forces of land cover changes.

Data for the classification and accuracy assessment of LULC types: Field data to extract training pixels for classification and reference points to validate the accuracy of thematic maps were collected using a hand-held GPS device at 432 and 528 sampling locations, respectively for the Landsat imagery in 2011. The reference data were generated using stratified random sampling method in ERDAS Imagine. A map showing the location of sampling points and false color composite TM 2011 image were produced to identify the points and land cover types in the field, respectively. Some of the LULC types are given in Fig. 6. See detail LULC classes in Paper I.

Data for the estimation of AGB: Tree variables such as diameter at breast height (DBH) and total height (H) were collected during the forest inventory. The ground size of the sample plots randomly selected within the forest strata was 35 m x 35 m. The size was chosen to be comparable with the processed spatial resolution of Landsat TM images used to classify forest cover. As expected, there were topographic barriers and ethnic unrest during the fieldwork that hindered a strict adherence to the sampling plan. Eventually, a total of 48 sample plots were considered consisting of 4617 tallied stems belonging to 58 species.

The scientific names of trees were identified in the field with the support of forest technicians, while others were coded and collected in a botanical press and labelled later using books and Arboretum at Wondo Genet College of Forestry.

Key informant interviews: The key informant interviews were conducted to collect data on the possible underlying driving forces of land cover changes. The interview questions were focused on identification of the major land cover types, changes that have occurred and the possible

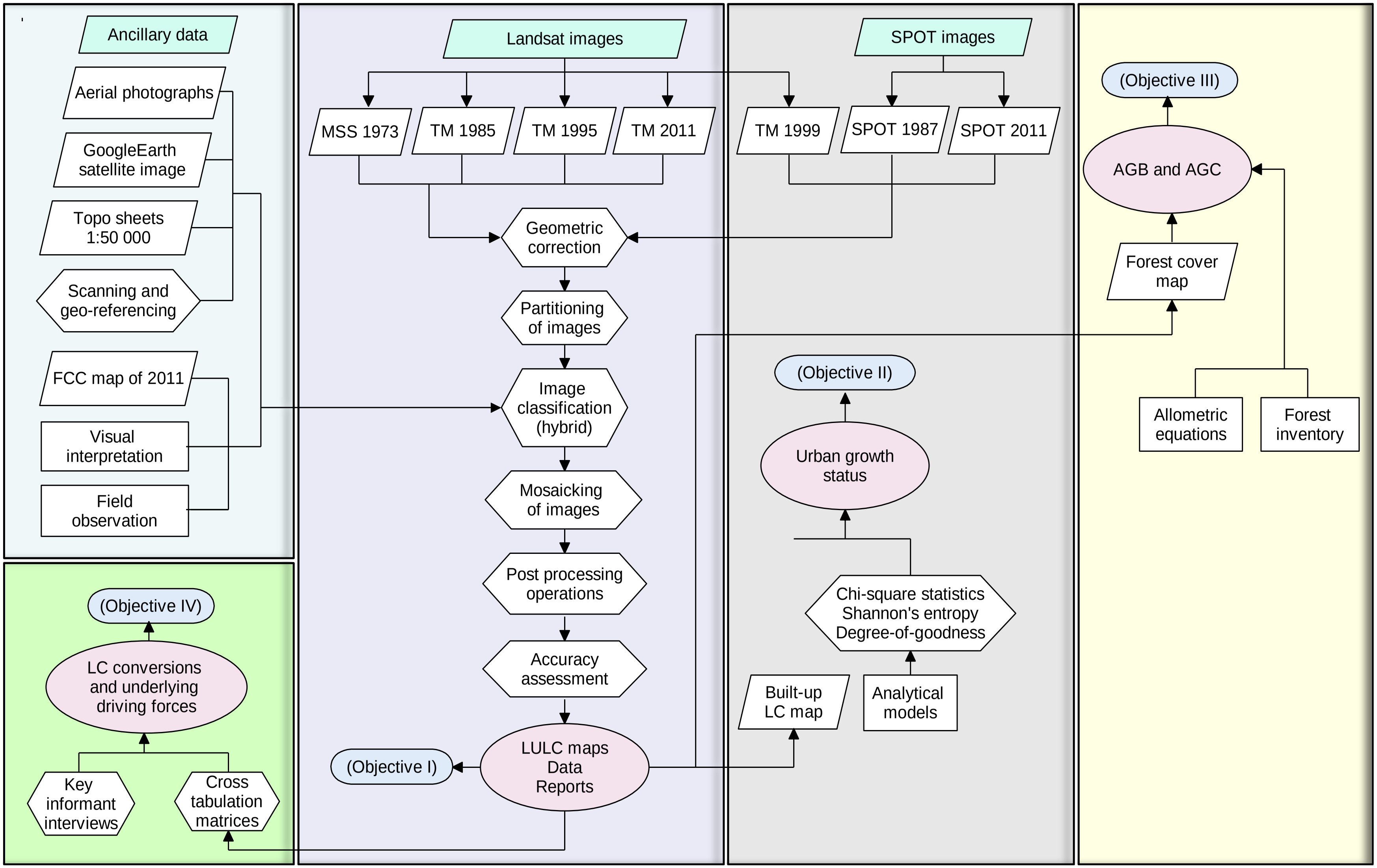


Fig. 5. Framework showing the research data and major steps pursued in the study.

causes of land cover conversions. The questions asked were composed of both open and close ended types. The question related to the possible causes of LC conversions was open ended to allow the informants to address all causative factors in their own terms. Close ended questions were prepared to prompt respondents to think and provide answers. The resulting qualitative data supplement the quantitative data obtained through remote sensing analysis. Research approaches mixed in such ways offer the best opportunities for answering important research questions (Johnson and Onwuegbuzie 2004). Interviews were done with 27 key informants, who were selected based on purposive sampling because of their knowledge of the watershed's natural resource management. The interview involved farmers, forest technicians, long serving forest guards, researchers, and experts from the bureau of agriculture, the forestry college, and the city municipality.

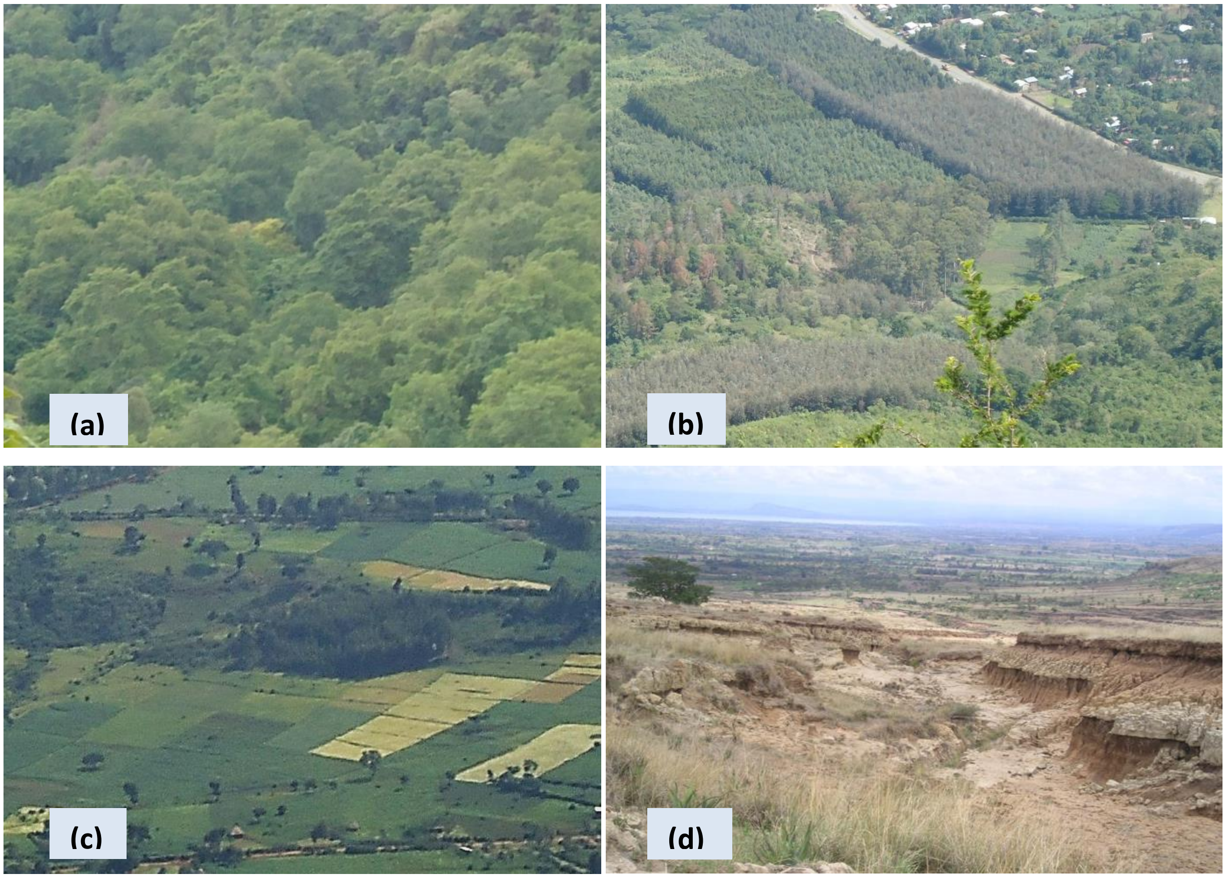


Fig. 6. Some of the LULC types: (a) Natural forest (Photo by the author 2012) , (b) Plantation forest (Photo by the author 2012), (c) Forest area converted into cropland (Photo by the author 2012), and (d) degraded land with gully formation (DELTA 2005).

3.2.2 Remotely sensed data

Remotely sensed data from Landsat and SPOT operations were used to extract LULC types for the study area. The Landsat images include: Multispectral Scanner (MSS) and Landsat 5 Thematic Mapper (TM) images acquired in 1973, 1985, 1995, 1999, and 2011, respectively. The Landsat images are downloaded from the Global Visualization Viewer (http://glovis.usgs.gov/) website, where image data sets are made available. SPOT1 and SPOT 4 images acquired in 1987 and 2011, respectively were procured from ***e-geos***, an Italian Space Agency, and the Telespazio Company. LULC conversion data were derived from a spatial overlay of successive thematic maps in ERDAS Imagine.

3.2.3 Ancillary data

Ancillary data both on raster and vector format were used for various purposes in Papers I, II, III, and IV. The ancillary data include: topographical maps, aerial photographs, Google Earth imagery (Quick Bird), and digital elevation models (DEM). Topographical maps and aerial photographs covering the study area were procured from the Ethiopian Mapping Agency (EMA). These map sheets were scanned, geo-referenced, mosaicked, and then used to register all remotely sensed data. Both the topographical maps and aerial photographs were used to validate the classified LULC maps. The vector files from the Map Library (2007) were useful to delineate and clip study area and administrative boundaries of regions, zones, districts, city, and other areas of interest. A DEM from the Shuttle Radar Topographic Mission (SRTM) was used to display the physiographic features and extract elevation data. The use of Google Earth imagery, which had a better spatial resolution than Landsat, facilitated the decision of LULC types during classification.

3.3 Methods

The study used both quantitative and qualitative research methods applicable to the selected site to answer the stated research questions.

3.3.1 GIS based mapping of land use land cover changes

Image data pre-processing: Pre-processing of image data is important to correct errors that are introduced during scanning, transmission and recording of the data (Das 2009). Particularly, pre-processing of satellite images prior to actual change detection is essential and has its unique goals-the establishment of a more direct linkage between the data and biophysical phenomena (Coppin et al. 2004). To perform pre-processing, the reflective bands are stacked into a single multi-band image excluding the thermal band. The images projected to the Universal Transverse Mercator System (UTM WGS84 Zone 37), were then geometrically corrected taking the scanned topographical maps as reference images. The subsets of corrected images were used for further analysis.

Classification scheme: Several institutions have developed classification systems for use with remote sensing data. However, there is no one ideal classification scheme that fits the land cover types and their nomenclature everywhere. Thus, the land cover classes in the study area were defined based on the specific nature of the landscape features and partly based on the Level I LULC classification system developed by Anderson et al. (1976).

Image classification: Classification was performed using a hybrid method, where spectral signatures for specific land cover classes were created using unsupervised training followed by supervised method to further discern the land cover types. Hybrid classification techniques offers more reliable and accurate results to assess land cover changes (Bakr et al. 2010). Before classification, the images were partitioned into smaller units to improve classification accuracy in the fragmented and heterogeneous African landscape. Partitioning was performed based on visually homogeneous land cover types, supported by ancillary data and knowledge of the study area. The partitioned image data were then classified and mosaicked to form the whole. The land cover types in the classified and mosaicked images were recoded to the same number of classes to produce thematic maps for 1973, 1985, 1995 and 2011 (Paper I) and 1987, 1999, and 2011 (Paper II).

Accuracy assessment: The accuracy assessment was performed using independent reference data created from aerial photographs, topographical maps, field data, and visual interpretation. One of the most common ways of representing accuracy assessment information is in the form of an error matrix or contingency table (Congalton 1991; Binaghi et al. 1999; Foody 2002). The tables produce many statistical measures of thematic accuracy including an overall accuracy, producer's accuracy, and user's accuracy. The kappa statistic, a metric that compares chance agreement between the remotely sensed classification and reference data, was also computed as a measure of thematic map accuracy.

Land cover change detection: This study applied a post-classification comparison method to perform pixel based land cover change detection analysis. Image pairs of consecutive dates were compared by overlaying thematic maps (1973-1985, 1985-1995, 1995-2011, and 1973-2011 in Paper I and 1987-1999, 1999-2011, and 1987-2011 in Paper II). To overcome the variation in pixel resolution and to enable the overlay process, the output cell size of Landsat MSS was resampled to 30m, which is the processed spatial resolution of TM images. The overlay procedure in ERDAS Imagine produced cross-tabulation matrices, which permitted to quantify changed and not changed land cover types between temporal instants over the study period.

3.2.2 Landscape mapping and modelling to quantify urban growth and sprawl

Pre-processing, classification, and accuracy assessment of images and detection of land cover types: These tasks were performed following similar procedures described in section 3.3.1. To retain the original pixel values, resampling of the Landsat image (from 1999) to match the spatial resolution of the SPOT images (from 1987 and 2011) was performed using the nearest-neighbor method. This permits overlaying and matching of images from different sensors to compare changes in LC types.

Analytical modelling of urban growth and sprawl: Remote sensing data extending over a period of 24 years were used to produce land use land cover maps. The maps identified seven LULC classes in the area under the jurisdiction of Hawassa City administration. However, built-up areas were used to quantify urban growth and sprawl. Pearson's Chi-square statistics, Shannon entropy, and Degree-of-goodness models were applied to analyze the pattern (Galster et al. 2001), process (Sarvestani et al. 2011), and overall (Bhatta et al. 2010) growth and sprawl status of the city. To apply the selected models and investigate the degree of sprawl, the built-up land cover was subdivided into eight zones (see Fig. 3 in Paper II). The subdivision was done in a circular pattern equidistant from the city center assuming that the urban areas will expand equally much in every direction from the center.

3.2.3 Estimating AGB/C by integrating remote sensing and allometric equations

Delineation of forest cover: This study characterizes the LULC, above ground biomass (AGB), and carbon status of the moist tropical forest in the Lake Hawassa Watershed, Ethiopia using remote sensing data and allometric equations for the base year 2011. Remote sensing is an effective and efficient tool in forestry studies (Roy and Ravan 1996; Kale et al. 2009), so analysis of the vegetation status and delineation of forest land cover was performed using a Landsat 5 TM image in ERDAS/ArcGIS. A brief description of the classification and production of the thematic maps is given in Paper I.

Forest inventory: The tallying of woody plants and measurement of tree variables such as diameter at breast height (DBH) and total height (H) were performed during the forest inventory. The data were recorded for all trees with DBH ≥ 5cm found in the 48 randomly selected sample plots (35 m x 35 m) within the forest strata. DBH was measured from the conventional height of 1.3 m (Shirima et al. 2011) using tree calipers and diameter tape, while individual tree height was measured using Clinometers and graduated poles.

Selection of allometric equations and estimation of AGB/C: Several allometric equations developed for moist tropical forests to estimate AGB and carbon were reviewed. The equations constructed by Chave et al. (2005) and Brown (1997) for mixed species were found to be more appropriate for describing the relationship between biomass and tree variables for natural and plantation forests, respectively. The AGB density of each tree in a sample plot, the total AGB density per plot per forest type, and the mean AGB density (t/ha) for all the sample plots was computed. The total mean was later multiplied by the total forest cover (ha) to obtain the total AGB stock in tons. Above ground carbon (AGC) was estimated with a generic assumption that 50% of terrestrial dry biomass is carbon (Martin and Thomas 2011).

Importance value index (IVI): Density, dominance and frequency, with their relative values for tree species were computed. The importance value index, calculated as a composite of these three ecological parameters following Rotaquio et al. (2007), measures different features of a species in its habitat.

3.2.4 Analysis of LULC conversions and underlying driving forces

LULC conversions: This study focuses on the magnitude and rates of land cover conversions and its causative agents. The temporal and spatial analysis of LULC conversions relied on classified Landsat images extending over 38 years. Considerable evidence is available demonstrating the use of Landsat data for investigating LC conversions (Loveland et al. 1999). To detect and quantify LULC conversions, thematic maps of successive dates were overlaid in a matrix function using ERDAS Imagine, which generates cross-tabulation matrices with systematic arrays of numbers. Each cell in the matrix contains the surface area converted from one land cover class to another and the surface area remained unchanged. Owing to unequal temporal intervals and uneven distribution of land cover conversions, the annual rates of changes in addition to the rates of changes in various temporal intervals were computed.

Underlying driving forces: Key informants interviews were conducted to identify the underlying driving forces of the LULC conversions that had been quantified using remote sensing methods. The key informants included both men (92.6%) and women (7.4%). The respondents were selected based on purposive sampling because of their specific knowledge on the topic of interest. The interviewees responded to the semi-structured list of questions, drawing on their own individual experience about the development and status of the natural resources in the Lake Hawassa Watershed ecosystem.

4 Results and discussion

4.1 GIS based spatial and temporal mapping of land cover change dynamics

The analysis of multi-temporal remotely sensed image data extracted nine distinct land cover themes in the Lake Hawassa Watershed. These were water, built-up area, cropland, woody vegetation, forest, grassland, swamp, bare land, and scrub. The overall classification accuracy of the produced thematic maps for 1973, 1985, 1995, and 2011 ranged from 82.5 to 85.0%. The achieved levels of accuracy indicated that partitioning of images into smaller units and applying a hybrid classification method was a reasonable alternative for mapping the fragmented and heterogeneous landscape of the study area. The predominant land cover class was found to be cropland, which accounted for 43.6% in 1973 and increased to 56.4% in 2011 (Fig. 7). This finding corroborates other studies performed in the region (Tadele and Forch 2007; Garedew et al. 2009), country (Zeleke and Hurni 2001; Ali et al. 2011), and Sub-Saharan Africa (Brink and Eva 2009; Bernard et al. 2010). Woody vegetation and forest, which covered 21.0 and 10.3% of the area in 1973, respectively, diminished to 13.6 and 5.6% in 2011.

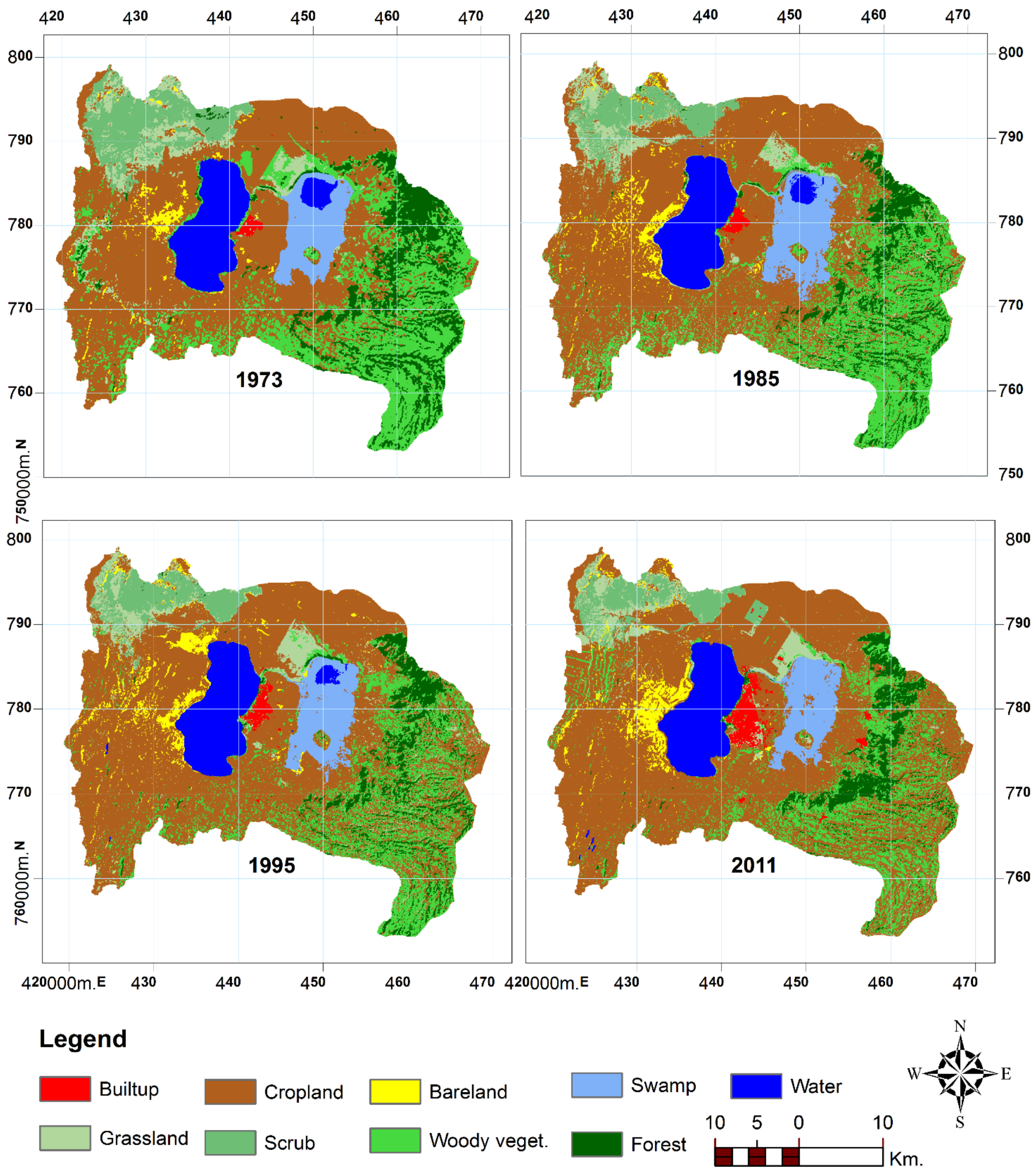


Fig. 7. Land cover maps of the Lake Hawassa Watershed.

The results revealed that cropland, woody vegetation, and forest had the highest magnitudes of change over the entire study period (Table 1). The results in Table 1 reveals a clear picture of LULC changes in space and time. The built-up area expanded more than fivefold compared to the original surface area coverage. The expansion of cropland and built-up area, and the rapid decline of the native ecosystem (woodland and forest cover) highlights the impact of anthropogenic activities.

Globally wetlands are among the most threatened ecosystems by uncontrolled and unsustainable human intervention (Hardlife et al. 2014). In the study area, wetlands were one of the most affected landscape features. Lake Cheleleka as part of the wetland, which covered about 11.3km^2 in 1973, had totally vanished in 2011. The streams emerging from the surrounding hills converge and drain into the Lake Cheleleka. Overflow from Lake Cheleleka drains into Lake Hawassa through Tikur Wuha River.

Wetlands play a major role in flood control, sediment trapping, and shore line stabilization. When Lake Cheleleka is filled with sediments and transformed into a mud flat and grass land due to extensive deforestation and subsequent increased run-off (Ayenew 2004; Ayenew and Gebreegziabher 2006), it destabilized the Lake level. The analysis revealed that the surface area of Lake Hawassa has increased by about 3.5km^2 between 1973 and 2011 (Wondrade et al. 2014).

Table 1. Magnitudes and changes of land cover classes.

LC class	Spatial coverage (km^2)				Change between two dates (km^2)			
	1973	1985	1995	2011	73-85	85-95	95-11	73-11
Water	103.3	101.5	100.3	95.8	-1.8	-1.2	-4.5	-7.5
Built-up	4.2	5.8	8.6	24.6	1.6	2.8	16.0	20.4
Cropland	625.3	699.7	766.7	809.1	74.4	67	42.4	183.8
Woody veg.	301.1	275.8	218.7	194.9	-25.3	-57.1	-23.8	-106.2
Forest	148.0	102.5	93.2	81.0	-45.5	-9.3	-12.2	-67.0
Grassland	71.8	78.2	73.8	65.8	6.4	-4.4	-8.0	-6.0
Swamp	67.8	77.3	70.7	64.2	9.5	-6.6	-6.5	-3.6
Bare land	18.1	28.4	42.1	39.9	10.3	13.7	-2.2	21.8
Scrub	95.2	66.5	61.7	60.5	-28.7	-4.8	-1.2	-34.7

The scrubland sheltering Swayne's Hartebeest Sanctuary, is one of the protected areas in Ethiopia (Nishizaki 2004). It was established in 1976 to protect the endangered Swayne's Hartebeest (*Alcelaphus buselaphus swaynei*) (Gebre and Yirga 2004). Since then, cutting trees, grazing, hunting, and clearing for farm land have been legally prohibited. However, due to illegal settlement, extraction of wood, grazing, and farm encroachment, the scrubland cover has diminished from 95.2 to 60.5km^2 over the study period.

The use of inexpensive remote sensing data, partitioning of the images, and applying a hybrid classification method to quantify LULC changes, have shown a promising potential for successful mapping and quantification of land cover change dynamics in a fragmented and heterogeneous landscape. The quantified land cover change data are in turn useful for decision support systems in natural resource management and sustainable development.

4.2 Mapping urban land cover and quantifying built-up area growth and sprawl status

4.2.1 Classification results

The spatial analysis of SPOT and Landsat images discriminated seven land cover types in the Hawassa City Administration between 1987 and 2011. The classification of land cover classes was aimed mainly at extracting built-up land cover. The following classes were extracted: built-up area, water, agriculture, vegetation, grassland, swamp, and bare land. To judge the applicability of the hybrid classification method, accuracy assessment was performed and the overall accuracies were all above 85%, a cutoff for acceptable results (Congalton and Green 2009). In this study, agriculture was the most predominant land cover in all temporal instants, accounting for about 60% of the total area. This was in agreement with the report that the Hawassa City was established in 1960 to accommodate people working in the nearby state farms (Zeleke and Serkalem 2006), and gradually some part of the farm has been appended to the city. Particularly, the recent redefinition of the city boundary to exceed the built-up area, envisaging the growing demand of land for residential and industrial areas have inflated the spatial coverage of agricultural land. It was estimated that agricultural land had grown at a rate of 4% over the entire study period at the expense of vegetation cover and marginal lands. Agricultural land has lost significant amount of its area to built-up land cover. Built-up area increased by 234.5% from 1987 to 2011 (Fig. 8).

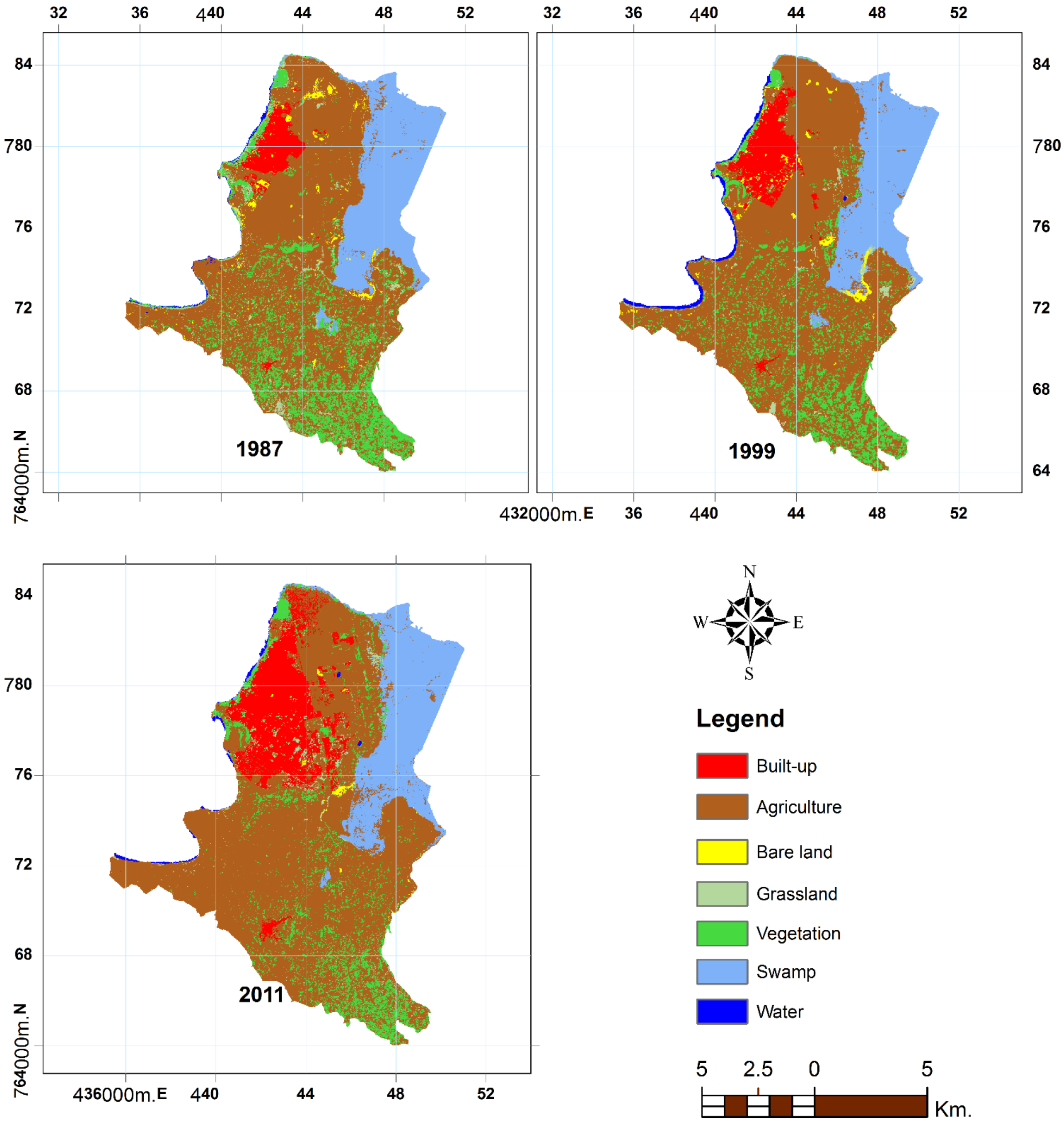


Fig. 8. Thematic maps of the redefined urban area.

Most conversions to built-up areas come from agricultural land, about 33% and 47% during the 1987-1999 and 1999-2011 temporal intervals, respectively. Summary of the land cover types and their magnitudes are depicted in Fig. 9.

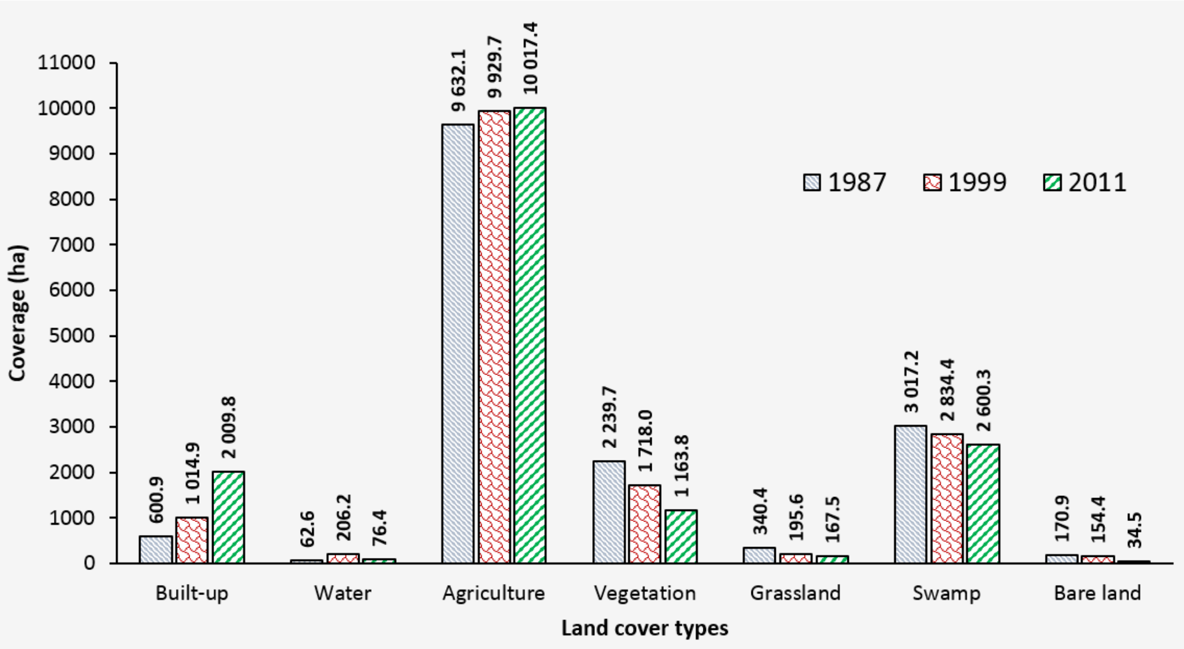


Fig. 9. Magnitudes of the established land cover types.

The generated maps and the radar chart indicated that the expansion of built-up area was skewed to the eastern side of the N-S line due to topographic barriers, such as lakes, hills and area closure for mechanized farms (Fig. 10). The policy on farm closure around the city has now changed and most of the farmlands are being used for infrastructure development.

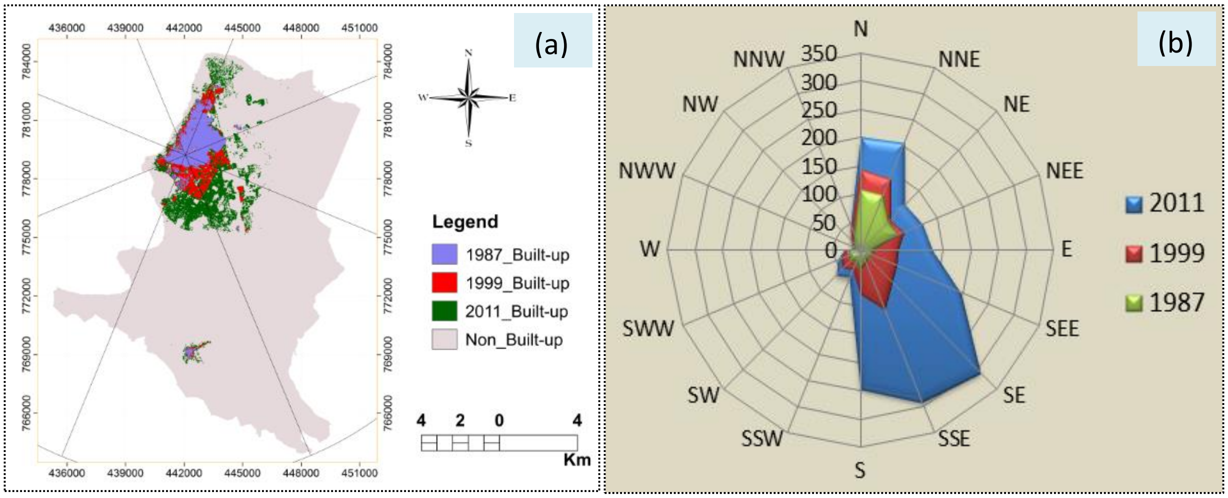


Fig. 10. (a) Built-up areas sub-divided into eight zones, (b) radar chart showing urban expansion (ha) through the three temporal instants, where the area has been sub-divided into 16 zones for better visualization.

4.2.2 Urban growth status and the degree of sprawl

Dividing built-up land cover into eight zones (Fig. 10a) and applying analytical models have produced valuable information on the growth status and the degree of sprawl of the city. Theoretically, the city was expected to grow equally in every direction from the city center. However, uneven growth was observed caused by natural barriers (lakes, hills, wetlands) and policy variables (restricted areas for the state farm, airport, military camp etc.). To quantify and explain the patterns of urban growth, analytical models were applied.

Pearson's Chi-square statistics: This takes into account checking the degree of deviation between observed and expected urban growth (Almeida et al. 2005; Bhatta 2012), and the results are summarized in Table 2. Expected growth is computed using Chi-square statistics, as there was no projected expectation for the city under investigation.

Table 2. Degrees of freedom for urban growth.

a) Degree of freedom for urban growth in each temporal interval

Temporal interval	1987-1999	1999-2011
Degree-of-freedom (X_i^2)	51.26	21.48

b) Degree-of-freedom for urban growth in each zone

Zone	N	NE	E	SE	S	SW	W	NW
Degree-of-freedom (X_j^2)	11.18	2.11	1.05	12.56	0.91	12.56	16.93	15.43

c) Overall degree-of-freedom (X^2)	72.74

The degree-of-freedom in this paper is the result of chi-square statistics and it represents the degree of deviation between observed and expected urban growth. It has a lower limit of zero when the observed value is exactly equal to the expected. Higher overall degree-of-freedom also indicates lack of consistent planned development in the city. The result revealed that the degree-of-freedom was high, indicating the disparity between observed and expected growth in pattern and/or process.

Shannon entropy: This is a widely applied method in urban sprawl studies and it measures the degree of spatial concentration or dispersion of a geographical variable, observed built-up growth rates in zones (Yeh and Li 2001; Li and Yeh 2004; Sarvestani et al. 2011). The entropy values are calculated and given in Table 3. The result indicated that the entropy values both in zones (m) and temporal intervals (n) are higher than the half-way mark of $log_e(m)$and$log_e(n)$, respectively. The overall sprawl calculated was also higher than the half-way mark of $log_e(nxm)$. The entropy values range from zero to $log_e(m) \vee log_e(n)$, and values close to zero indicate a compact built-up growth distribution (non-sprawled city). Thus, since the entropy values both for temporal intervals and zones are higher than the half-way mark of $log_e(m) \vee log_e(n)$, respectively, the city has a tendency of sprawl. The lowest sprawl was observed in NW zone. This is because the area is on the beach side and much demanded land for development. The image analysis showed that the N and NE zones had experienced more dispersed urban growth in 2011, mainly attributable to illegal settlements. Such illegal occupation of public lands by squatters was estimated at 19.8 and 14.5% of the built-up areas in N and NE zones, respectively (Wondrade et al. 2014).

Table 3. Shannon entropy.

a) Shannon entropy for each temporal interval.

Temporal interval	Entropy (H_i)	$\log_e$ (m)	$\log_e$ (m)/2
1987-1999	1.76	2.08	1.04
1999-2011	1.65	2.08	1.04

b) Shannon entropy for each zone.

Zone	Entropy (H_j)	$\log_e$(n)	$\log_e$(n)/2
N	0.69	0.69	0.35
NE	0.59	0.69	0.35
E	0.68	0.69	0.35
SE	0.69	0.69	0.35
S	0.69	0.69	0.35
SW	0.66	0.69	0.35
W	0.59	0.69	0.35

c) Overall entropy (H)	2.40

Degree-of-goodness of urban growth: The goodness analysis presented in Table 4 reveals the combined effect of $X^2$and sprawl. The magnitude and algebraic signs of the degree-of-goodness are direct indications of whether the urban growths are good or bad. It is good when the values are positive and small in magnitude. Such values are obtained when the observed growth relates to the planned growth and the magnitude of compactness as well.

Based on the analysis, except for the S zone, the study area has not experienced goodness during the entire study period, the worst being during the period 1987-1999. However, the dramatic increase in the price of land, the expansion of new construction sites, and the infilling of open spaces since 1990s, have improved the degree of sprawl and goodness of urban growth. This is exemplified by the improvement from -3.77 during 1987-1999 to -2.84 during 1999-2011 (Table 4).

Table 4. Degrees-of-goodness of urban growth.

a) Degree-of-goodness for urban growth in each temporal interval

Temporal interval	1987-1999	1999-2011
Goodness (G_i)	-3.77	-2.84

b) Degree-of-goodness for urban growth in each zone

Zone	N	NE	E	SE	S	SW	W	NW
Goodness (G_j)	-2.41	-0.58	-0.03	-2.53	0.10	-2.48	-2.67	-2.25

c) Overall Degree-of-goodness (G)	-4.14

4.3 Estimating AGB and carbon by integrating remote sensing and allometric equations

Remote sensing analysis exhibited that the total forest cover, for the base year 2011, was 8130.5 ha. To integrate with remote sensing data, field inventory was conducted in 48 stratified random sample plots. The inventory identified 58 tree species with diameter at breast height (DBH) ≥5cm. The DBH and height (H) of the 4617 tallied trees ranged between 5-75.4cm and 2-57m, respectively. The pantropic allometric equations (Brown 1997; Chave et al. 2005) developed for moist tropical forests produced a mean AGB of 200.9 Mg ha^{-1} (natural forest) and 223.6 Mg ha^{-1} for plantation forest. A summary of the estimated mean AGB in each constituent district is given in Table 5.

The total AGB stock for the forests was estimated at 1.72 Mt, while the above ground carbon (AGC) was 0.86Mt, assuming that the carbon concentration of different parts of a tree is 50% of its dry biomass (IPCC 2003; Losi et al. 2003).

Table 5. The estimated mean AGB of forest in the Lake Hawassa Watershed.

District	Geographic area (ha)	Forest cover (ha)	Total AGB[a] (ton)	Total AGC (ton)
Hawassa Zuria	84512.2	6550.6	1390683.9	695341.9
Boricha	14286.3	72.7	15438.5	7719.2
Shebedino	12116.3	236.7	50251.4	25125.7
Arbegona	306.1	14.8	3133.5	1566.8
Siraro	11518.0	0.0	0.0	0.0
Shashemene	17124.2	521.4	110686.9	55343.4
Kofele	4038.2	733.7	155760.3	77880.1
Kokosa	72.1	0.7	152.9	76.4
Total	*143973.4*	*8130.5*	*1726107.3*	*863053.6*
	Mt=Megaton		*1.726 Mt*	*0.863 Mt*

[a]Total AGB is the product of forest cover & the mean AGB of all plots in both forest types (212.3 t/ ha)

The absence of forest cover in the Siraro district reveals the presence of heavy anthropogenic activities and active LULC changes on the border between the two regional states. This finding is consistent with the work of Dessie and Kleman (2007), who reported the complete replacement of border forests by agricultural land in the same area. The result indicated that the majority of trees in the study area belonged to the diameter at breast height class of 5–25 cm (Fig. 11). The population structure and insignificant number of mature trees can mainly be explained as an indication of disturbance where mature stems are removed by selective felling across the area. This corresponds to a report from the Harenna forest, in Bale zone (Tesfaye et al. 2002).

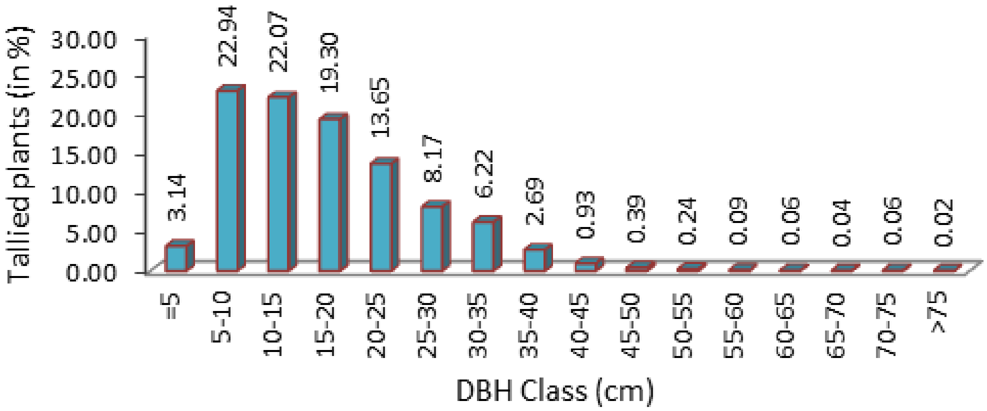


Fig. 11. The distribution of sampled trees based on DBH class.

The analysis indicated that the distribution of DBH classes did not conform to an uninterrupted reversed ‘J’ curve, implying an unhealthy and unstable regeneration process (Kunwar and Sharma 2004). The relationship between DBH class and frequency of sampled stems for selected species are given in Fig. 12, where none of the species followed a reversed ‘J’ distribution.

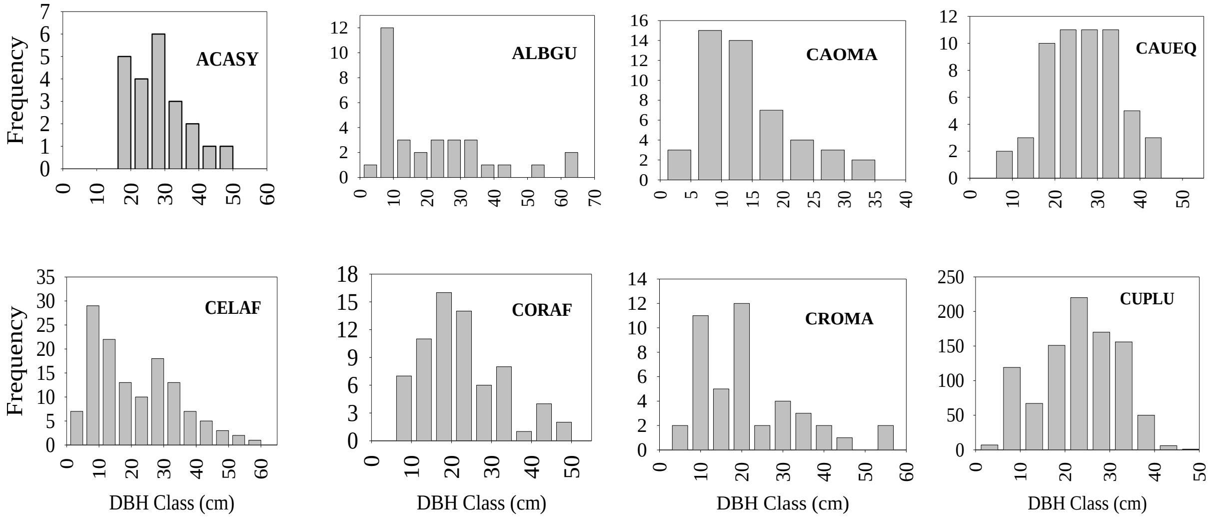


Fig. 12. Population structure of selected tree species indicating disturbance and inadequate regeneration pattern. For the expanded form of tree species codes depicted here, see Table 2 of Paper III.

The results of AGB analysis in forests revealed that the stand density of trees was not the main contributor for the increased AGB and carbon. For instance, the stand density of trees in the plot with the lowest AGB was 1 314 stems ha^{-1}, while the plot with the highest AGB had 278 stems ha^{-1}. For better visualization, the scatter plot of AGB density and stem density per plot is given in Fig. 13. The result suggests that DBH and height of trees contribute to biomass and carbon stock than the stem density.

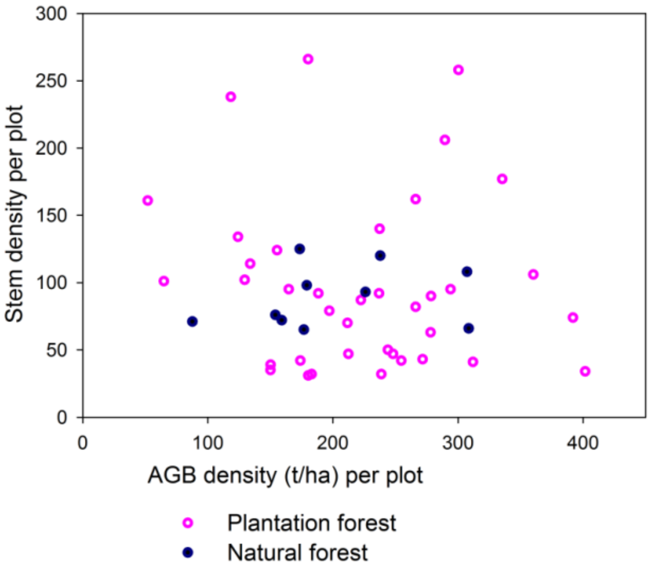


Fig. 13. Scatter plot of AGB and stem density per plot.

Part of this study which aimed at calculating the density, frequency, dominance, as well as the rank order of each species in terms of importance value, indicated that *Cupressus lucitanica* was the most important species which accounted for 60.09% followed by *Grevillea robusta* (28.65%) and *Eucalyptus citriodora* (20.87%). Forest assessment indicated that the biodiversity of the region was affected owing to uncontrolled population growth and dependence on natural resources. Thus, exploring the available species diversity is essential to establish conservation measures that could minimize the loss of local biodiversity. The composition and diversity curve of the 58 species recorded in the watershed ecosystem is presented in Fig. 14. The methods used are beneficial for environmental managers to estimate biomass loss and support policy decisions to reduce land cover conversions and carbon emission.

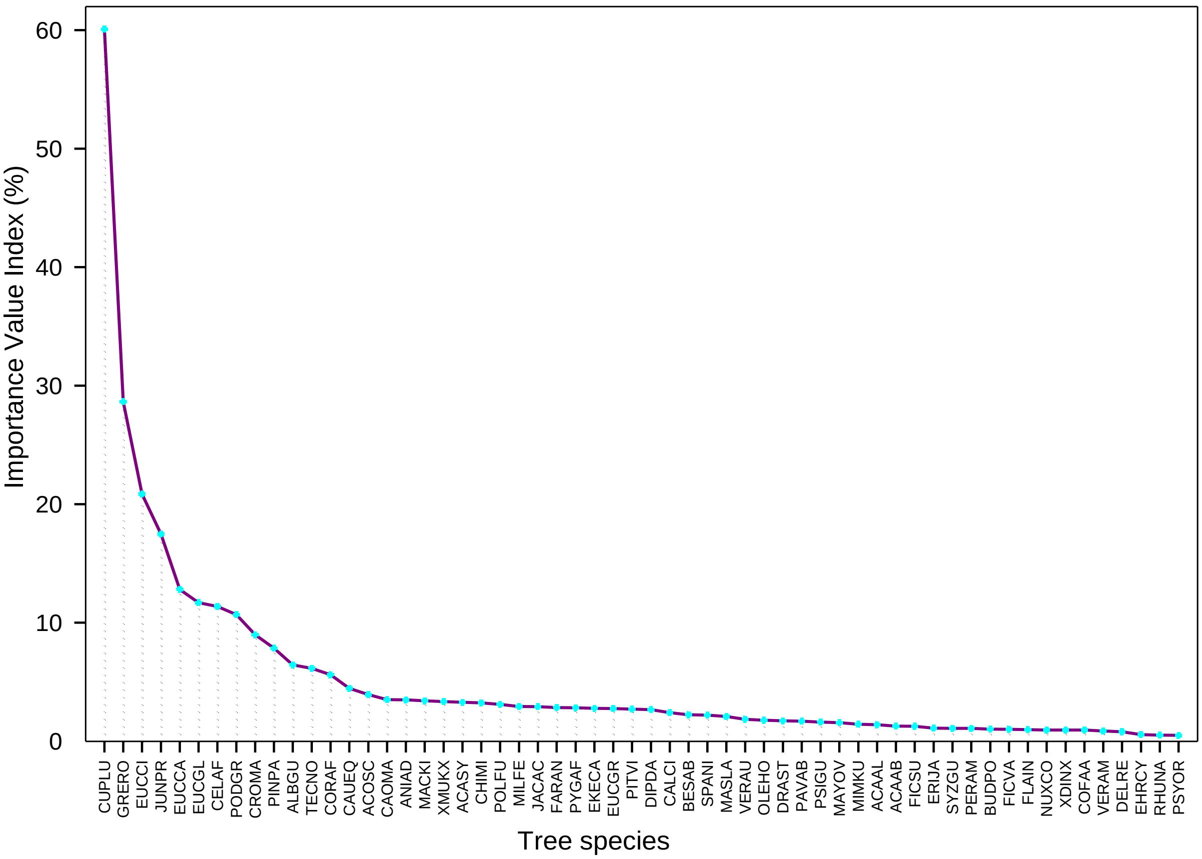


Fig. 14. Species diversity curve. For abbreviations of coded species, see Table 2, Paper III.

4.4 Analysis of land use land cover conversions and underlying driving forces

4.4.1 LULC conversions

The spatial and temporal distribution of land cover conversions between 1973 and 2011 (Fig. 15) were produced by analyzing remote sensing data. Cross-tabulation matrices presented in Table 2, Paper IV, exhibited quantified and multi-directional land cover conversions between two selected dates. Nearly 396 km^2 (27.6%), 425 km^2 (29.6%), and 465 km^2 (32.4%) of land cover have been converted into other LC classes during the 1973-1985, 1985-1995, and 1995-2011 periods, respectively. Cropland expansion was estimated at 29.4% (183.8 km^2) from 1973 to 2011, while cropland lost about 18 km^2 of its area to built-up between the same temporal instants. This was in agreement with reports from Rembold et al. (2000) in the Lakes region, north of the study site.

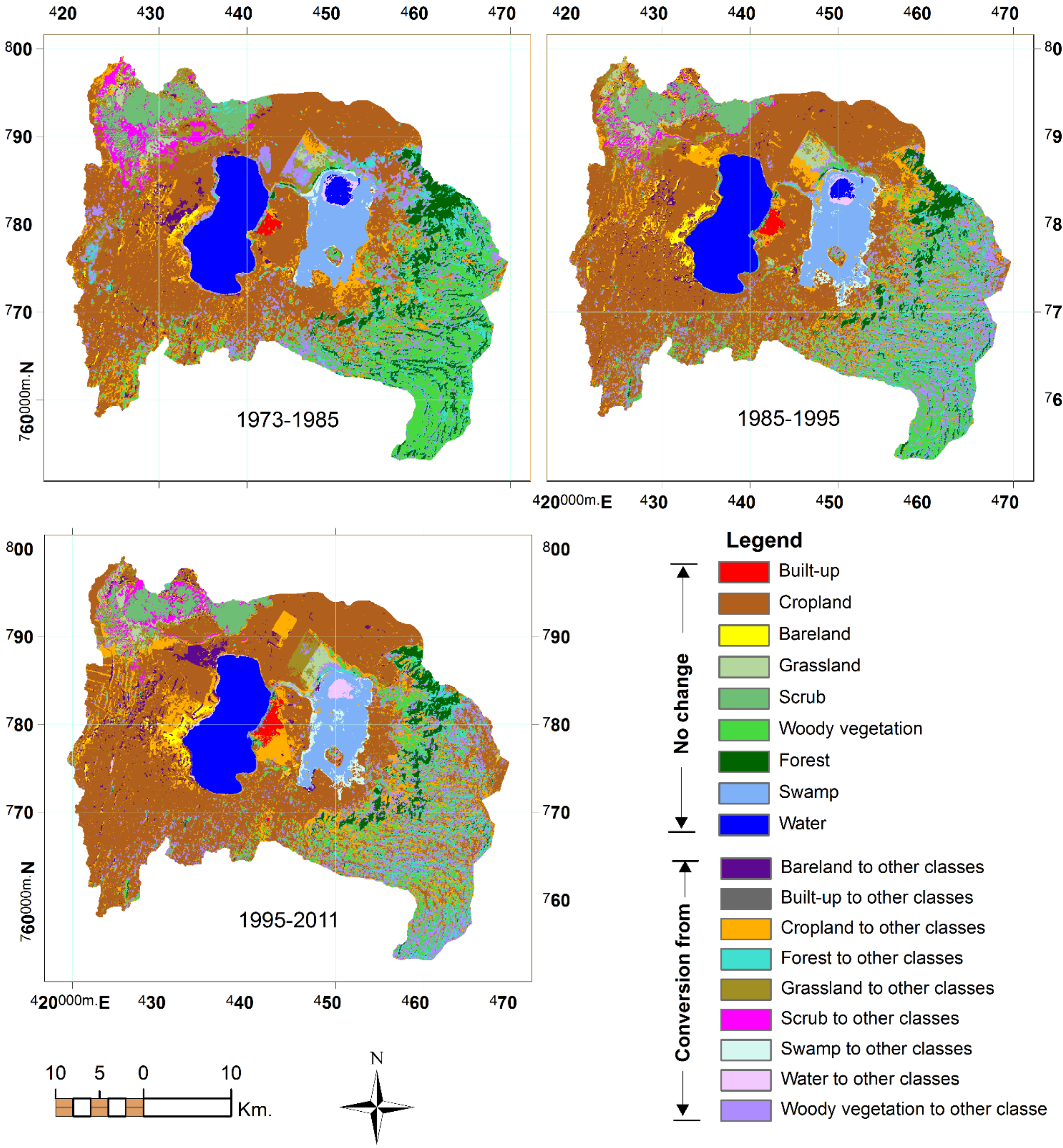


Fig. 15. Thematic maps showing the spatial distribution of LC conversions in the Lake Hawassa Watershed. Quantitative data on land cover conversions is given in Table 2, Paper IV.

The transformation of woody vegetation into other classes was the highest during the entire study period accounting for 198km^2 (13.8%). Forest cover experienced continuous decline, -30.8% from 1973 to 1985 and -13.1% from 1995 to 2011 (an annual rate of change of -1.2% over the study time). The predominant trend of vegetation cover being converted into cropland and other land cover classes signifies the pressure exerted on natural resources by the ever increasing human and livestock population. The rapid increase in LULC conversions and deforestation were found to be the major causes for the desiccation of Lake Cheleleka which had a volume of 60×10^6 m^3 in 1972 (Ayenew 2004).

Attributable to unequal temporal intervals and uneven distribution of LULC conversions across each year, temporal and annual rates of changes were calculated. The annual rate of change is the LULC change computed by dividing the temporal rates of change by the number of years in the interval (Sleeter and Raumann 2006; Zhang et al. 2010). The results revealed a slight deceleration in cropland expansion both at annual and temporal rates. (Fig. 16). This slight deceleration in the expansion of cropland could be attributed either to shortage of suitable land for further conversion or that the remaining area cannot be used for cropping due to policy restrictions. Built-up area has shown the highest annual rate of growth (12.7%) followed by bare land (3.2%), while forest cover (-1.2%) and woody vegetation (-0.9%) were the biggest losers during the entire time span of the study. The result also revealed an interchange between cropland, grassland, and bare land with other land cover classes. Due to management practices, some areas that once were covered by grassland were converted to cropland and then back to grassland. For example, more temporal change rates for grassland were observed during the period 1995-2011 (-10.7%) than during the wider interval 1973-2011 (-8.3%). Here one can also observe that the analysis of coarse temporal resolution images may mask some change processes that have occurred within short temporal intervals. Bare land increased with the highest rate between 1973 and 1985, but declined by 5.2% during 1995-2011 as farmers started to cultivate more marginalized lands. Scrubland in the north-western part of the study area, protected for Swayne's Hartebeest, had also continuously declined as clearing for farming, construction materials, and firewood continued by encroaching settlers.

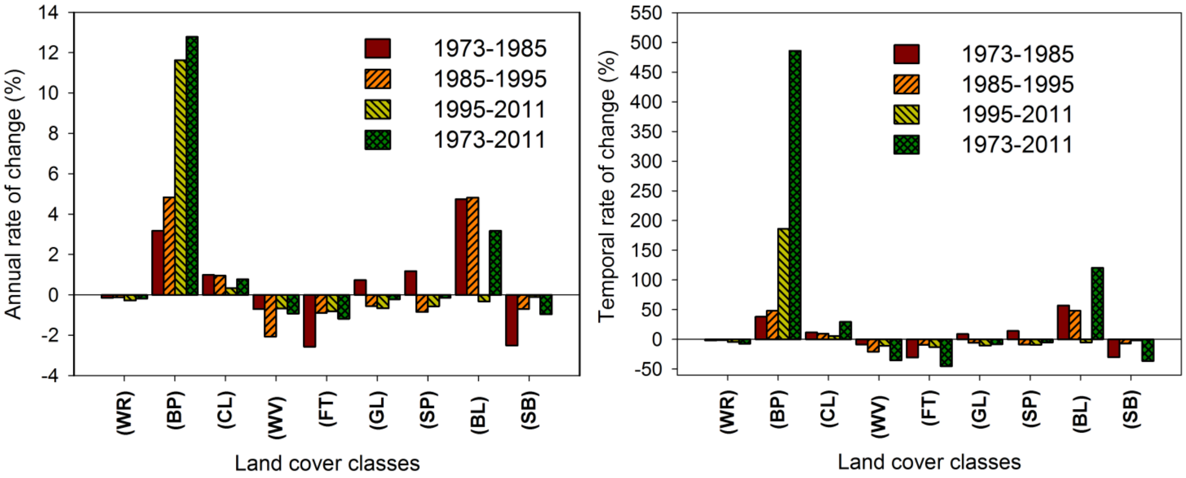


Fig. 16. Annual and temporal rates of change in land cover classes. The expanded form of the abbreviated LC classes is found in Table 2, Paper IV.

4.4.2 Analysis of underlying driving forces of land cover conversions

The key informant interviews identified that land cover conversions were mainly driven by a combination of demographic, low technology agriculture, institutional, economic, and biophysical factors. This is consistent with a report for the Ethiopian highlands including the current site (Birhanu 2014). Understanding the state of land cover conversions and the underlying driving forces is critical when looking for options to mitigate land degradation and loss of biodiversity.

The **population** of the study area, extracted from Census data based on population density and delineated geographical area, shows an increase from 44 086 in 1973 to 1 103 507 in 2014 (CSA 1973; BoFED 2014). In a similar scenario, data from agricultural surveys by CSA (1985) and BoFED (2014) indicated that the livestock population in the Watershed has shown a parallel growth with human population. Based on the livestock population density extracted from the Census data, the increase in livestock population was from 74 810 in 1985 to 1 136 670 in 2014. These numbers refer to only private holdings. According to key informants, most of the LC conversions and deforestation were population induced land clearance and overstocking of grazing lands. Moreover, the population increase has led to shortage of land and fallowing practice is becoming uncommon which in turn reduces soil fertility and agricultural yield.

According to respondents, lack of **technological know-how** and the necessary inputs (fertilizer, seed, and secure land) have led the farming community to pursue labor-intensive and rain-fed agricultural expansion resulting in deforestation and LC conversions. In the southern region, 84% of households depend on agriculture and only about 6.1% and 2.5% of households are self-employed and salaried members, respectively (Deininger et al. 2008).

The result of key informant interviews indicated that the presence of several **institutions** with legal jurisdiction to administer land resources, their frequent restructuring, and overlapping responsibilities among those institutions have been causing severe deforestation and land degradation in the area. The informants also confirmed that power vacuum during regime changes, weak law enforcement, insecure land ownership, and ignoring local people during planning have all contributed to increased land degradation.

Based on the feedback from key informants and own observation, soaring prices of timber and other wood products aggravated by overstocking of saw mill and joinery enterprises in the surrounding towns have negatively contributed to the LC change and deforestation in the area. Introduction and prioritization of high return crops promoted agricultural expansion and has resulted in a decline in wood lands. These findings are consistent with a report from the region on economic crops (Dessie and Christiansson 2008). Key informants also recognized that some households were engaged in illegal logging and clearing forest for charcoal burning to earn instant cash to pay for schooling and health care, increasing the pressure on natural resources. Quarrying of building and road filling materials (sand, gravel, red ash, and clay) for **economic** benefits have also made the area vulnerable to erosion and regrowth on such surfaces is rare or very slow.

Informants concluded, and we concur, that **biophysical factors** such as the suitability of flat land and the availability of water have contributed considerably to the expansion of agricultural and livestock production. Gully formations were observed in areas with steep slopes and on lands with reduced vegetation cover. Besides, human-induced fires have adversely affected forests and dense bush lands on hillsides. Respondents noted, as a recent phenomenon, that the seasonal variability and irregular changes in rainfall are negatively affecting the growth and regeneration of vegetation cover.

4.5 Limitations of the current research

Remote sensing and GIS have proven to be powerful tools for the analysis of LULC change dynamics. However, their application is a complex process and introduces uncertainties to the output thematic maps and associated reports. One of the limitations is related to the accuracy of classified LULC maps. The classification accuracy of the thematic maps, as revealed by the accuracy measures, was not 100% (Paper I). Uncertainty and errors in classification are mainly due to spectral confusion when classifying landscapes containing varying spectral mixtures of two or more land cover classes. The estimated magnitudes and rates of land cover change, quantified urban growth status, and estimated above ground biomass/carbon stocks were, in different ways, based on the created LULC maps. Therefore, classification errors will influence the estimated values. Besides, the reference data used to validate the thematic maps were from different sources (aerial photographs, topographic maps, and field observation). Calculating the three urban growth status indicators (Paper II), using analytical models, on the basis of percentage of built-up area without excluding areas that cannot be developed may be the other limitation in model results. We were not able to exclude areas that cannot be developed because of lack of reliable data and an area may be undevelopable due to natural barriers and policy restrictions. The uncertainties related to the use of models (Paper III) to estimate AGB include error sources from tree variable measurements and uncertainties in using allometric equations. A pixel classified as forest may contain other land cover class though the share of that class may be small. However, when this is extrapolated to the entire study area, it may induce an error propagation into the subsequent estimates of above ground biomass/carbon stocks. The other limitation in AGB/C stock estimates using allometric equations and field data is related to the variation in tropical forest tree height, diameter, wood density, and species composition across plots, regions, or countries within similar biophysical environments. One site specific allometric equation for each forest type (natural and plantation) was used as part of an effort to validate the models used to estimate AGB. This may influence the model results presenting an opportunity for further research. The use of coarse temporal and/or spatial resolution images is never completely free of limitations. Particularly, analysis of wider (low) temporal resolution images tend to mask some sudden LULC changes that have occurred and may obscure the true picture of change trends.

5 Conclusions, recommendations, and future research

In conclusion, the four papers included in this thesis have investigated the spatial and temporal land cover changes, above ground biomass stock, urban growth status, and the underlying driving forces of land cover conversions in the Lake Hawassa Watershed, Ethiopia, by integrating remote sensing data, field observations, and key informant interviews. The analysis of land cover changes at different spatial and temporal scales and investigating their causal factors provides an up-to-date land cover conversion information. Such information is useful for sound planning and decision making in sustainable natural resource management.

5.1 Conclusions

Based on the research findings, the major conclusions drawn include:

i. The Lake Hawassa Watershed and its hinterlands have undergone landscape transformation, mainly due to anthropogenic activities over the study period (1973-2011). The combined estimates of forest, woody vegetation, grassland, and scrub which accounted for 42.9% in 1973 have been reduced to 28% in 2011.

ii. Cropland, woody vegetation and forest were the land cover types with higher magnitudes of change than others, while built-up area experienced the highest annual rate of change over the study period.

iii. Cropland was the dominant land cover observed throughout all the temporal intervals. The primary conversions to cropland was from woody vegetation, forest, grassland and scrubland. Woody vegetation was the biggest loser followed by forest, while cropland was the biggest gainer followed by built-up area. Cropland expansion was a continuous process, however, a deceleration was observed through time presumably due to shortage of land for further conversion.

iv. The proximity to big cities (Hawassa and Shashemene) and road networks, have contributed to the widespread clearance of vegetation cover and biomass depletion. This was demonstrated by the absence of forest cover (biomass depletion) in Siraro district at the end of the study period.

v. As a result of deforestation, the area has become vulnerable to erosion. The Shallo wetlands has attenuated surface runoff and stored sediment loads leading to the desiccation of Lake Cheleleka.

vi. AGB depletion and land degradation is particularly severe in the western part of the Watershed and currently the spatial concentration of forests is limited to the eastern and north-eastern part of the study area. The amount of AGB and carbon stored in forests varies according to forest types and the level of human and natural disturbances. The most important determinants for the variation of the estimated AGB were the differences in DBH and height of individual trees.

vii. The spatial distribution of the built-up areas in Hawassa City, the capital of SNNPRS, has more than tripled between 1987 and 2011. However, the city has an overall sprawled pattern exacerbated by the lack of projected expectations of urban growth and illegal settlements in recent years. Comparing the entropy values of two temporal intervals, the city has shown a tendency of improvement in the degree of sprawl.

viii. The following underlying driving forces have generally determined the LULC changes in the Lake Hawassa Watershed: demographic, economic, institutional, technological, and biophysical factors.

5.2 Recommendations

Concluding summary: The research outputs provided biophysical information of the area for the past 38 years and contributed knowledge which is critical for the formulation of effective environmental policies and management strategies. The analysis indicated that the rates and patterns of changes that have occurred and the land resources available are the result of many causal factor synergies that need attention in order to halt the ongoing land cover conversions. In the light of these findings, the following recommendations are made for the recovery of natural resources:

a. Carry out regular evaluation of the LULC conversions, land degradation, and sediment transport to the wetlands and Lake Hawassa using applicable models to guide the implementation of sustainable land use management by giving more attention to erosion prone areas.

b. Create increased awareness and understanding of environmental and resource issues among the local community so that they (1) learn to value an ecosystem more than the odd commodity that it produces for daily subsistence, (2) plant trees in their farmyards to overcome the shortage of fuel wood and housing materials and thereby reduce biomass depletion, and (3) follow appropriate tillage practices that will reduce land degradation.

c. Establish inter-regional (SNNPR and Oromiya) collaboration to thwart threats to ecosystems, upgrade institutional capacity at the district level to be able to implement policies and enforce law, devise clear mechanisms to facilitate community participation in forest management (rights, duties and benefit sharing), and coordinate efforts in the management and conservation of the available natural resources and rehabilitation of affected areas.

d. Devise mitigation strategies not only for the whole area as an entity, but also develop different planning policies for each zone. This is because the urban growth in the different zones has different levels of compactness, leading to different patterns of growth. Thus, a single policy for the entire city will never work with equal degree of effectiveness for all zones.
e. Develop alternative energy sources (such as rural electrification, biogas, solar and wind power, and energy saving stoves) to wood fuel and charcoal in order to reduce destruction of the remaining forest resources.
f. Establish an appropriate institution with a mandate to identify actions that cause wetland degradation and support the protection and wise use of wetland ecosystems.
g. If the biophysical resources are to regenerate and improve, mitigation strategies should be developed that are geared towards the underlying driving forces. These may include: (i) strengthening of family planning and reproductive health education to slow down the rate of population growth, because if population growth continues with the current pace, resource conservation and other development initiatives will not yield encouraging results in the long run. Promote livestock development that does not depend on mere livestock number, but on quality, and uses minimum grazing system that avoids overgrazing. (ii) transforming low agricultural technology and organizing farmers who are able to adopt intensification measures to improve agricultural productivity and reduce widespread expansion of croplands. (iii) enabling local users to influence resource management institutions through policies, and introducing secure land tenure system.
h. Any assistance to the rural community should not be aimed at providing charity of massive food, but at a continuous transfer of adaptable technologies, ensured land tenure security, and development of human capacity that will enable sustainable use of natural resources and ensure food security.

5.3 Future research

This thesis, in its endeavor to analyze LULC change and the underlying driving forces, has pointed out several needs for further study. Some of the important areas for future research include:

1. The need for mapping LULC changes within and around the study area to create a land cover database that could be used as a source of information for land use planning and sustainable resource management.
2. The growing population of the area is largely reliant on fuel wood and charcoal for its energy consumption and wood resources for housing materials, leading to massive depletion of forests. This is also anticipated to continue in the foreseeable future which calls for further research to identify fast growing trees that may replace the role of forests as a source of energy and housing materials and find out to what extent it works, with a view to ease the pressure on forests and woodlands.
3. The analysis of LULC change using wide temporal intervals and coarse spatial resolutions may tend to mask some change process that has taken place. For instance, a higher temporal change rate was observed for grassland during the period 1995-2011 (-10.7%) than during the wide interval 1973-2011 (-8.3%). This shows that more change processes may be masked when using wider interval than when using shorter intervals. Thus, further research aiming at using more refined temporal and spatial resolution images would be useful to better interpret and detect the change processes in the heterogeneous African landscape.
4. Above ground biomass and carbon stocks were estimated using pan tropic allometric equations. The use of such generic equations may have some influence on the model results due to variation in the type and composition of tree species for which the equations were developed. Thus, more research is needed to develop site and species specific allometric equations using destructive method to reduce uncertainties in estimating AGB and verify the achieved results of the models.
5. In urban growth monitoring, degree-of-freedom, Shannon entropy and degree-of-goodness were calculated based on the percentage of built-up areas within a zone by including tracts of land that cannot be developed due to natural barriers and policy restrictions. Further research is needed to quantify non-developable land in the area to improve the results of models in determining the degree of spatial concentration or dispersion of built-up area in the city.

References

Ali, H., Descheemaeker, K., Steenhuis, T., & Pandey, S. (2011). Comparison of land use land cover changes, drivers and impacts for a moisture-sufficient and drought-prone region in the Ethiopian highlands. *Experimental Agriculture*, 47(S1), 71-83.

Almeida, C. M., Monteiro, A. M. V., Camara, G., Soares-Filho, B. S., Cerqueira, G. C., Pennachin, C. L., & Batty, M. (2005). GIS and remote sensing as tools for the simulation of urban land-use change. I*nternational Journal of Remote Sensing*, 26(4), 759–774.

Anderson, J. R., Hardy, E. E., Roach, J. T., & Witmer, R. E. (1976). A land use and land cover classification system for use with remote sensor data. USGS Professional Paper 964, USA.

Ango, G. T., & Bewket, W. (2007). Challenges and prospects for sustainable forest management in Wondo Genet area, Southern Ethiopia. Ethiopian Journal of Development Research, 29(2), 27-64.

Asfaw, A., & Demissie, Y. (2012). Sustainable household energy for Addis Ababa, Ethiopia. *Consilience: The Journal of Sustainable Development*, 8(1), 1-11.

Ayenew, T. (2004). Environmental implications of changes in the levels of lakes in the Ethiopian Rift since 1970. *Regional Environmental Change*, 4, 192-204.

Ayenew, T., & Gebreegziabher, Y. (2006). Application of a spreadsheet hydrological model for computing the long-term water balance of Lake Awassa, Ethiopia. *Hydrological Sciences Journal*, 51(3), 418-431.

Bakr, N., Weindorf, D. C., Bahnassy, M. H., Marei, S. M., & El-Badawi, M. M. (2010). Monitoring land cover changes in a newly reclaimed area of Egypt using multi-temporal Landsat data. *Applied Geography*, 30, 592-605.

Bedru, S. M. (2006). Remote sensing & GIS for land cover/land use change detection and analysis in the semi-natural ecosystems and agriculture landscapes of the central Ethiopian Rift Valley. PhD Thesis/Dissertation. Technical University of Dresden, Dresden, Germany.

Bekele, M. (2011). Forest plantations and woodlots in Ethiopia. *African Forest Forum*, 1(12), 1-52.

Bekele, M., & Berhanu, L. (2001). State of forest genetic resources in Ethiopia. In working papers of the sub-regional workshop FAO/IPGRI/ICRAF on the conservation, management, sustainable utilization and enhancement of forest genetic resources in Sahelian and North-Sudanian Africa, Ouagadougou, Burkina Faso, September 1998. Rome: Working Paper Forestry Department.

Bernard, B., Anthony, E., Patrick, O., & Fridah, M. (2010). Dynamics of land use/cover trends in Kanungu district, south-western Uganda. *Journal of Applied Sciences and Environmental Management*, 14(4), 67-70.

Bhatta, B. (2012). *Urban growth analysis and remote sensing*. Springer briefs in Geography, Kolkata.

Bhatta, B., Saraswati, S., & Bandyopadhyay, D. (2010). Quantifying the degree-of-freedom, degree-of-sprawl, and degree-of-goodness of urban growth from remote sensing data. *Applied Geography, 30*, 96-111.

Binaghi, E., Brivio, P. A., Ghezzi, P., & Rampini, A. (1999). A fuzzy set-based accuracy assessment of soft classification. *Pattern Recognition Letters*, 20, 935-948.

Birhanu, A. (2014). Environmental degradation and management in Ethiopian highlands: Review of lessons learned. *International Journal of Environmental Protection and Policy*, 2(1), 24-34.

Bishaw, B. (2001). Deforestation and land degradation in the Ethiopian highlands: A strategy for physical recovery. *Journal of East African Studies*, 8(1), 7-26.

BoFED. (2014). Bureau of Finance and Economic Development. Hawassa and Shashemene, Ethiopia.

Bogale, A., Taeb, M., & Endo, M. (2006). Land ownership and conflicts over the use of resources: Implication for household vulnerability in eastern Ethiopia. *Ecological Economics*, 58, 134-145.

Brink, A. B., Bodart, C., Brodsky, L., Defourney, P., Ernst, C., Donney, F., Lupi, A., & Tuckova, K. (2014). Anthropogenic pressure in East Africa-Monitoring 20 years of land cover changes by means of medium resolution satellite data. *International Journal of Applied Earth Observation and Geoinformation*, 28, 60-69.

Brink, A. B., & Eva, H. D. (2009). Monitoring 25 years of land cover change dynamics in Africa: A sample based remote sensing approach. *Applied Geography*, 289, 501-512.

Brown, S. (1997). *Estimating Biomass and Biomass Change of Tropical Forests: A Primer*. FAO-Forestry-Paper 134, Forest Resources Assessment Publication: Illinois, IL, USA.

Campbell, J. B. (1996). *Introduction to remote sensing (2nd Ed.)*. London: Taylor & Francis.

Chave, J.; Andalo, C.; Brown, S.; Cairns, M. A.; Chambers, J. Q.; Eamus, D.; Folster, H.; Fromard, F.; Higuchi, N.; Kira, T.; et al. (2005). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia*, 145, 87-89.

Chen, G., Hay, G. J., Carvalho, L. T., & Wulder, M. A. (2012). Object-based change detection. *International Journal of Remote Sensing*, 33(14), 4434-4457.

Chhabra, A., Geist, H., Houghton, R. A., Habrei, H., Braimoh, A. K., Vlek, P. L. G., Patz, J., Xu, J., Ramankutty, N, Coomes, O., etc. (2006). Multiple impacts of land-use/cover change. In E. F. Lambin, & H. Geist (Eds.), *Land-use and Land-cover change-Local processes and global impacts*. Berlin: Springer.

Congalton, R. G. (1991). A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing of Environment*, 37, 35–46.

Congalton, R. G., & Green, K. (2009). *Assessing the accuracy of remotely sensed data: Principles and practices (2nd ed.)*. Boca Raton, FL: Taylor & Francis Group.

Coppin, P., Jonckheere, K., Nackaerts, K., Muys, B., & Lambin, E. (2004). Digital change detection methods in ecosystem monitoring: a review. *International Journal of Remote Sensing*, 25(9), 1565–1596.

Crewett, W., & Korf, B. (2008). Ethiopia: Reforming land tenure. *Review of African Political Economy,* No. 116: 203-220.

CSA. (1973). Central Statistical Abstract of Ethiopia. Central Statistical Office, Addis Ababa, Ethiopia.

CSA. (1985). Central Statistical Abstract of Ethiopia. Central Statistical Office, Addis Ababa, Ethiopia.

CSA. (2011). Central Statistical Agency. Central Statistical Authority, Addis Ababa, Ethiopia.

Das, T. (2009). Land use and land cover change detection: an object oriented approach. MSc Thesis. Munster, Germany.

Deininger, K., Ali, D.A., Holden, S., Zevenbergen, J. (2008). Rural land certification in Ethiopia: Process, initial impact, and implications for other African Countries. *World Development*, 36(10), 1786-1812.

DELTA (2005). Development Management Consultancy Services. Land Use/Land Cover Change and Erosion Hazard Assessment in Lake Hawassa Catchment (Unpublished results), Hawassa, Ethiopia.

Dessie, G., & Christiansson, C. (2008). Forest decline and its causes in the South-Central Rift Valley of Ethiopia: Human impact over a one hundred year perspective. *AMBIO: A Journal of the Human Environment*, 37(4), 263-271.

Dessie, G, & Kleman, J. (2007). Pattern and magnitude of deforestation in the South Central Rift Valley region of Ethiopia. *Mountain Research and Development*, 27(2), 162-168.

Dewidar, K. H. M. (2004). Detection of land use/land cover changes for the northern part of the Nile delta (Burullus region), Egypt. *International Journal of Remote Sensing*, 25(20), 4079-4089.

Eshete, K. F. (2014). Charcoal is used in almost every household in Ethiopia. http://www. *kateferedayeshete.net/section626577_288452.html. Accessed 05 April 2015.*

Eshetu, A. A. (2013). Forest resource management systems in Ethiopia: Historical perspective. *International Journal of Biodiversity and Conservation*, 6(2), 121-131.

FAO. (2003). Role of planted forests and trees outside forests in sustainable forest management in the Republic of Ethiopia. Contributed by I. Thomas and M. Bekele, Planted forests and trees working paper No. 29. Rome: Forest Resources Development service, Forest resources division.

Foody, G. M. (2002). Status of land cover classification accuracy assessment. *Remote Sensing of Environment,* 80, 185–201.

Galster, G., Hanson, R., Ratcliffe, M. R., Wolman, H., Coleman, S., & Freihage, J. (2001). Wrestling sprawl to the ground: Defining and measuring an elusive concept. *Housing Policy Debate*, *12*, 681, http://dx.doi.org/10.1080/10511482.2001.9521426

Garedew, E., Sandewall, M., Soderberg, U., & Campbell, B.M. (2009). Land-use and land-cover dynamics in the Central Rift Valley of Ethiopia. *Environmental Management*, 44, 683-694

Gashaw, T., Bantider, A., & G/Silassie, H. (2014). Land degradation in Ethiopia: Causes, impacts and rehabilitation techniques. *Journal of Environment and Earth Science*, 4(4), 98-104.

Gashaw, T., Bantider, A., & Mahari, A. (2014). Evaluation of land use/land cover changes and land degradation in Dera district, Ethiopia: GIS and remote sensing based analysis. *International Journal of Scientific Research in Environmental Sciences*, 2(6), 199-208.

Gebre, B., & Yirga, S. (2004). Seasonal home range of Swayne's Hartebeest (Alcelaphus buselaphus swaynei) in Senkele's Hartebeest sanctuary. *SINET: Ethiopian Journal of Science*, 27(2), 121-126.

Gebremariam A. H., Bekele, M., & Ridgewell, A. (2009) *Small and medium forest enterprises in Ethiopia*. IIED small and medium forest enterprise series No. 26. FARM-Africa and International Institute for Environment and Development. London: Russell Press.

Geist, H. J., & Lambin, E. F. (2002). Proximate and underlying driving forces of tropical deforestation. *BioScience*, 52(2), 143-150.

Girma, A., & Mosandl, R. (2012). Structure and potential regeneration of degraded secondary stands in Munessa-Shashemene Forest, Ethiopia. *Journal of Tropical Forest Science*, 24(1), 46-53.

Guler, M., Yomralioglu, T., & Reis, S. (2007). Using Landsat data to determine land use/land cover changes in Samsun, Turkey. *Environmental Monitoring and Assessment*, 127, 155-167.

Hardlife, Z., David, C., Godfrey, M., Somandla, N., & Proud, M. (2014). The implications for loss and degradation of wetland ecosystems on sustainable rural livelihoods: Case of Chingombe Community, Zimbabwe. *Greener Journal of Environmental Management and Public Safety*, 3(2), 43-52.

Hurni, H., Abate, S., Bantider, A., Debele, B., Ludi, E., Portnero, B., Yitaferu, B., & Zeleke, G. (2010). Land degradation and sustainable land management in the highlands of Ethiopia. In H. Hurni, & U Wiesmann (Eds.), *Global Change and Sustainable Development: A Synthesis of Regional Experiences from Research Partnerships (pp. 187-207). Bern: Geographica Bernensia.*

Hurni, H., A. Bantider, K. Herweg, B. Portner, & H. Veit (Eds.). (2007). Landscape transformation and sustainable Development in Ethiopia. Background information for a study tour through Ethiopia, 4-20 September 2006. University of Bern, Bern: Centre for Development and Environment.

Hussain, M., Chen, D., Cheng, A., Wei, H., & Stanley, D. (2013). Change detection from remotely sensed images: From pixel-based to object-based approaches. *ISPRS Journal of Photogrammetry and Remote Sensing*, 80, 91-106.

Hussain, M. S., Sultana, A., Khan, J. A., & Khan, A. (2008). Species composition and community structure of forest stands in Kumaon Himalaya, Uttarakhand, India. *Tropical Ecology*, 49(2), 167-181.

IGBP-HDP. (1993). Relating land use and global land-cover change: A proposal for an IGBP-HDP core project. In B.L. Turner II, R.H. Moss, & D.L. Skole (Eds.), A Report from the IGBP/HDP Working Group on Land-Use/Land-Cover Change. Stockholm.

IGBP-IHDP. (1999). Land-use and land-cover change (LUCC) implementation strategy. International Geosphere-Biosphere Programme report No. 48 and the International Human Dimensions Programme report No. 10 on global environmental change. Prepared by the scientific steering committee and international project office of LUCC. Stockholm and Bonn.

Imam, E. (2011). Use of geospatial technology in evaluating landscape cover type changes in Chandoli National Park, India. Computational Ecology and Software, 1(2), 95-111.

Ioannis, M., & Meliadis, M. (2011). Multi-temporal Landsat image classification and change analysis of land cover/use in the Prefecture of Thessaloiniki, Greece. Proceedings of the International Academy of Ecology and Environmental Sciences, 1(1), 15-25.

IPCC. (2003). Intergovernmental Panel on Climate Change. Good Practice Guidance for Land Use, Land-Use Change and Forestry. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanable, K., & Wagner, F., Eds.; Institute for Global Environental Strategies: Hayama, Japan.

Jensen, J. R. (2007). *Remote sensing of the environment: An earth resource perspective (2nd Ed.)*. Upper Saddle River, NJ: Pearson Prentice Hall.

Jianzhong, Y., Yili, Z., Wanqi, B., Yanhua, L., Weikai, B., Linshan, L., & Du, Z. (2005). Land cover changes based on plant successions: Deforestation, rehabilitation and degeneration of forest in the upper Dadu River watershed. *Science in China Series D: Earth Sciences*, 48(12), 2214-2230.

Johnson, R. B., & Onwuegbuzie, A. J. (2004). Mixed methods research: A research paradigm whose time has come. *Educational Research*, 33(7), 14-26.

Kale, M. P., Ravan, S. A., & Singh, S. (2009). *Journal of the Indian Society of Remote Sensing*, 37(3), 457-471.

Kunwar, R.M., & Sharma, S. (2004). Quantitative analysis of tree species in two community forests of Dolpa district, mid-west Nepal. *Himalayan Journal of Sciences*, 2(3), 23-28.

Lambin, E. F. (1999). Monitoring forest degradation in tropical regions by remote sensing: Some methodological issues. *Global Ecology and Biogeography*, 8, 191-198.

Lambin, E. F., & Ehrlich, D. (1997). Land-cover changes in Sub-Saharan Africa (1982-1991): Application of a change index based on remotely sensed surface temperature and vegetation indices at a continental scale. *Remote Sensing of Environment*, 61, 181-200.

Lambin, E. F., Geist, H. J., & Lepers, E. (2003). Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environment and Resources*, 28, 201-241.

Lemma, A. (2005). Site action plan for the conservation and sustainable use of the Lake Awassa biodiversity. Institute of Biodiversity Conservation, Addis Ababa, Ethiopia.

Li, X., & Yeh, A. G. (2004). Analyzing spatial restructuring of land use patterns in a fast growing region using remote sensing and GIS. *Landscape and Urban Planning,* 69, 335–354.

Lillesand, T. M., Kiefer, R. W., & Chipman, J. W. (2008). *Remote sensing and image interpretation (6th Ed.).* New York, NY: John Wiley & Sons.

Losi, C. J., Siccama, T. G., Condit, R., & Morales, J. E. (2003). Analysis of alternative methods for estimating carbon stock in young tropical plantations. *Forest Ecology and Management*, 184, 355-368.

Loveland, T. R., Sohl, T., Sayler, K., Gallant, A., Dwyer, J., Vogelmann, J., Zylstra, G., Wade, T., Edmobds, C., Chaloud, D., etc. (1999). Land cover trends: Rates, causes, and consequences of late-twentieth century US land cover change. *EPA*, /600/R-99/105.

Lu, D., & Weng, Q. (2007). A survey of image classification methods and techniques for improving classification performance. *International Journal of Remote Sensing*, 28(5), 823-870.

Martin, A. R., & Thomas, S. C. (2011). A reassessment of carbon content in tropical trees. PLOSONE, 6(8), e23533. doi:10.1371/journal.pone.0023533

Mengistu, D. A. (2008). Remote sensing and GIS-based land use and land cover change detection in the upper Dijo river catchment, Silte Zone, Southern Ethiopia: Working paper on population and land use change in Central Ethiopia Nr. 17. *Acta Geographica-Trondheim*, Series A, No. 23.

Meshesha, D. T., Tsunekawa, A., & Tsubo, M. (2010). Continuing land degradation: Cause-effect in Ethiopia's Central Rift Valley. *Land Degradation and Development*, DOI: 10.1002/ldr.1061.

Millennium Ecosystem Assessment (2005). *Ecosystems and human well-being*: *Synthesis*. Washington, DC: Island Press.

Moran, E., Skole, D. L., & Turner, B. L. (2004). The development of the international land-use and land-cover change (LULC) research program and its links to NASA's land-cover and land-use change (LCLUC) initiative. In F. D. van der Meer (Ed.), *Land Change Science (pp. 1-15).* Dordrecht: Kluwer Academic Publisher.

MWUD. (2006). Ministry of Works and Urban Development: Report on Awassa integrated development plan. Federal Urban Planning Institute, Addis Ababa, Ethiopia.

Nemani, R. R., & Running, S. W. (1995). Satellite monitoring of global land cover changes and their implication on climate. *Climatic Change*, 31, 395-413.

Nishizaki, N. (2004). Resisting imposed wildlife conservation: Arsi Oromo and the Senkelle Swayne's Hartebeest sanctuary, Ethiopia. *African Study Monographs*, 25(2), 61-77.

Oromiya Regional State. (2002). Report on a strategic plan for the sustainable development, conservation, and management of the woody biomass resources. Addis Ababa, Ethiopia.

Petit, C., Scudder, T., & Lambin, E. (2001). Quantifying processes of land-cover change by remote sensing: Resettlement and rapid land-cover changes in south-eastern Zambia. *International Journal of Remote Sensing*, 22(17), 3435-3456.

Ramankutty, V., & Foley, J. A. (1999). Estimating historical changes in global land cover: Croplands from 1700 to 1992. *Global Biochemical Cycles*, 13(4), 997-1027.

Rembold, F., Carnicelli, S., Nori, M., & Ferrari, A. (2000). Use of aerial photographs, Landsat TM imagery and multidisciplinary field survey for land-cover change analysis in the lakes region (Ethiopia). *JAG,* 2(3/4), 181-189.

Reynolds, T. W., Farley, J., & Huber, C. (2010). Investigating in human and natural capital: An alternative paradigm for sustainable development in Awassa, Ethiopia. *Ecological Economics*, 69, 2140-2150.

Rogan, J., & Chen, D. (2004). Remote sensing technology for mapping and monitoring land-cover and land-use change. *Progress in Planning*, 61, 301-325.

Rotaquio, E. L., Nakagoshi, N., & Rotaquio, R. L. (2007). Species composition of mangrove forests in Aurora, Philippines-A special reference to the presence of Kandelia Candel (L.) Druce. *Journal of International Development and Cooperation*, 13(1), 61-78.

Roy, P. S., & Ravan, S. A. (1996). Biomass estimation using satellite remote sensing data-An investigation on possible approaches for natural forest. *Journal of Biosciences,* 21(4), 535-561.

Sarvestani, M. H., Ibrahim, A. L., & Kanaroglou, P. (2011). Three decades of urban growth in the city of Shiraz, Iran: A remote sensing and geographic information systems application. *Cities*, 28, 320-329.

Scottsdale, J. (2013). Vival la voyage, the people of Ethiopia. http://vivalavoyage.blogspot.com-/2013/12/the-people-of-ethiopia.html. Accessed 05 April 2015.

Selassie, Y. G., & Amede, T. (2014). Investing in land and water management practices in the Ethiopian Highlands: Short-or long-term benefits? In B. Vanlauwe et al. (Eds.), Challenges and Opportunities for Agricultural Intensification of the Humid Highland Systems of Sub-Saharan Africa. Switzerland: Springer International Publishing.

She, J. (2014). Wood fuel use and its influence on people's livelihood in Ethiopia-Comparison among three peasant associations in Wondo Genet. MSc Thesis. University of Helsinki, Finland.

Shirima, D. D., Munishi, P. K. T., Lewis, S. L., Burgess, N. D., Marshall, A. R., Balmford, A., Swetnam, R. D., & Zahabu, E. M. (2011). Carbon storage, structure and composition of miombo woodlands in Tanzania's Eastern Arc Mountains. *African Journal of Ecology,* 49, 332-342.

Sima, S. (2011). Forest carbon partnership facility (FCPF): Readiness preparation proposal (R-PP) for Ethiopia. Environmental Protection Authority, Addis Ababa, Ethiopia.

Sleeter, B.M., & Raumann, C.G. (2006). Land-cover trends in the Mojave Basin and range ecoregion. *Science for a Changing World*, 1-15.

SNNPRS. (2001). Report on a strategic plan for the sustainable development, conservation, and management of the woody biomass resources. Addis Ababa, Ethiopia.

Symeonakis, E., Caccetta, P. A., Wallace, J. F., & Koukoulas, S. (2006). Multi-temporal land use/cover change detection in the Spanish Mediterranean Coast. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 34, Part XXX.

Tadele, K., & Forch, G. (2007). Impact of land use/cover change on stream flow: The case of Hare River Watershed, Ethiopia. *LARS*, 6, 80-85.

Taubenbock, H., & Esch, T. (2011). Remote sensing-An effective data source for urban monitoring. Earthzine, Fostering Earth Observation & Global Awareness. Wessling-Oberpfaffenhofen, Germany.

Tefera, B., Ayele, G., Atnafe, Y., Jabbar, M. A., & Dubale, P. (2002). *Nature and causes of land degradation in the Oromiya Region: A review (pp. 1-82)*. Socio-economics and policy research working paper No. 36. International Livestock Research Institute, Nairobi, Kenya.

Tefera, Z. (2006). The Ethiopian highland ecosystem. In S. Mengistu, & C. De Stoop (Eds.), Environment for survival-Taking stock of Ethiopia’s environment; Proceedings of the first green forum conference held in Addis Ababa, 2-4 October, 2006.

Tesfaye, G., Teketay, D., & Fetene, M. (2002). Regeneration of fourteen tree species in Harenna forest, south-eastern Ethiopia. *Flora*, 197, 461-474.

The Map Library (2007). Map maker Ltd., a software company based in Scotland, UK. http://www.mapmakerdata.co.uk.s3-website-eu-west-1.amazonaws.com/library/about.htm. Accessed 02 February 2012.

Turner II, B. L., Meyer, W. B., & Skole, D. L. (1994). Global land-use/land-cover change: Towards an integrated study. *AMBIO: Integrated Earth System Science*, 23(1), 91-95.

Wells, J. (1995). Population, settlement and the environment: The provision of organic materials for shelter. *Habitat International*, 19(1), 73-90.

Wondafrash, M., & Tessema, Z. (2011). A Glimpse at Biodiversity Hotspots of Ethiopia. http://www.ewnhs.org.et/wpcontent/uploads/downloads/2011/03/Biodiversity-Hotspots-of-Ethiopia.pdf. Accessed 04 September 2014.

Wondrade, N., Dick, Ø. B., & Tveite, H. (2014). GIS based mapping of land cover changes utilizing multi-temporal remotely sensed image data in Lake Hawassa Watershed, Ethiopia. *Environmental Monitoring and Assessment*, 186(3), 1765-1780.

Wondrade, N., Dick, Ø. B., & Tveite, H. (2014). Landscape mapping to quantify degree-of-freedom, degree-of-sprawl, and degree-of-goodness of urban growth in Hawassa, Ethiopia. *Environment and Natural Resources Research*, 4(4), 223-237.

Xie, Y., Sha, Z., & Yu, M. (2012). Remote sensing imagery in vegetation mapping: A review. *Journal of Plant Ecology*, 5(4), 9-23.

Yeh, A. G., & Li, X. (2001). Measurement and monitoring of urban Sprawl in a rapidly growing region using Entropy. *Photogrammetric Engineering & Remote Sensing*, 67(1), 83-90.

Yibeltal, G. (1995). Population pressure, agricultural land fragmentation and land use: a case study of Dale and Shashemene Weredas, Southern Ethiopia. In A. Dejene, & D. Mulat (Eds.). Ethiopian Agriculture Problems of Transformation, Proceedings of the 4th annual conference on the Ethiopian economy (pp. 23-64). Addis Ababa, Ethiopia.

Yigrem, S., Beyene, F., Tegegne, A., & Gebremedhin, B. (2008). Dairy Production, Processing and Marketing Systems of Shashemene-Dilla Area, South Ethiopia: Improving Productivity and Market Success of Ethiopian Farmers Project Working Paper 9 (pp. 62). International Livestock Research Institute, Nairobi, Kenya.

Yirdaw, E. (2002). Restoration of the native woody-species diversity, using plantation species as foster trees, in the degraded highlands of Ethiopia. PhD Thesis. University of Helsinki, Helsinki, Finland.

Zak, M. R., Cabido, M., Caceres, D., & Diaz, S. (2008). What drivers accelerated land cover change in Central Argentina? Synergistic consequences of climatic, socioeconomic, and technological factors. *Environmental Management*, 42, 181-189.

Zeleke, G., & Hurni, H. (2001). Implications of land use and land cover dynamics for mountain resource degradation in the northwestern Ethiopian highlands. *Mountain Research and Development*, 21(2), 184-191.

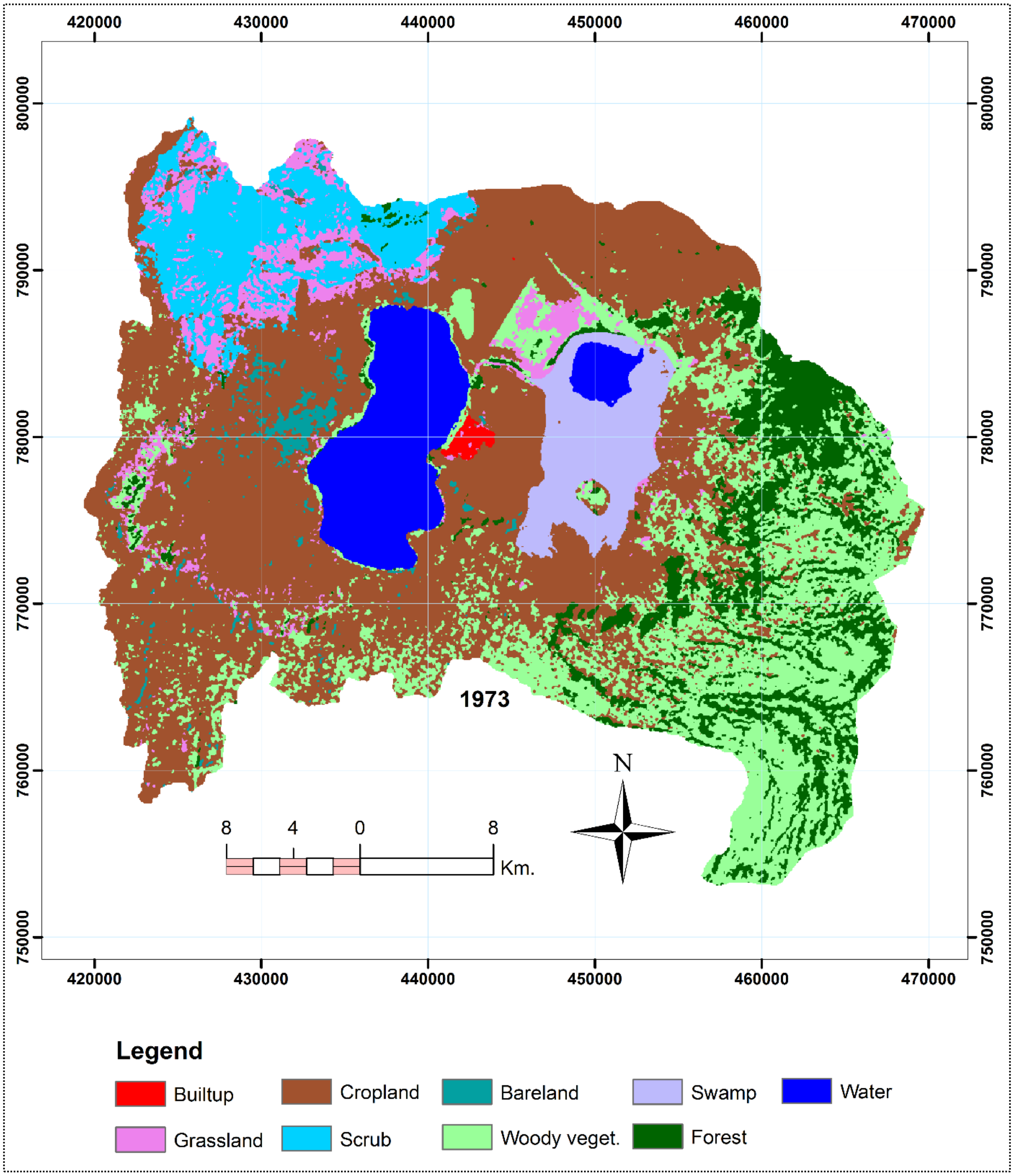
Zeleke, K., & Serkalem, A. (2006). *History of Hawassa, 1960-2006*. Hawassa: Tony Printing Services.

Zhang, X., Kang, T., Wang, H., & Sun, Y. (2010). Analysis on spatial structure of land use change based on remote sensing and geographical information system. *International Journal of Applied Earth Observation and Geoinformation*, 12S, S145-S150.

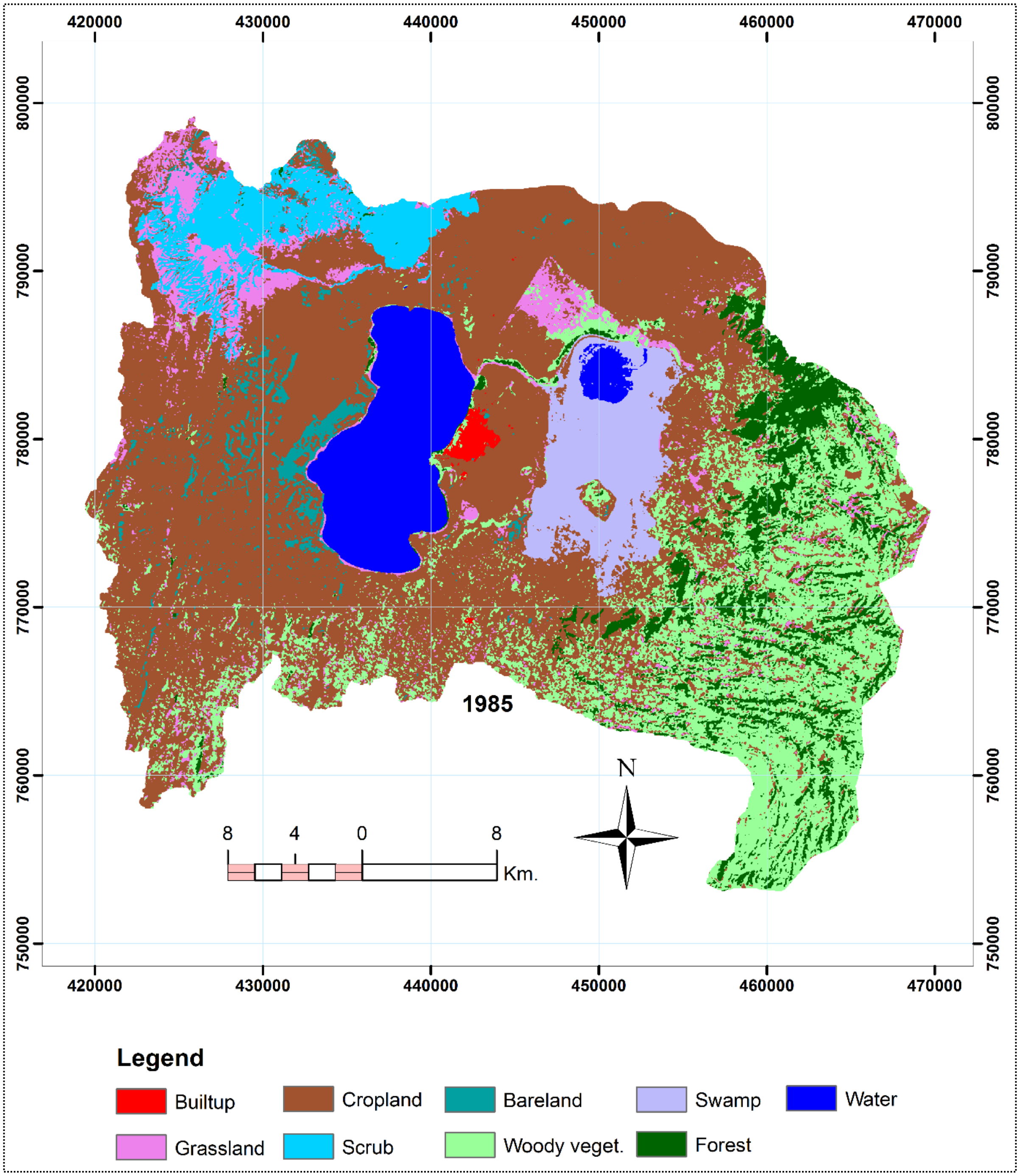
This page is intentionally left blank

Attachments

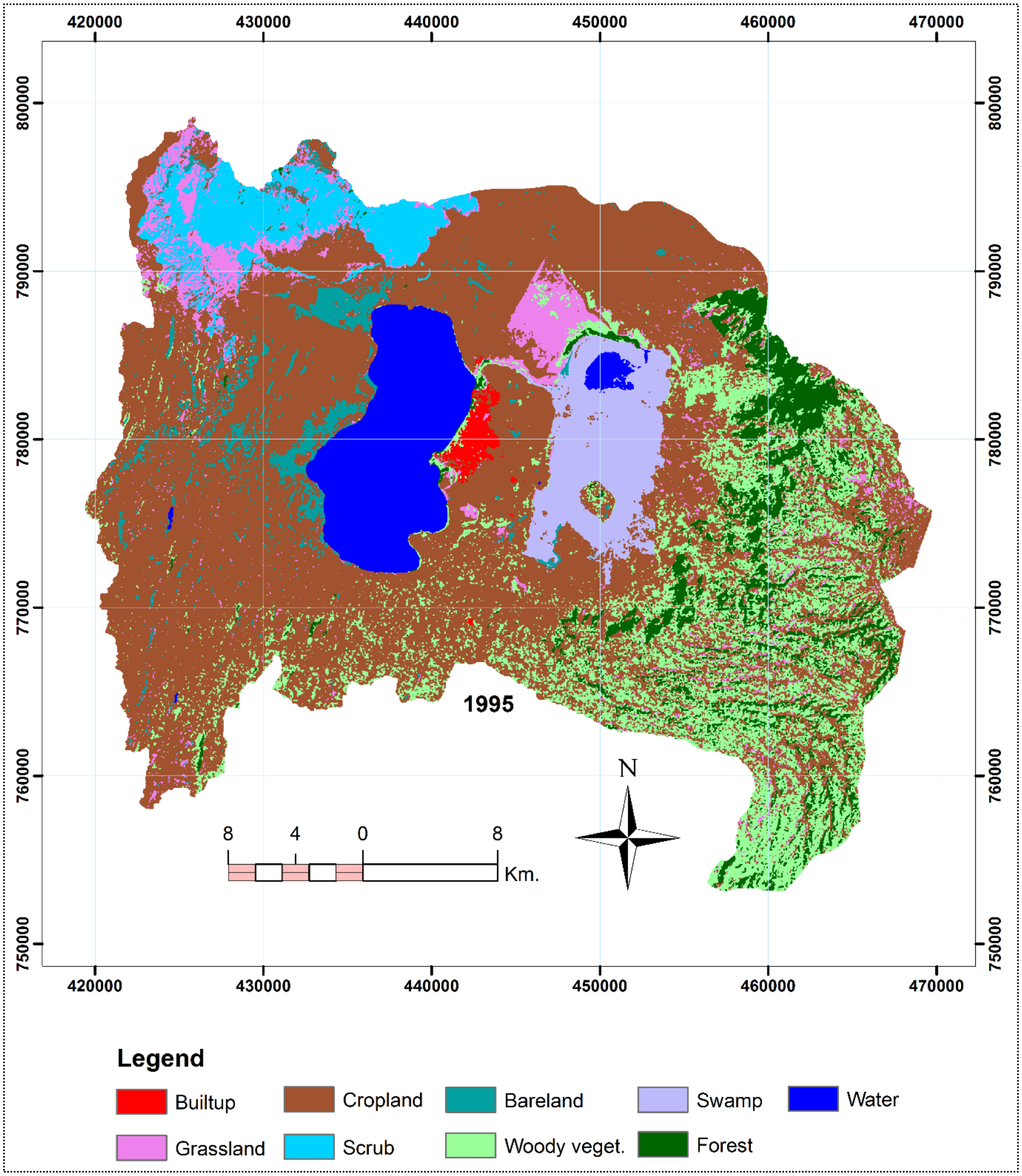
Enlarged thematic maps from the four Papers are given here under for better visualization.



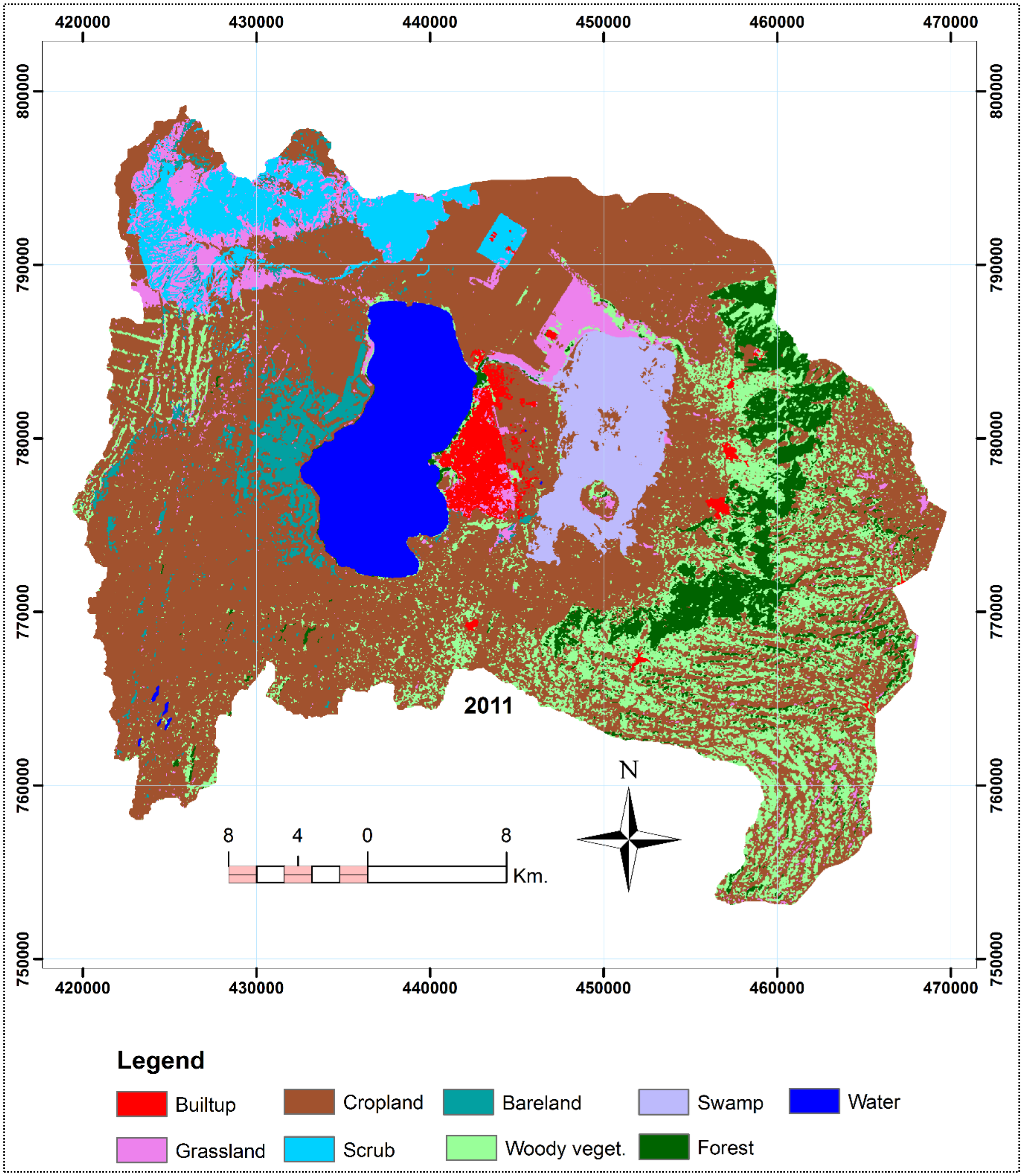
A. Enlarged thematic map from Paper I (Fig. 3)



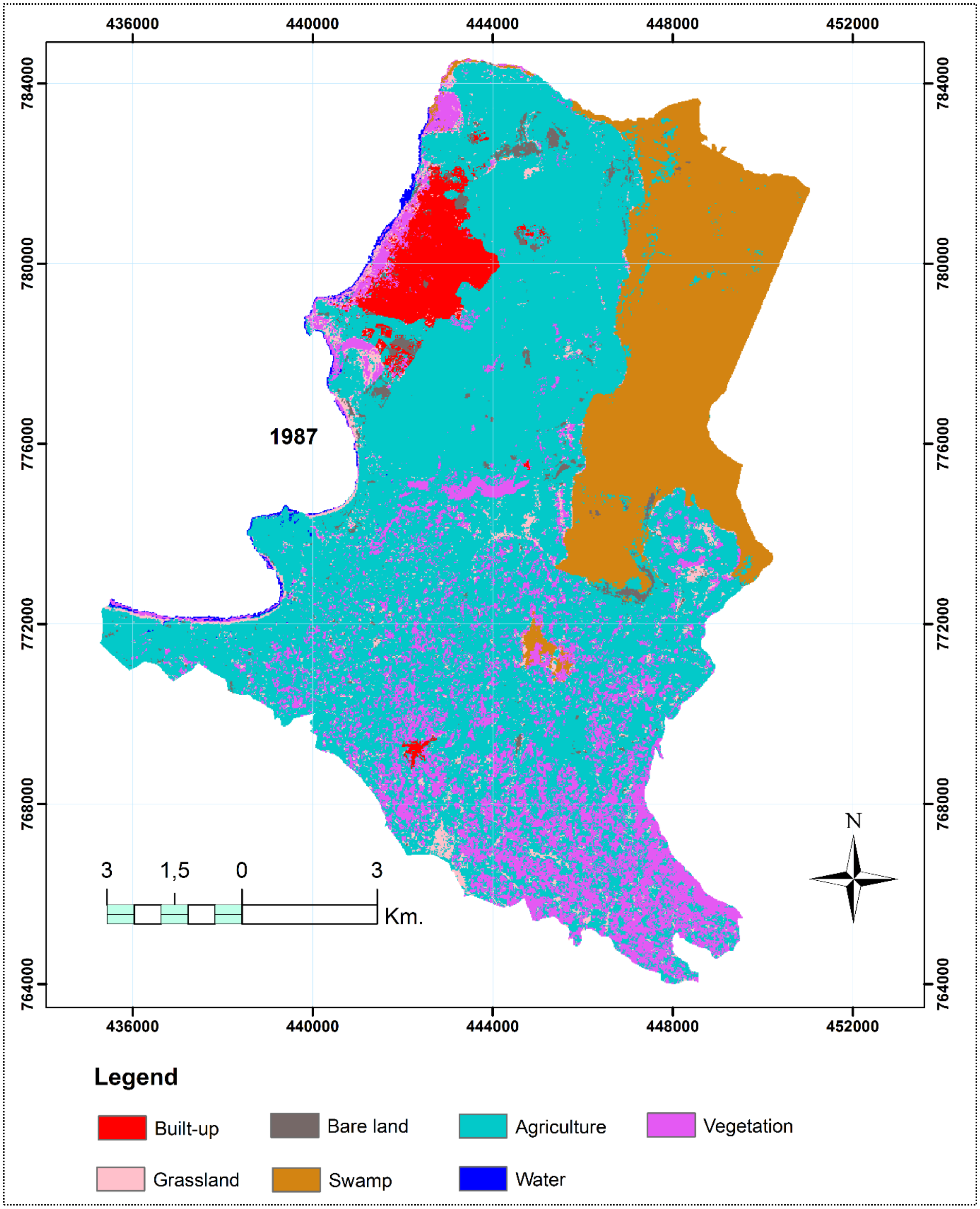
B. Enlarged thematic map from Paper I (Fig. 3)



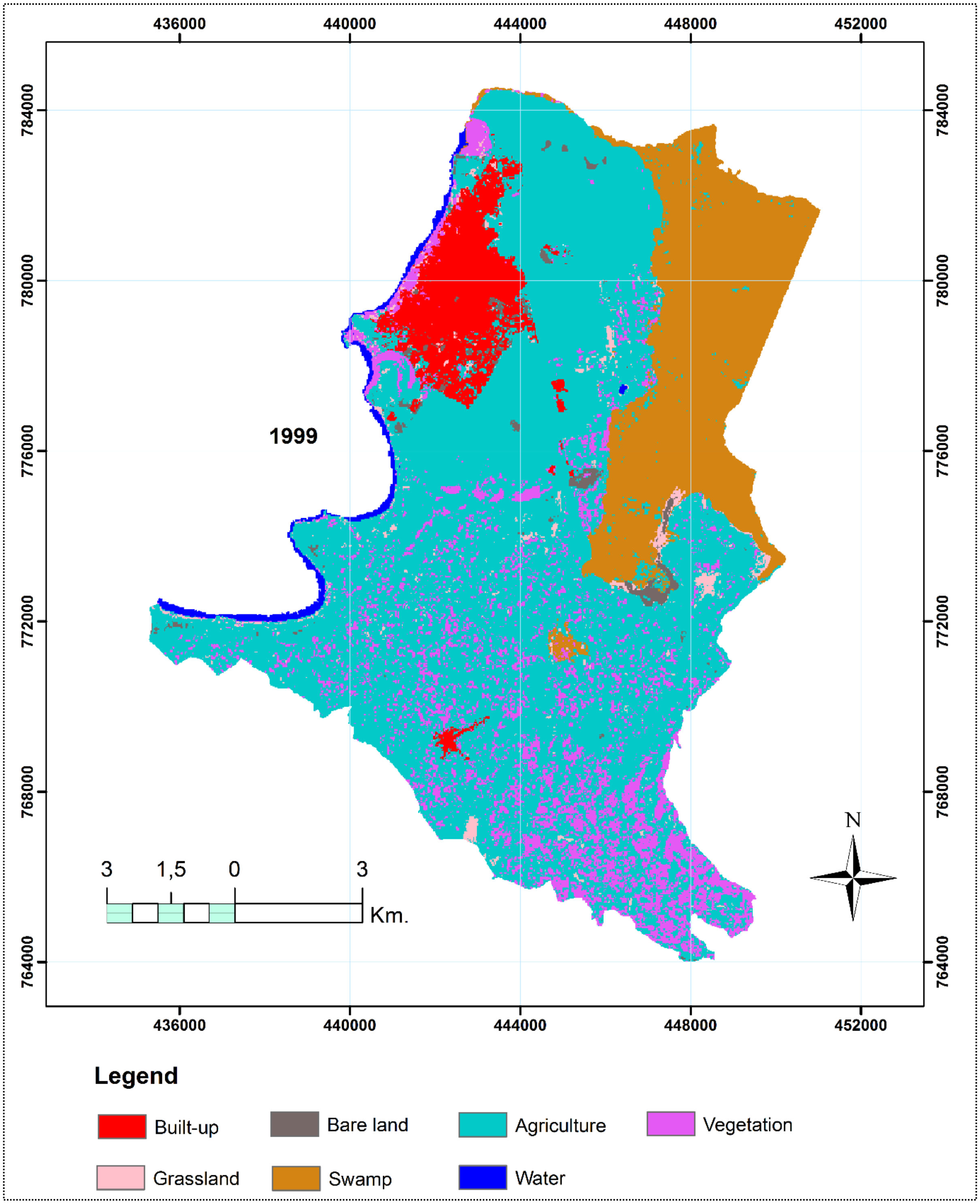
C. Enlarged thematic map from Paper I (Fig. 3)



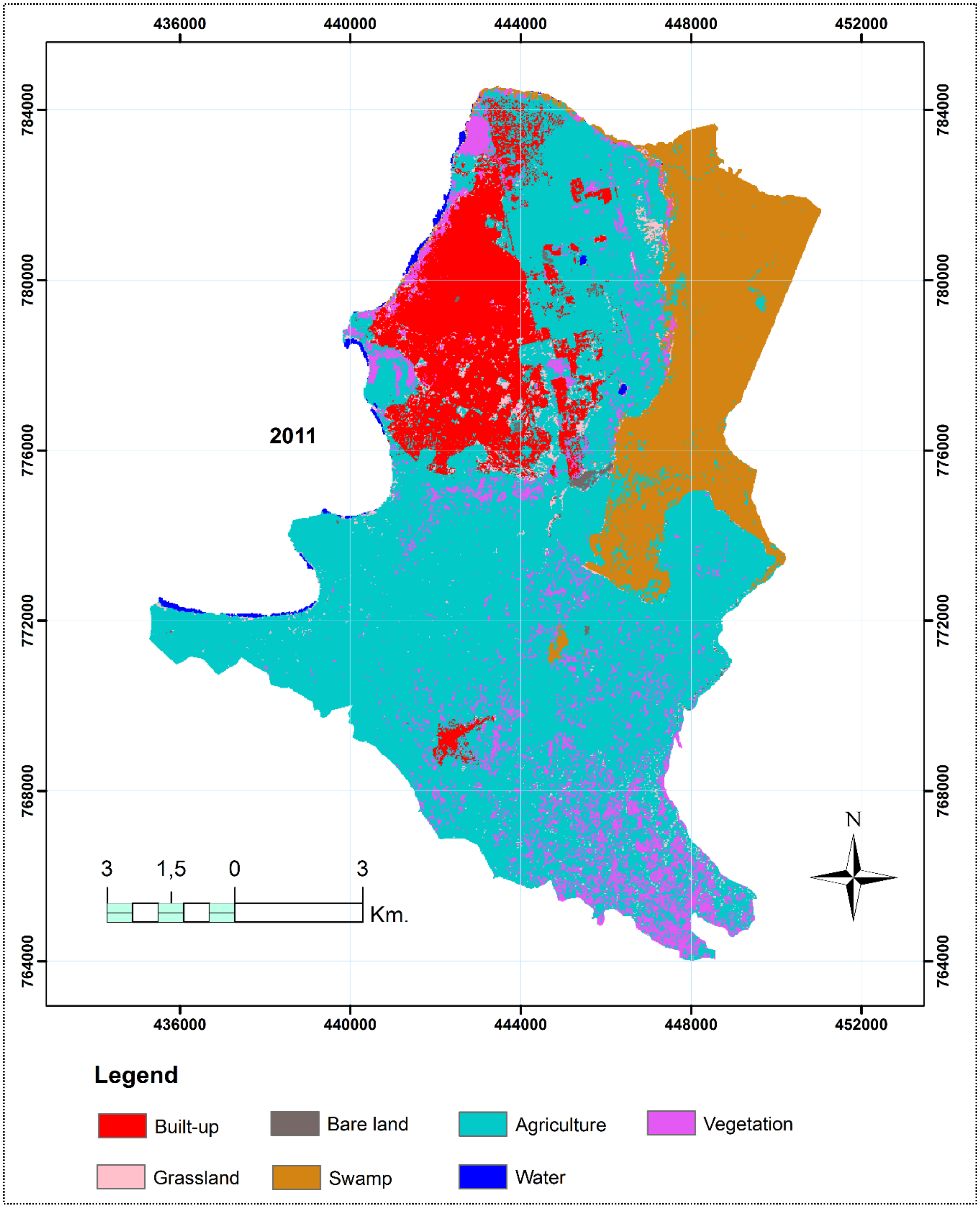
D. Enlarged thematic map from Paper I (Fig. 3)



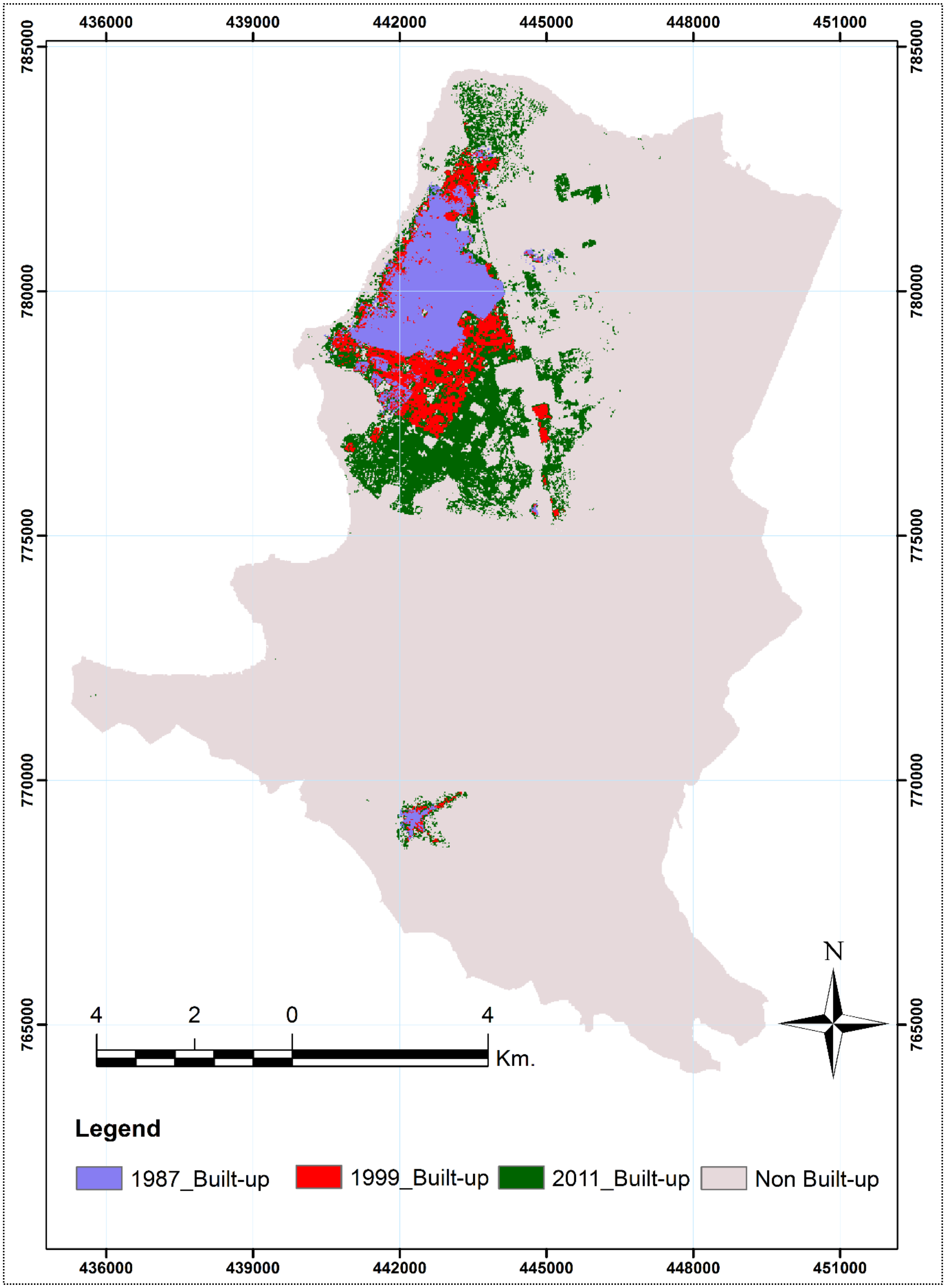
E. Enlarged thematic map from Paper II (Fig. 2)



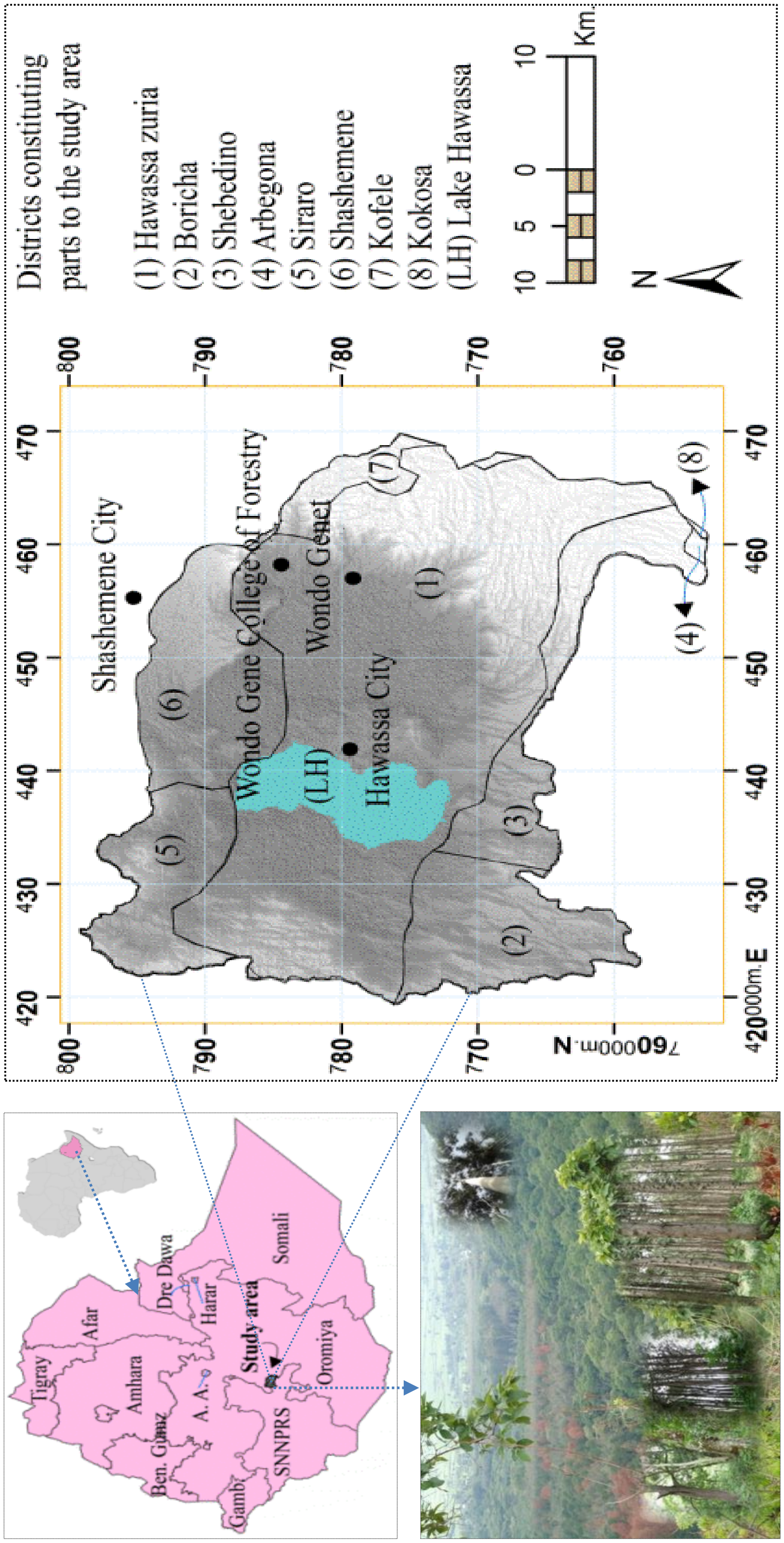
F. Enlarged thematic map from Paper II (Fig. 2)



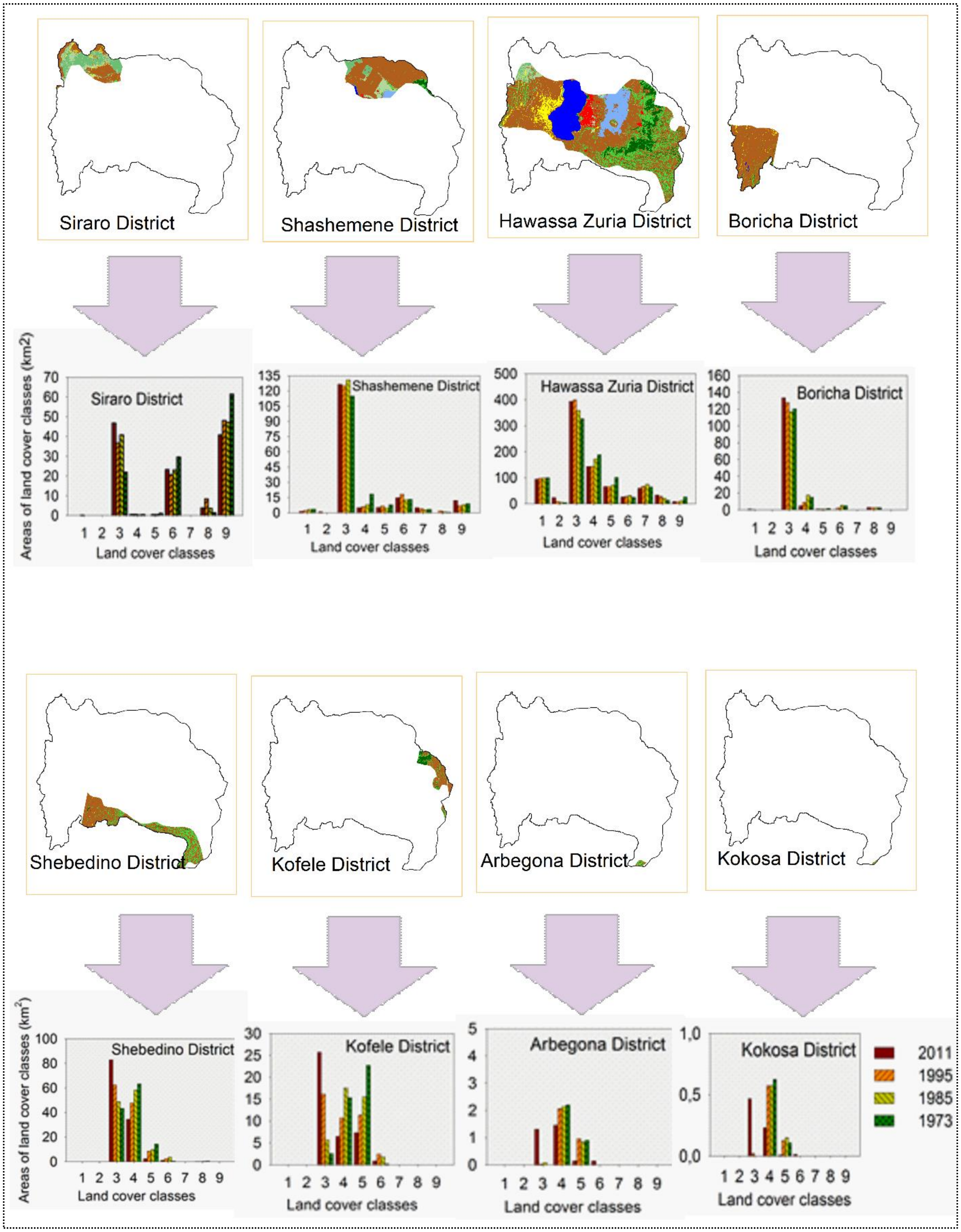
G. Enlarged thematic map from Paper II (Fig. 2)



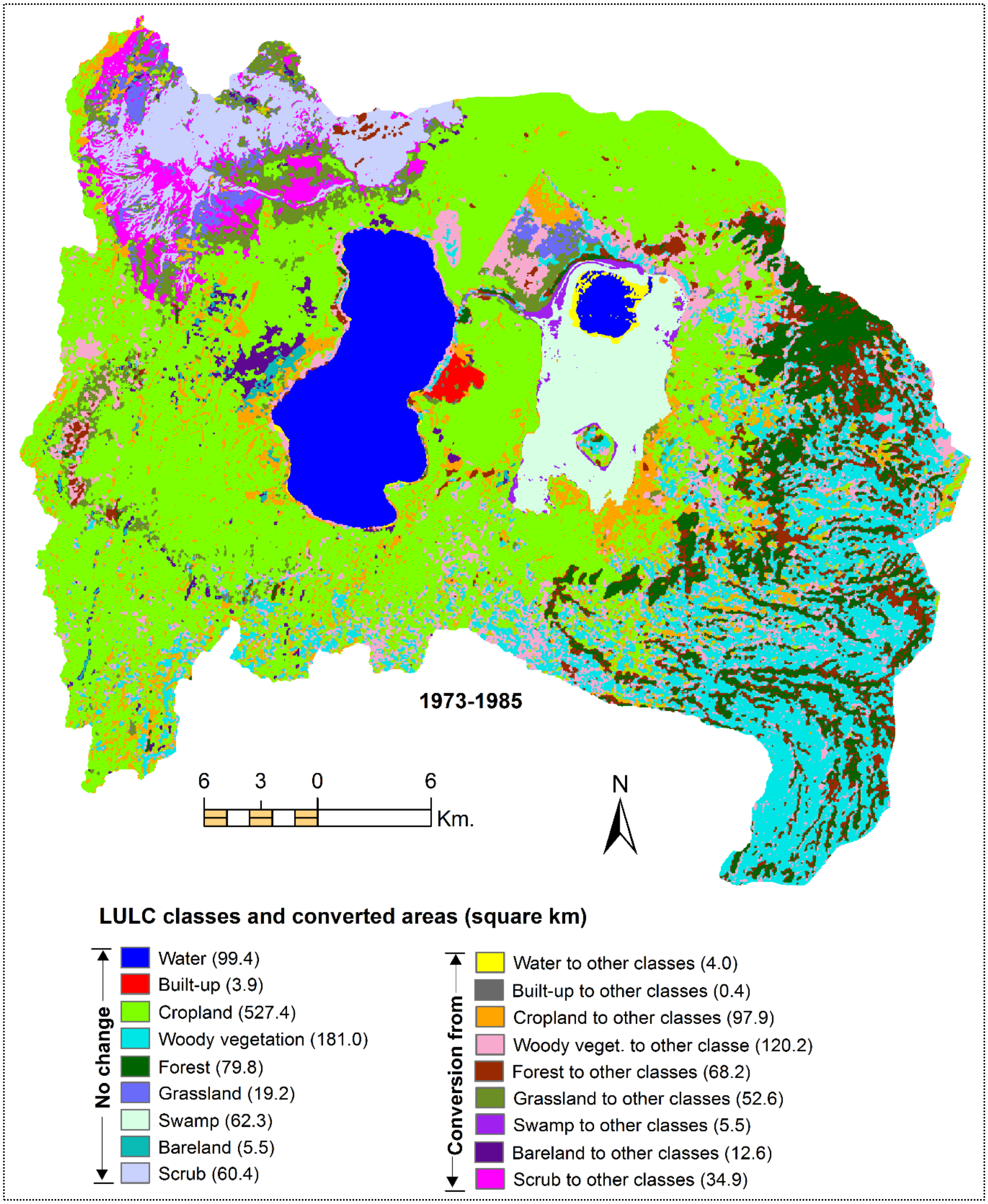
H. Overlay of classified built-up areas from Paper II (Fig. 3)



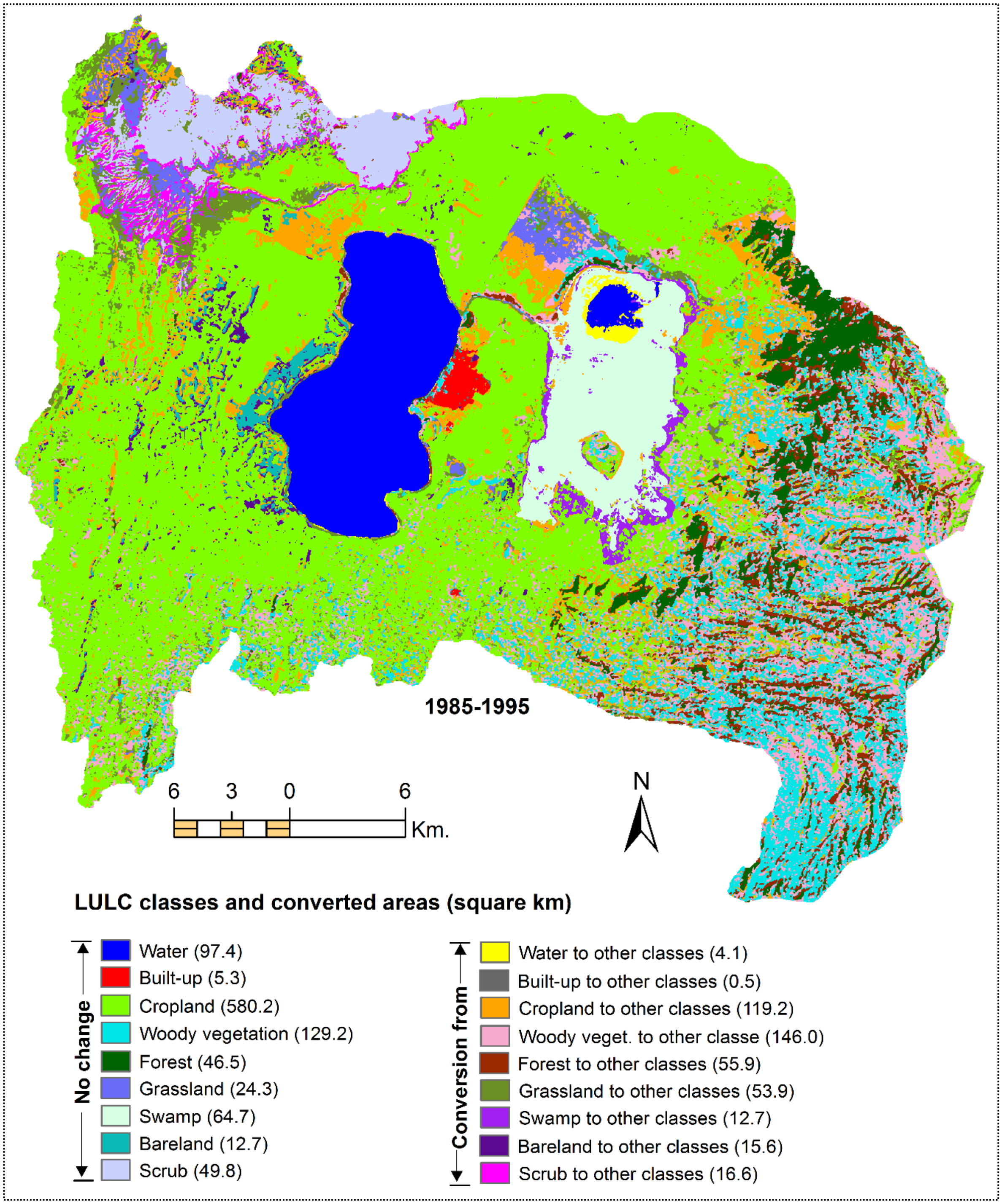
I. Maps describing the study area from Paper III (Fig. 1)



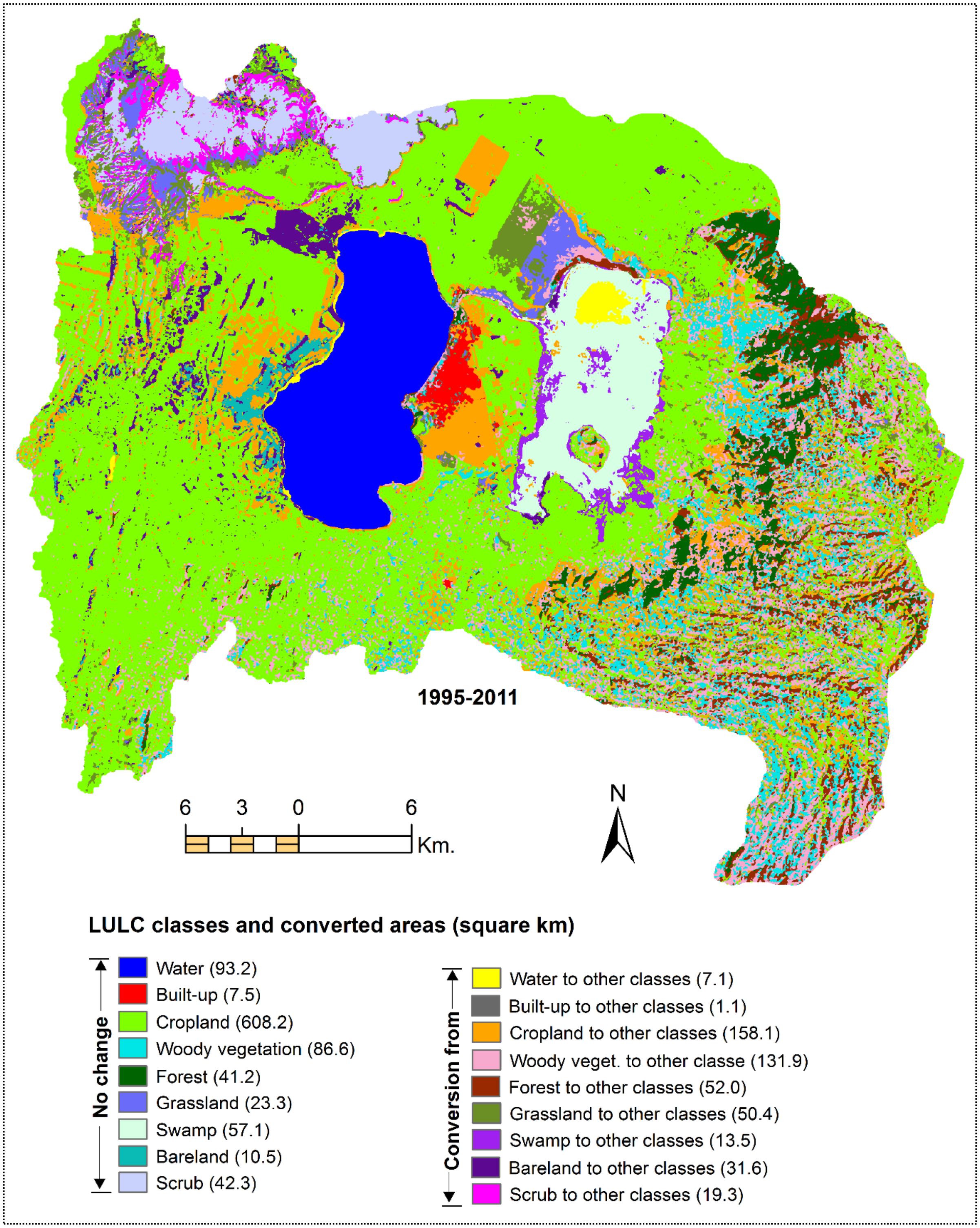
J. Land cover classes and their corresponding areas (km2) in each district (Paper III, Fig. 2)



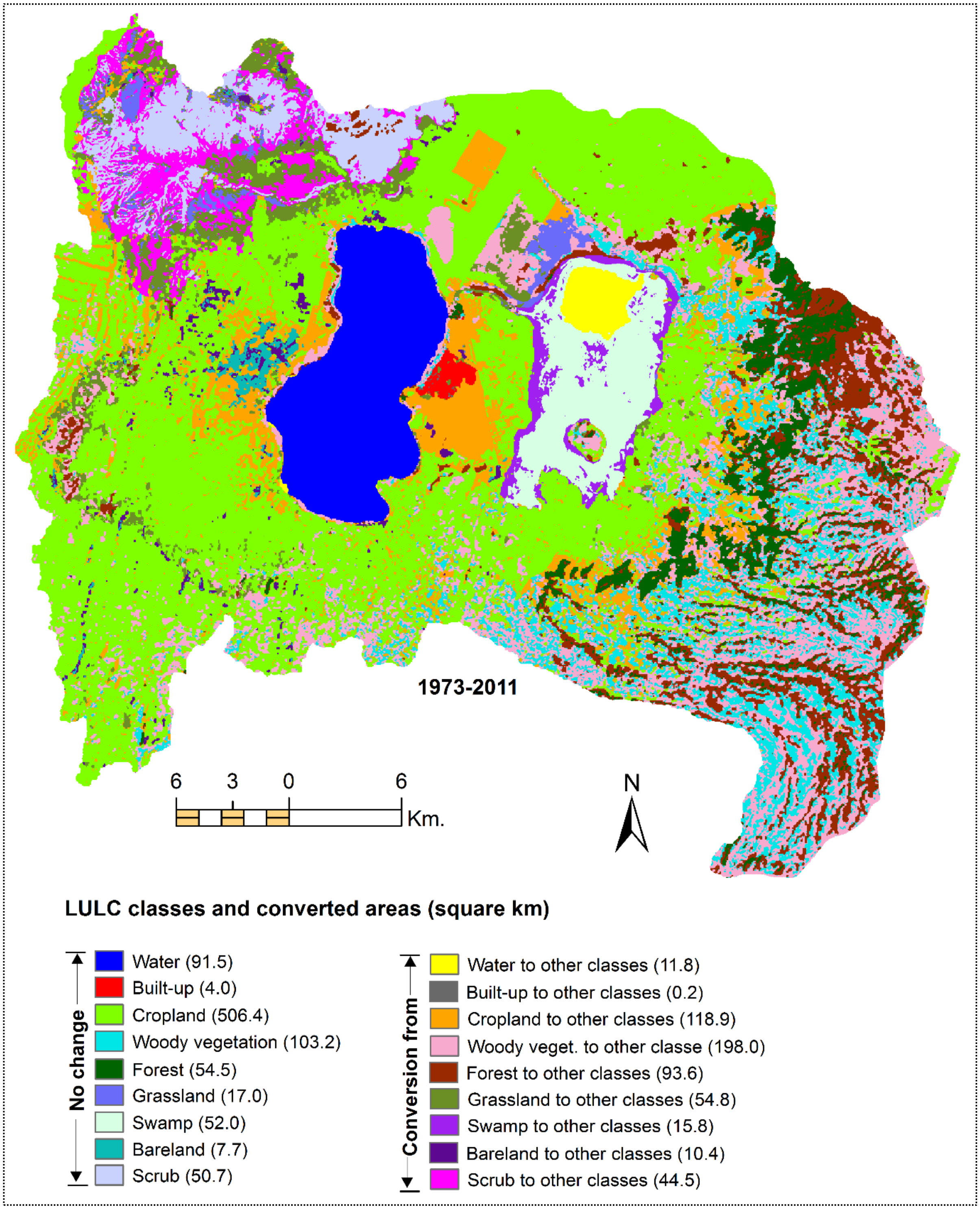
K. Patterns of LC conversions between two dates (Paper IV, Fig. 2)



L. Patterns of LC conversions between two dates (Paper IV, Fig. 2)



M. Patterns of LC conversions between two dates (Paper IV, Fig. 2)



N. Patterns of LC conversions between two dates (Paper IV, Fig. 2)

List of questions prepared to collect information from key informants

These questions are prepared to collect data about land scape changes and their underlying driving forces in the Lake Hawassa watershed for the study periods extending from 1973 to 2011 G. C. The intention of the questionnaire is to eventually generate information about the trends and possible driving forces of land cover (LC) changes that could be used for planning and sustainable management of natural resources and make associated decisions by development practitioners and policy makers. Thus, we kindly request you to freely respond to all enquiries. Your inputs are highly valuable and the information you provide will be used only for research purpose and kept confidential.

Part I: Personal data

Q1. Date of interview: ………………………………………………………………………………

Q2. Name (Code No.) of interviewee ……….Age: ………Position/occupation …………………..

Q3. Permanent residence ……………………………Educational background…………………….

Part II: Questions to collect information on driving forces of change

Q4. What are the major LC types of Lake Hawassa Watershed? (Explanation needed).

a. ………….. c. ………….. e. …………….. g. ………………... i. ………………….

b. ………….. d. ………….. f. …………….. h. ………………... j. ………………….

Q5. Do you think that these land cover types are subjected to change over the study period (1973-2011)? Mark ✓ in the box of your response. Yes ☐ No ☐

Q6. Describe the proportion of land cover types in Q4 above in terms of coverage? Use the table given below and write the numbers 1-5 indicating the proportion from highest (1) to lowest (5):

Land Cover Classes	Proportion In 1973	Proportion In 1985	Proportion In 1995	Proportion In 2011	Remark
a.					
b.					
c.					
.					
.					
i.					
j.					
Note: 1=Very high; 2=High; 3=Medium; 4=Low; 5=Insignificant					

Q7. Is there land degradation problem in Lake Hawassa watershed? Yes ☐ No ☐

Q8. What types of land, in your view, are vulnerable to degradation? The answer could be one or more. This applies to all temporal intervals.

i. Highly vegetated area
ii. Land with scarce vegetation cover
iii. Bare land
iv. Water stressed land
v. Over grazed land
vi. Intensively cultivated land
vii. Others (specify)……………………………………………………………………..

Q9. How do you characterize land degradation? The answer could be more than one.

a. intensity of soil erosion
b. extent of gully formation
c. scarcity of vegetation cover
d. amount of unfertile soil
e. degree of water stress
f. deforestation rate
g. Others (specify) …………………………………………………………………..

Q10. Give detail explanation on the possible causes of land cover change and degradation in the watershed? Please give due emphasis to this question.

No.	Explanation
1	
2	
.	
.	
.	

Q11. List the major sources of (a_i) energy, (b_i) construction materials, and (c_i) animal feed in the area between the points in time considered for land cover change analysis?

No.	Source of energy	Source of construction material	Source of animal feed	Remark
	a_1..............................	b_1..	c_1..............................	
	a_2..............................	b_2..	c_2..............................	
	a_3..............................	b_3..	c_3..............................	
	a_4..............................	b_4..	c_4..............................	
	a_5........................	b_5..	c_5..............................	

Note: If you have more answers than enumerated above, please use additional paper or back of this page.

Q12. Please give your evaluation about the status of forest and woody vegetation resources in the study area over the last 40 years?

Q13. What are the major problems associated with water resources in this watershed area?

Q14. Name the types and preferences of crops grown in the area?

Q15. What are the main sources of livelihood in the area?

Q16. What are socio-economic factors contributing to land cover change?

Q17. What major policy changes, regulations, or new practices have occurred during the last four decades that affected the land management system in the study area?

Q18. Describe the most critical issues that need intervention along with the possible solutions to address those issues?

Q19. Other additional comments: ……………………………………………………………

Erratum

Cited literature numbering was incorrectly entered into the reference list which is found at the end of **Paper III**. The correct numbering along with the missing source that caused the shifting of citations is given in the table below.

Citation numbers in text (no error)	Read the citation numbers in the reference list as	Remark
1	1	No correction
2	Not given	Bekele M (2011)*
3	2	
4	3	
5	4	
. . .	. . .	
58	57	
59	58	
60	59	

*Bekele M (2011) Forest plantations and woodlots in Ethiopia. African Forest Forum 1 (2): 1-52.

This page is intentionally left blank

Individual Papers I-IV

Paper I

Wondrade, N., Dick, Ø. B., & Tveite. H. (2014). GIS based mapping of land cover changes utilizing multi-temporal remotely sensed image data in Lake Hawassa Watershed, Ethiopia. *Environmental Monitoring and Assessment*, 186(3), 1765-1780.

.

This page is intentionally left blank

GIS based mapping of land cover changes utilizing multi-temporal remotely sensed image data in Lake Hawassa Watershed, Ethiopia

Nigatu Wondrade, Øystein B. Dick & Havard Tveite

Environmental Monitoring and Assessment
An International Journal Devoted to Progress in the Use of Monitoring Data in Assessing Environmental Risks to Man and the Environment

ISSN 0167-6369

Environ Monit Assess
DOI 10.1007/s10661-013-3491-x

ONLINE FIRST

ENVIRONME
MONITORING
AND ASSESSMENT

An International Journal devoted to progress in the use of monitoring data in assessing environmental risks to Man and the environment.

ISSN 0167-6369

Editor: G. B. Wiersma

Volume 185 No. 12 December 2013

Springer

Springer

Environ Monit Assess
DOI 10.1007/s10661-013-3491-x

GIS based mapping of land cover changes utilizing multi-temporal remotely sensed image data in Lake Hawassa Watershed, Ethiopia

Nigatu Wondrade · Øystein B. Dick · Havard Tveite

Received: 14 March 2013 / Accepted: 10 October 2013

Abstract Classifying multi-temporal image data to produce thematic maps and quantify land cover changes is one of the most common applications of remote sensing. Mapping land cover changes at the regional level is essential for a wide range of applications including land use planning, decision making, land cover database generation, and as a source of information for sustainable management of natural resources. Land cover changes in Lake Hawassa Watershed, Southern Ethiopia, were investigated using Landsat MSS image data of 1973, and Landsat TM images of 1985, 1995, and 2011, covering a period of nearly four decades. Each image was partitioned in a GIS environment, and classified using an unsupervised algorithm followed by a supervised classification method. A hybrid approach was employed in order to reduce spectral confusion due to high variability of land cover. Classification of satellite image data was performed integrating field data, aerial photographs, topographical maps, medium resolution satellite image (SPOT 20 m), and visual image interpretation. The image data were classified into nine land cover types: water, built-up, cropland, woody vegetation, forest, grassland, swamp, bare land, and scrub. The overall accuracy of the LULC maps ranged from 82.5 to 85.0 %. The achieved accuracies were reasonable, and the observed classification errors were attributable to coarse spatial resolution and pixels containing a mixture of cover types. Land cover change statistics were extracted and tabulated using the ERDAS Imagine software. The results indicated an increase in built-up area, cropland, and bare land areas, and a reduction in the six other land cover classes. Predominant land cover is cropland changing from 43.6 % in 1973 to 56.4 % in 2011. A significant portion of land cover was converted into cropland. Woody vegetation and forest cover which occupied 21.0 and 10.3 % in 1973, respectively, diminished to 13.6 and 5.6 % in 2011. The change in water body was very peculiar in that the area of Lake Hawassa increased from 91.9 km^2 in 1973 to 95.2 km^2 in 2011, while that of Lake Cheleleka whose area was 11.3 km^2 in 1973 totally vanished in 2011 and transformed into mud-flat and grass dominated swamp. The "change and no change" analysis revealed that more than one third (548.0 km^2) of the total area was exposed to change between 1973 and 2011. This study was useful in identifying the major land cover changes, and the analysis pursued provided a valuable insight into the ongoing changes in the area under investigation.

Keywords Lake Hawassa Watershed · Land cover · Remote sensing · Change detection

Introduction and background

A rapidly expanding human population and associated demands for goods and services is exerting an

Nigatu Wondrade (✉)
Department of Biosystems and Environmental Engineering,
Institute of Technology, Hawassa University,
P. O. Box 5, Hawassa, Ethiopia
e-mail: nigatwond@yahoo.com

Ø. B. Dick · H. Tveite
Department of Mathematical Sciences and Technology,
University of Life Sciences,
P. O. Box 5003, Ås N-1432, Norway

increasing pressure on ecological systems. This is justified as, on the one hand, demands for every natural resources have dramatically increased and will continue to increase (FAO 1997), and on the other hand, natural resources have reduced both in quantity and quality as extraction has become more intensive and extensive than before (Vitousek et al. 1997). As a result, much of the world's biodiversity has been lost and many species have become threatened and endangered (Wilson and Peter 1988). Other ecological consequences include degradation of ecosystem, goods and services, landscape fragmentation, and unsustainable use of natural resources (WCED 1987). Furthermore, the management of natural resources has become more constrained and complex due to the interactions among ecological, political, socioeconomic, demographic, and behavioral factors (Liu and Taylor 2002).

Land use land cover (LULC) changes have been given increasing attention from both the environmental and socioeconomic points of view. These changes are spreading rapidly involving large areas, especially in developing countries, and their influence on the environment is getting immense (Rembold et al. 2000). One of the relatively inexpensive methods of dealing with land cover changes is through the use of remotely sensed data. In developing countries, however, availability of high-resolution remotely sensed data is often limited. One way of overcoming limitations in change observability is to extend analysis over longer time-spans, say 20–40 years. In this way, change trends are allowed more time to exhibit their physical effects on the land surface for better change detection (ibid). But extending the time span covered by change analysis in turn may limit us to use only low resolution satellite imagery which is demanding in relation to identification of ground control points (GCP).

Studies have shown that there remain only few landscapes on earth which are still in their natural state. Due to anthropogenic activities, the Earth surface is being significantly altered in some manner and human presence on Earth and their use of land has had a profound effect upon the natural environment thus resulting in an observable pattern in the LULC change over time (Zubair 2006). It is also believed that LULC change is a major component of global change with an impact perhaps greater than that of climate change (Jensen 2005). Therefore, it is not surprising that significant efforts are directed to the development of land cover change detection methods using remotely sensed data as an indispensable tool that provides the required information for decision makers in natural resource management and sustainable development (Das 2009).

Certain problems related to land cover changes are not yet fully addressed. The world's forest cover shrunk by 3.1 % between 2000 and 2005, according to satellite observations detailed in a study published recently (FCSG 2010). The findings indicate that the forest area in Ethiopia declined from about 40 % at the end of the nineteenth century to less than 3 % in the year 2000 (Dessie and Christiansson 2008).

Horizontal expansion of rain-fed agriculture replacing the existing woody vegetation and grasslands is an intense event in the current research area. Demographic factors, soaring prices of wooden products, low agricultural technology, and urbanization are some of the visible causes of land cover changes in the Lake Hawassa watershed. The study area, in general, is experiencing remarkable changes in the last four decades. These calls for land cover change analysis and generating updated land cover maps that could provide useful information for development practitioners, and environmental policy and decision makers to sustainably manage natural resources. To address the problem, there were studies conducted with varying area of focus and smaller temporal intervals. Rembold et al. (2000) focused on land cover changes in the upper part of the middle Ethiopian Rift Valley between 1972 and 1994, but did not cover the whole of Lake Hawassa watershed. Moreover, Bedru (2010) reported that there were active LULC change processes in the whole Rift Valley between 1973 and 2000.

Therefore, this study aims at mapping and analyzing land cover changes between 1973 and 2011 utilizing multi-temporal image data from space-borne platforms, and disclosing the findings for further planning and support decision making in resource management. It involves classification of the selected image data, production of land cover maps, and quantification of changes that occurred during the study periods. Thus, the study is expected to provide updated information about the ongoing LULC changes and their causes for decision makers to develop strategies that will enable sustainable use of the available resources, and preservation of the ecosystem.

Materials and methods

Description of the study area

Lake Hawassa watershed lies within 6°48′48″ to 7°13′47″N latitude and 38°16′15″ to 38°43′36″ E longitude extending both in Southern Nations, Nationalities, and People's Regional State (SNNPRS) and Oromiya Regional State, Ethiopia. About 58.6 % of the study area is part of Hawassa Zuria district making the total area of the catchment 77 % in SNNPRS. The research area is composed of parts from eight "Weredas" or districts as shown in Fig. 1. The naming and demarcation line between these districts vary from time to time as the spatial setting is on border between the two regional states. This study area (Fig. 1) is situated 275 km south of Addis Ababa in the Central Main Ethiopian Rift Valley covering 1435 km^2. The watershed is characterized by a flat-lying plain and dissected rolling topography with an altitude ranging from 1,571 to 2,962 m above sea level.

Ethiopia is located in the region where the main rainy season is from June through September. However, Lake Hawassa watershed has even more extended period of wet season (March to October) with mean monthly rain fall varying from 85 to 133 mm (Yemane 2004). The mean annual rainfall based on 18 to 38 years of recorded metrological data from five rain fall stations that contribute to the watershed is estimated to be 1,060.07 mm.

The mean annual temperature of the area varies from 12.5 to 26.01 °C as computed from the metrological data recorded for ten years in Hawassa and Wondo Genet stations. The temperature data for Shashemene was obtained from the Ministry of Agriculture.

The population of Hawassa watershed reported for the year 2007 was 757,496 (AG Consults 2007, cited in Demelash 2008).

Lake Hawassa, the smallest and located at the highest altitude in the central Main Ethiopian Rift Valley, is one of the tourist attractions of Hawassa City, the capital of regional State which is located at its eastern shore. At the national level, Hawassa Lake is a major source of income through tourism and is one of the biggest bird sanctuaries in Ethiopia (Tenalem and Yemane 2006).

The major land cover in the study area is agriculture, involving rearing of animals. The main crops grown include maize, barley, sugarcane, enset, khat, coffee, and other perennials. Barley is cultivated in the south eastern highlands of the watershed while Perennial crops are mostly grown in the eastern part. Eastern

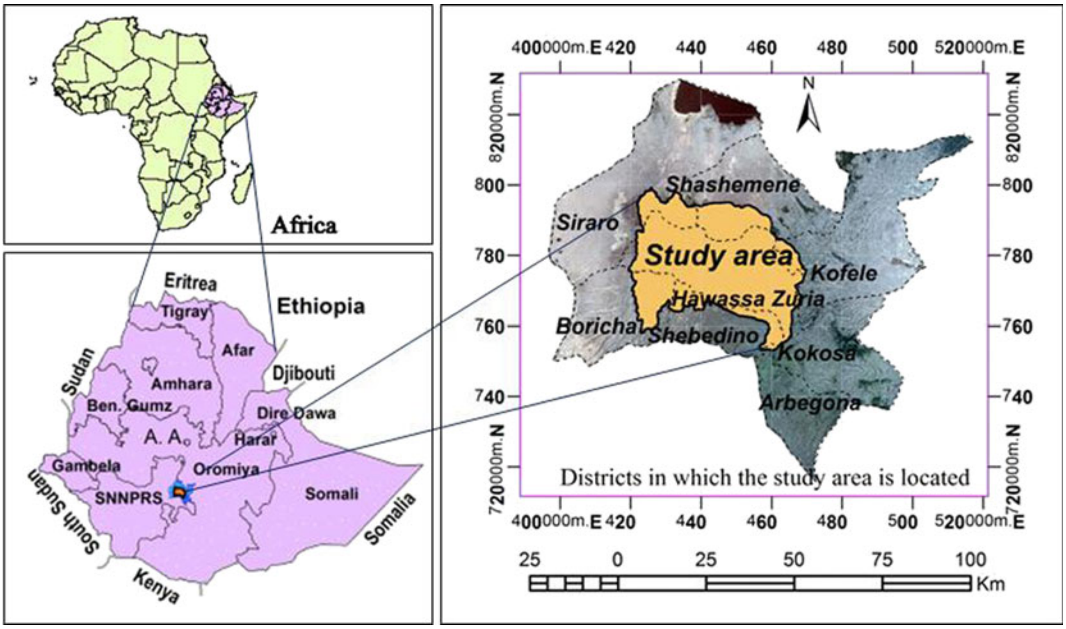


Fig. 1 Map showing location of the study area

and north-eastern portions of the study area are covered much more by vegetation than the western part. The north-western part of the watershed, sheltering Senkelle Swayne's Hartebeest sanctuary, was identified as scrubland. The Abaro highlands and some Wondo Genet areas are characterized by natural and plantation forest dominated by species like *Cupressus lucitanica*, *Juniperus procera*, *Grevillea robusta*, *Pinus patula* and different species of Eucalyptus trees.

Data acquisition and preparation

Satellite image data sets

The choice of appropriate satellite image data sources was determined based on the available funding, suitable image data covering the study area, and the availability of sufficiently long time image series for the analysis of land cover change dynamics.

With the above criteria, the following four Landsat satellite image data sets were used in this study: One historical Landsat Multi Spectral Scanner (MSS) image acquired on 31 January, 1973, and three Landsat Thematic Mapper (TM) images acquired on 02 January, 1985, 14 January, 1995, and 10 January, 2011 covering a period of nearly four decades. These images were downloaded from the Website, Global Visualization Viewer at http://glovis.usgs.gov/, where image data sets are archived. The characteristics of the image data are described in Table 1. Such Landsat imageries have been used for land use land cover change analysis in similar landscape settings (Bedru 2010).

To deal with land cover change detection, the choice of appropriate image data sources and their availability at different points in time is essential. Here, the Landsat image data sets used for this study were with reasonable time series and were acquired on dates that are as close as possible. The time is also in the same vegetation season (dry season) to take satellite images without cloud cover. Using anniversary date imagery minimizes the influence of seasonal Sun-angle and plant phenological difference that can negatively impact a change detection process (Coppin et al. 2004; Samimi and Kraus 2004; Jensen 2005; Congalton and Green 2009).

The image acquired on 02 January, 1985 has 10 % cloud cover on the full scene, but this was limited to its lower right quadrant. The small patches of cloud covering less than 10 km^2 in the study area were masked and replaced by the underlying cover types using SPOT image data from 1987 as the dots of cloud were on discernible cropland, woody vegetation and forest land categories.

All images used were obtained geometrically corrected and projected to Universal Transverse Mercator (UTM) coordinate system (WGS 84 datum, UTM Zone 37 N).

Ancillary data

Four topographical map sheets were used, two from 1976 which was published by the Ethiopian Surveying,

Table 1 Landsat MSS and TM sensor system characteristics

Date of acquisition	Sensors	Path/row	Processed spatial resolution (m)	Bands	Bandwidth (μm)	Spectral region
31-Jan-1973	Landsat MSS	181/55	57×57	1	0.5–0.6	Green
				2	0.6–0.7	Red
				3	0.7–0.8	NIR
				4	0.8–1.1	NIR
02-Jan-1985	Landsat TM	168/55	30×30	1	0.45–0.52	Blue
				2	0.52–0.60	Green
				3	0.63–0.69	Red
14-Jan-1995	Landsat TM	168/55	30×30	4	0.76–0.90	NIR
				5	1.55–1.75	SWIR
				6	10.4–12.5	TIR
10-Jan-2011	Landsat TM	168/55	30×30	7	2.08–2.35	SWIR

NIR near infrared, *SWIR* short wave infrared, *TIR* thermal infrared

Mapping and Geography Institute, and one each from 1979 and 1988 which were published by the Ethiopian Mapping Agency (EMA). These topographic maps with scale 1:50,000 that cover the study area were scanned using high-resolution scanner (1,500 dpi) in BMP file format. Each map sheet was scanned in six pieces living a common area for georeferencing and mosaicking. Geometric correction was applied to each piece in ERDAS Imagine GCP tool. After choosing the output projection (UTM), input and reference coordinates were entered in digital correction tool. Reference coordinates of 12 points that were taken from the topographic map were entered manually using keyboard. Using the entered coordinates, each map piece was geocoded. Then, all pieces were georeferenced and mosaicked to form the map that covers the study area. The output topographic maps were then used to register all the Landsat MSS and TM image data. The field work related to all attributes in the topographic map which was published in 1988 was completed in 1985. This gave us the opportunity to use it for generating training areas and reference data for the analysis of image data set from 1985. SPOT image data that was acquired on 20 January, 1987 with spatial resolution of 20 m was also used as a supplemental ancillary data.

The other ancillary data used in this study to extract training areas for classification and accuracy assessment were aerial photographs from 1972/73 and topographical maps from 1976 that were obtained from EMA. Training pixels and polygons were generated from aerial photographs that were rectified by the supplier and topographical maps from 1976. Identification of training pixels for each LULC classes was performed through visual interpretation augmented by knowledge of the study area. The training polygons were overlaid to the image to classify and produce cover maps. In the absence of better ancillary data, the aerial photographs were found useful to generate training and reference data for the historical Landsat image from 1973.

Classification and accuracy assessment for the Landsat TM image data from 1995 was performed following a different approach. Landsat TM images acquired on 21 November, 1989 and 25 January, 1999 (before and after the image from 1995) were classified to identify pixels/polygons where no changes have occurred. To classify image from 1989 and 1999, the topographic map from 1988 and Google Earth satellite images (QuickBird 2003) were used, respectively. The two classified image data were overlaid in ERDAS Imagine with matrix function and image areas for each LULC class where no changes occurred and which were common for both files were identified. This procedure also allows us to quantify land cover classes that are exposed to change into one category: changed area. It is believed that an area where definite land cover class remains unchanged on both images will also bear the same type of land cover class in the image between them. Training pixels and reference data were selected within those areas on the output image data common to both image files. The selection of training and reference data on unchanged areas of images from 1989 and 1999 were performed using the ancillary data following similar procedures applied in other TM images. The selected training pixels and reference points were transferred to the image data from 1995 to perform classification and accuracy assessment. This approach was augmented by visual interpretation and knowledge of the study area. The output thematic map of 1989 and 1999 along with the selected training pixels for each category is shown in Fig. 2.

Fieldwork was undertaken from mid-January to the end of February, 2012 to collect ground data. The field work took into account the notion that the ground data collection should be around the date of image acquisition. Number of training samples and their representativeness is critical for image classification (Lu and Weng 2007). More specifically, one has to plan to collect a minimum of 50 samples for each map class for maps of less than one million acres (404,687.26 ha) in size and fewer than 12 classes (Congalton 2001; Congalton and Green 2009).

The research area covers a relatively large watershed, 143,500 ha, and nine land cover classes were identified. Hard copies of topographical maps and a false color composite TM 2011 image were used in the field to identify existing land cover types. During this fieldwork, a total of 962 reference points that were dispersed throughout the research area were collected in two runs using a hand held Global Positioning System (GPS).

In the first round, 434 reference points were collected to locate training pixels and extract training areas on the image from 2011, while the remaining 528 reference points were collected during the second round to evaluate thematic map accuracy. The training pixels and reference points were overlaid with the TM

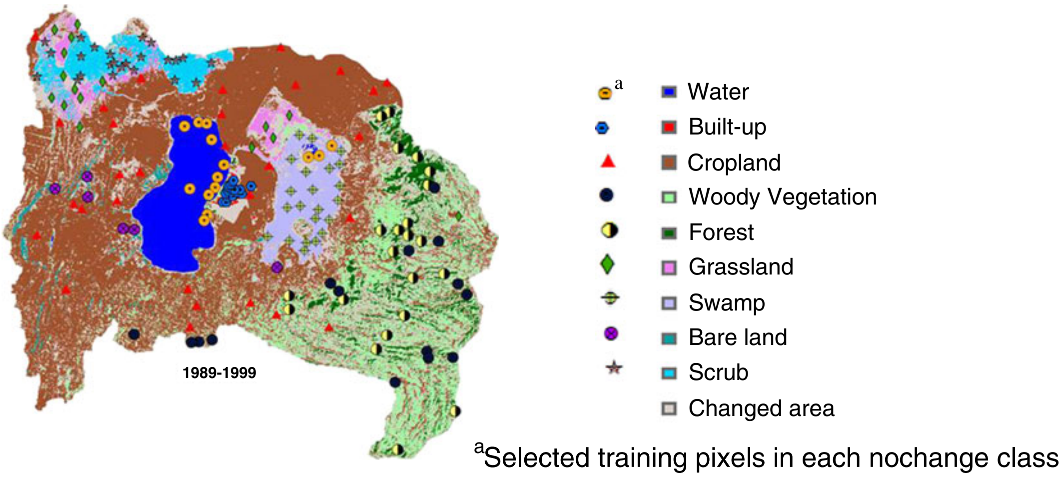


Fig. 2 Thematic map of unchanged land cover classes with the selected training pixels

image from 2011 in ArcGIS 10.1 to select training polygons and perform accuracy assessment.

Image pre-processing

Pre-processing of satellite images prior to change detection is essential and has the unique goal of establishing a more direct linkage between the data and biophysical phenomena (Abd El-Kawy et al. 2010). Accordingly, geometric correction was applied to all Landsat image data taking the scanned topographical maps as reference images with the aim to make temporal images spatially compatible before classification. This was done after all the reflective bands with Tagged Image File format were stacked into a single multi-band image excluding thermal band because of its low resolution and uncertainty that may arise when resampled to 30×30 m to match the other bands. The geometric correction was applied using GCPs collected using GPS at easily recognizable locations like road intersection and stream confluences (Jensen 2005). Nearest neighbor resampling method was employed not to alter the original pixel values before classification. The total Root Mean Square Error (RMSE) achieved was 0.97 and 0.76 pixels for MSS image and TM images, respectively, which are within the conventionally permissible limits of less than 1 pixel (Rozenstein and Karnieli 2011). Radiometric corrections and removing systematic errors were performed by the image data set providers. Each image data set was then subsetted to include only the study area by importing a vector file in ERDAS Imagine.

Classification scheme

When planning a project involving remotely sensed data, it is very important that sufficient attention is given to the classification scheme to be used. Such classification scheme should first of all be mutually exclusive and totally exhaustive (Congalton 1991). To this end, classification systems for use with remote sensing data have been developed by USGS, European Coordination of Information on the Environment (CORINE), and Africover. However, there is no one ideal classification of land use and land cover, and it is unlikely that such a system could ever be developed (Anderson et al. 1976).

Considering the specific nature of the landscape in the study area and the heterogeneous character of the land cover types, one or the other classification scheme alone was not adopted. Most of the land cover types identifiable by remote sensing are organized on the basis of the USGS Level I classification scheme (Jensen 2005). For classification, nine land cover classes were established in the scheme as water, built-up, cropland, woody vegetation, forest, grassland, swamp, bare land, and scrub. Detailed descriptions of the land cover classes are given in Table 2.

Image classification

Perhaps the most basic form of land cover analysis within the field of remote sensing is land cover classification. This involves the association of features within remotely sensed imagery (often, pixels) with

Table 2 Land cover classes considered and their description

No.	Land cover class	Description
1	Water	All areas of open water, including lakes, rivers, and ponds
2	Built-up	Included in this category are residential, commercial, and industrial buildings, transportation infrastructures, and play grounds.
3	Cropland	Mechanized and small holder's farms are components of cropland. Both are characterized by tilled and planted, bare crop fields, and limited areas temporarily left as fallow.
4	Woody Vegetation	Land covered by bushes and shrubs, in some cases mixed with grasses. Ground cover often composed of patches of woodland, scattered trees and perennial crops, such as Khat (*Catha edulis*) and Coffee (*Coffea arabica*).
5	Forest	Natural and plantation forest with trees forming open to closed canopies, 30–70 % and more than 70 % respectively. Predominant species in plantation forest are *Cupressus lucitanica*, *Juniperus procera*, *Grevillea robusta*, *Pinus patula* and different species of Eucalyptus.
6	Grassland	Areas dominated by herbaceous vegetation with low occurrence of shrubs.
7	Swamp	Area with topographic low where water table is near, or above the land surface. The occurrence of herbaceous vegetation is also obvious.
8	Bare land	Land surface devoid of vegetation, sand along lake side, exposed rocks, and quarries.
9	Scrub	Specific area characterized by scattered bushes to closed canopy vegetation dominated by shrubs, grasses, and small trees usually less than 5 m tall, and occasionally with few scattered trees.

specific land cover classes and results in the production of land cover maps (Aplin 2004).

The study area considered for classification was characterized by highly fragmented land holding system and heterogeneous land cover. Landsat images that were taken from this area contain land cover types some of which, for instance, cropland covers significantly large areas, while others occupy relatively much smaller areas. Automatically detecting regions of such widely varying sizes and heterogeneity using available algorithms always presents a challenging task.

Classification of each segment was accomplished by a hybrid method, whereby spectral signatures for specific land cover classes were created using unsupervised training followed by supervised training. Using a combination of supervised and unsupervised classification may yield optimum results, especially with large data sets. Unsupervised classification was used for generating a basic set of classes, and supervised classification for further definition of the classes (ERDAS 2005).

Unsupervised classification algorithms compare pixel spectral signatures to the signatures of computer-determined clusters and assign each pixel to one of these clusters. Knowledge of the materials contained within the scene is not needed beforehand as the computer assesses the inherent variability and determines cluster identification. The *Iterative Self-Organizing Data Analysis Technique* (ISODATA) is one of and by far the most commonly used clustering method. The ISODATA clustering method uses spectral distance of pixels and iteratively clusters pixels, redefines the criteria for each class, and classifies again so that the spectral distance patterns in the data gradually emerge (ERDAS 2005; Jensen 2005, cited in Bedru 2010).

The other method, the vast majority of land use land cover monitoring approaches have traditionally used for classification, is the supervised method (Rogan and Chen 2004). Supervised (Maximum Likelihood) classification is characterized by the need to use training areas to specify to the computer algorithm the brightness values that will represent one category of land use or land cover in each band of the digital image (Lo and Yeung 2002). This approach requires having a set of desired classes in mind and knowledge of ground truth and ancillary data.

Before classification, images were segmented into several units. This partitioning of image data into several geographical units was performed based on visually homogeneous land cover types supported by ancillary data, ground reference points, and knowledge of the study area. Accordingly, one Landsat MSS and three TM image data were partitioned into 38, 42, 40, and 45 parts, respectively. The rationale behind this segmentation of the study area, by means of importing and overlaying a vector file in the image processing software, was to minimize misclassification errors of different land cover classes with similar spectral signatures.

Each segment of image data was classified using ISODATA allowing a large number of classes (15–30) depending on the heterogeneity of the land cover, maximum iteration of 30, and a convergence threshold value of 0.95. The result of this operation was a map with natural grouping of pixels. Such maps were then overlaid with ancillary data to select training samples for all established land cover types. Supervised classification was performed using a set of classes generated from unsupervised classification and training samples created using ancillary data. This operation was performed repeatedly until the required thematic map was produced.

All segments of the images were classified following the same procedure and then mosaicked to form the whole. The land cover types in the classified and mosaicked images were recoded to the same number of classes. Following the recoding, a majority filter function with an operating window size of 3 by 3 was run in ERDAS Imagine to smooth the classified image by weeding-out isolated pixels (Mather 1987). Afterwards, the classified images (Fig. 3) were exported to the ArcGIS for map preparation.

Results and discussion

Accuracy assessment

In remote sensing, accuracy assessment is mandatory (Okeke and Karnieli 2006), and is important for providing information about the quality of the produced classification. One of the most common ways of representing accuracy assessment information is in the form of an error matrix (Congalton 1991; Lillesand and Kiefer 2000; Foody 2002; Lu and Weng 2007; Congalton and Green 2009). The use of classification measures such as overall accuracy, Kappa statistics, producer's accuracy, and user's accuracy are quite common (ibid).

Before using the classification results for change detection, the Landsat-based thematic maps were accordingly assessed to evaluate the percentage of pixels classified correctly and incorrectly per land cover category. The accuracy assessment was performed using independent reference data created from aerial photographs (Rembold et al. 2000), topographical maps, finer resolution image, field data (Dewan and Yamaguchi 2009), and visual interpretation (Abd El-Kawy et al. 2010). The reference points were generated with a stratified random sampling method. For each map considered, the error matrix was created in ERDAS Imagine and classification accuracy measures were derived. Tables 3, 4, 5, and 6 show the error matrices with pixel distribution in each class.

Accuracy assessment for the land cover map from 2011 was performed by importing 528 field reference points collected using a hand held GPS device while reference points for all other image data were extracted using the ancillary data described in section "Ancillary data". The accuracy of the classified maps from 1973, 1985, and 1995 were assessed by a set of 511, 583, and 560 points, respectively.

The result of the accuracy assessment for the 1973, 1985, 1995, and 2011 land cover maps showed overall accuracy of 82.4, 84.2, 83.2, and 85.0 %, respectively. Overall accuracy is a descriptive statistic which is computed by dividing the total sum of correctly classified by the total number of reference pixels in the error matrix. The producer's accuracy in all the thematic maps ranged from 75.5 to 94.3 %. User's accuracies of the maps from 1973 and 2011 were all over 80 %, except for cropland, whereas the user's accuracy for the maps from 1985 and 1995 varied between 74.2 and 94 %. The kappa technique was also utilized to assess the classification accuracy and all maps complied with the standards described by (Wilkinson 1998; Congalton 2001) that kappa values greater than 0.75 and/or 0.8 indicate strong agreement between the remotely sensed classification and reference data beyond the chance agreement.

Accuracy assessment is usually a matter of compromise between the ideal and the affordable. According to Anderson et al. (1976), Foody (2002), and Congalton and Green (2009), overall accuracy and accuracy for all classes are acceptable if greater than 85 %. Accordingly, the overall accuracies of all maps were obtained within 80 and 85 %.

The user's and producer's accuracies achieved were reasonable, but as expected, there were some difficulties in separating pixels in each class. This is exemplified by the low accuracies in cropland, grassland and woody vegetation. Such errors occur due to coarse spatial resolution of images used and land cover representing a varying spectral mixture of two or more classes. Eastern part of the study area was predominantly marked by perennial crops and woody vegetation. The difficulty to distinguish some perennial crops from woody vegetation and cropland from grassland due to similarity in spectral signature were the other sources of error. Spectral confusions were observed between bare land and paved road, and bare land and concrete

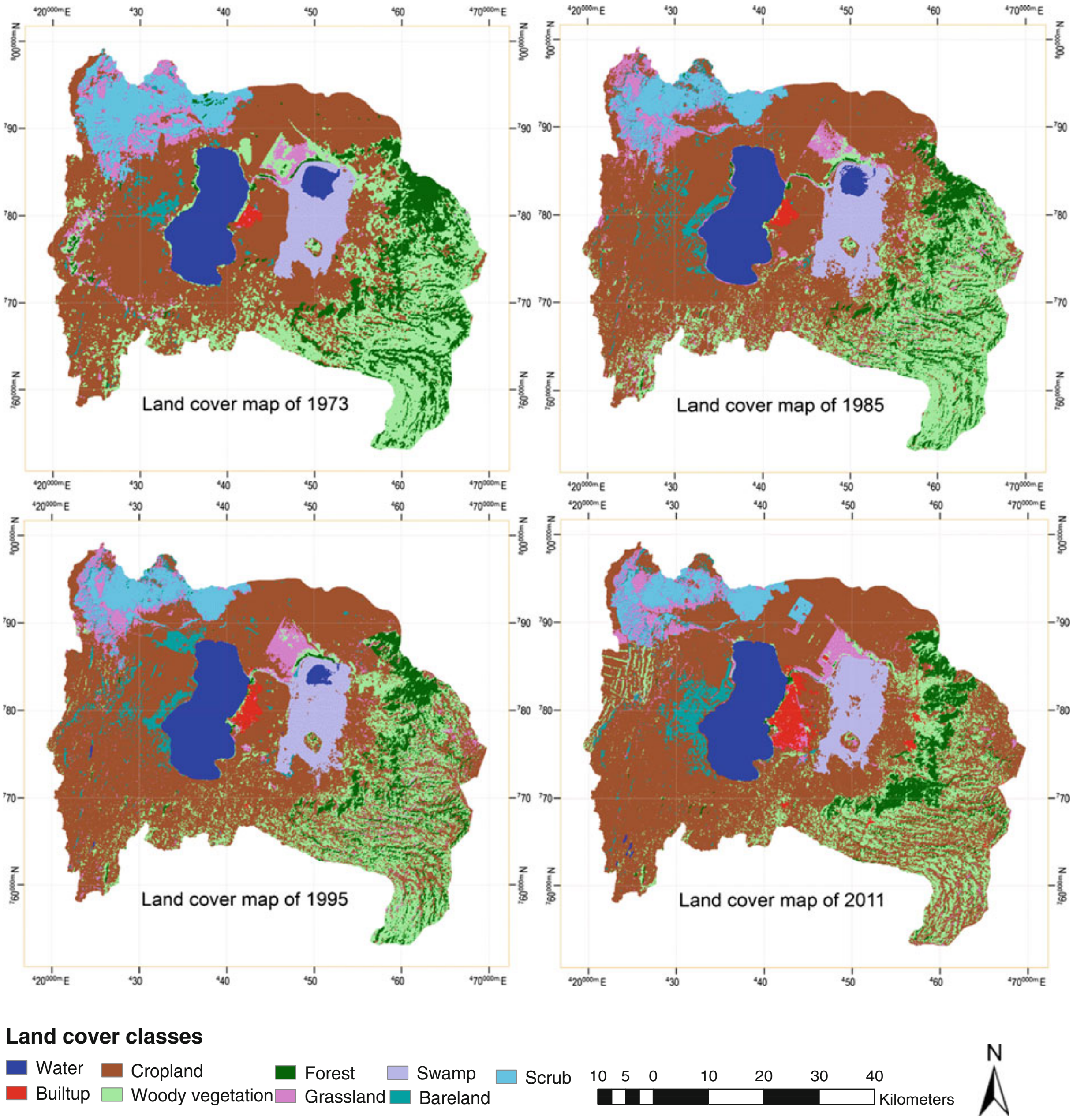


Fig. 3 Land cover maps of the study area

surfaces. Some misclassifications have also stemmed from the difficulty to discern grass dominated wet land from other classes with similar spectral responses.

Classification of the images from 1973, 1985, and 1995 was more challenging since reference points were collected from ancillary data and there were no ground trust points.

Uncertainty and error are intrinsic to spatial data (Liu et al. 2004). In the process of image acquisition, processing and thematic map production, uncertainty may be introduced and propagated. In this study, uncertainties associated with classification errors include: (1) the heterogeneity of the study area and fuzzy boundaries between LULC classes, (2) geometric distortions that remain after correction as a result of inability to correctly capture the surface in a flat perspective, (3) imperfection of the selected GCP's identified from generalized maps which

Table 3 Confusion matrix and accuracy assessment measures for 1973 image

	Land cover classes	Reference data									Row Total	User's Acc. (%)
		WR	BP	CL	WV	FT	GL	SP	BL	SB		
Classified data	Water (WR)	*50*	0	0	1	0	0	4	0	0	55	90.9
	Built-up (BP)	0	*38*	6	0	0	0	0	0	0	44	86.4
	Cropland (CL)	1	5	*66*	3	0	6	0	8	0	89	74.2
	Woody veg. (WV)	0	0	2	*40*	1	0	0	0	2	51	78.4
	Forest (FT)	0	0	1	4	*53*	0	1	0	2	61	86.9
	Grassland (GL)	0	2	2	1	0	*40*	3	2	2	52	76.9
	Swamp (SP)	3	0	2	2	1	0	*41*	0	0	49	83.7
	Bare land (BL)	0	0	4	0	0	0	0	*35*	1	40	87.5
	Scrub (SB)	0	0	0	1	4	7	0	0	*58*	70	82.9
	Column total -	54	45	83	52	65	53	49	45	65	511	–
	Producer's acc. (%)	92.6	84.4	79.5	76.9	81.5	75.5	83.7	77.8	89.2	–	–
	Overall accuracy=82.5 %					Overall kappa statistics=0.8						

are crucial for the registration process, (4) the classification algorithm itself , because it is uncertain which class the classifier assigns when the dominant land cover type covers much less than 50 % of the pixel, and (5) the subjectivity of the human interpreter.

Spatial pattern and magnitude of land cover changes

Many methods of change detection have been used to study land cover change, but by far the most common has been the use of a post-classification comparison method (Foody 2002; Seto et al. 2002).

This study employed a multi-date post-classification change detection technique, which is efficient in detecting the nature, proportion and location of changes, and has been successfully used by a number of researchers in different environments (Dewan and Yamaguchi 2009). The post-classification comparison of change detection was performed using ERDAS Imagine.

The area coverage of land cover classes (Table 7) extracted as a result of the classification indicated that cropland was the most dominant land cover in all study points in time. Cropland occupied 43.6 % (625.3 km^2),

Table 4 Confusion matrix and accuracy assessment measures for 1985 image

	Land cover classes	Reference data									Row Total	User's Acc. (%)
		WR	BP	CL	WV	FT	GL	SP	BL	SB		
Classified data	Water (WR)	*52*	0	1	1	1	2	2	0	0	59	88.1
	Built-up (BP)	0	*49*	4	1	0	1	0	1	0	56	87.5
	Cropland (CL)	0	7	*60*	1	0	2	2	2	2	76	79.0
	Woody veg. (WV)	0	0	1	*54*	5	1	2	2	2	67	80.6
	Forest (FT)	1	0	0	6	*55*	0	0	0	1	63	87.3
	Grassland (GL)	1	0	1	1	0	*55*	2	3	3	66	83.3
	Swamp (SP)	3	0	1	1	1	1	*55*	2	0	64	85.9
	Bare land (BL)	0	0	7	0	0	4	0	*55*	1	67	82.1
	Scrub (SB)	0	0	0	2	3	3	0	2	*55*	65	84.6
	Column total -	57	56	75	67	65	69	63	67	64	583	–
	Producer's acc. (%)	91.2	87.5	80.0	80.6	84.6	79.7	87.3	82.1	85.9	–	–
	Overall accuracy=84.1 %					Overall kappa statistics=0.8						

Table 5 Confusion matrix and accuracy assessment measures for 1995 image

	Land cover classes	Reference data									Row Total	User's Acc. (%)
		WR	BP	CL	WV	FT	GL	SP	BL	SB		
Classified data	Water (WR)	*51*	1	1	2	2	1	2	2	0	62	82.3
	Built-up (BP)	0	*50*	1	1	0	1	0	0	0	53	94.3
	Cropland (CL)	1	1	*55*	2	1	2	2	3	3	70	78.6
	Woody veg. (WV)	2	1	2	*55*	4	2	1	0	2	69	79.7
	Forest (FT)	0	1	0	2	*55*	0	0	0	1	59	93.2
	Grassland (GL)	0	2	2	1	0	*50*	3	2	5	65	76.9
	Swamp (SP)	0	0	1	4	1	2	*50*	2	0	60	83.3
	Bare land (BL)	0	1	2	0	0	5	2	*50*	2	62	80.7
	Scrub (SB)	0	0	2	1	2	2	0	3	*50*	60	83.3
	Column total -	54	57	66	68	65	65	60	62	63	560	–
	Producer's acc. (%)	94.4	87.7	83.3	80.9	84.6	76.9	83.3	80.7	79.4	–	–
	Overall accuracy=83.2 %				Overall kappa statistics=0.8							

48.7 % (699.7 km^2), 53.4 % (766.7 km^2), and 56.4 % (809.1 km^2) in 1973, 1985, 1995, and 2011, respectively. Close examination of the land cover classes also revealed that out of the areas covered by cropland, 36.8 km^2 from 1973, 74.8 km^2 from 1985, 59.2 km^2 from 1995, and 42.8 km^2 from 2011 belonged to mechanized farms, while the remaining croplands were categorized under fragmented small holders farms.

Recent studies conducted in the Lake Tana Basin, Ethiopia, from 1985 to 2003 indicated an increase in cropland from 46.6 % to 50.8 % (Yitaferu 2007, cited in Hussien et al. 2011), while the other study conducted in Lenche Dima (Wollo) between 1972 and 2005 showed an increase in cropland from 43 % to 57 % (Hussien et al. 2011). Both research results corroborate our findings in Hawassa Watershed.

For the agricultural domain in Africa, Brink and Eva (2009) estimated a 57 % increase from the year 1975 to 2000.

The major reasons for the expansion of cropland can be attributed to population pressure which is growing

Table 6 Confusion matrix and accuracy assessment measures for 2011 image

	Land cover classes	Reference data									Row Total	User's Acc. (%)
		WR	BP	CL	WV	FT	GL	SP	BL	SB		
Classified data	Water (WR)	*50*	1	1	0	1	0	0	0	0	53	94.3
	Built-up (BP)	0	*58*	2	2	0	3	0	0	0	65	89.2
	Cropland (CL)	0	6	*86*	5	3	4	4	5	0	113	76.1
	Woody veg. (WV)	1	1	7	*49*	3	0	0	0	0	61	80.3
	Forest (FT)	2	0	1	3	*54*	0	0	0	1	61	88.5
	Grassland (GL)	0	2	1	0	0	*45*	0	1	4	53	84.9
	Swamp (SP)	0	0	1	0	0	3	*32*	0	0	36	88.9
	Bare land (BL)	0	1	2	0	0	2	0	*42*	0	47	89.4
	Scrub (SB)	0	0	1	1	1	3	0	0	*33*	39	84.6
	Column total	53	69	102	60	62	60	36	48	38	528	–
	Producer's acc. (%)	94.3	84.1	84.3	81.7	87.1	75.0	88.9	87.5	86.8	–	–
	Overall accuracy=85.0 %					Overall kappa statistics=0.8						

Table 7 Spatial coverage and proportion of land cover classes resulted from classified images

Land cover (LC) classes	1973		1985		1995		2011	
	Area of LC		Area of LC		Area of LC		Area of LC	
	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)
Water	103.3	7.2	101.5	7.1	100.3	7.0	95.8	6.7
Built-up	4.2	0.3	5.8	0.4	8.6	0.6	24.6	1.7
Cropland	625.3	43.6	699.7	48.7	766.7	53.4	809.1	56.4
Woody veget.	301.1	21.0	275.8	19.2	218.7	15.2	194.9	13.6
Forest	148.0	10.3	102.5	7.1	93.2	6.5	81.0	5.6
Grassland	71.8	5.0	78.2	5.5	73.8	5.1	65.8	4.6
Swamp	67.8	4.7	77.3	5.4	70.7	4.9	64.2	4.5
Bare land	18.1	1.3	28.4	2.0	42.1	2.9	39.9	2.8
Scrub	95.2	6.6	66.5	4.6	61.7	4.3	60.5	4.2
Total[a]	1,434.9	100.0	1,435.7	100.0	1,435.8	100.0	1,435.9	100.0

[a] The total areas of images are not the same due to change in pixel size and partitioning of the subsets into several units

at a rate of 4.02 % per annum around Hawassa (Abinet et al. 2011) and migration into new areas in search of agricultural land. Lambin et al. (2003) in their work on dynamics of land use and land cover change in tropical regions identified that expansion of cropland in Africa is dominated by small holders farm as opposed to the case in Latin America where large-scale forest conversion and colonization for live-stock based agriculture is prevalent.

Woody vegetation and forest were the other classes with the highest coverage following cropland varying in magnitude. Forest cover declined from 10.3 % (148.0 km^2) in 1973 to 5.6 % (81.0 km^2) in 2011. Likewise, woody vegetation diminished from 21.0 % (301.1 km^2) in 1973 to 13.6 % (194.9 km^2) in 2011. The annual rate of change in woody vegetation cover was also the highest (−2.1 %) between 1985 and 1995. According to our observation and other reports (Million 2001), the primary causes for the decline in wood lands and bush lands were due to the fact that they are important sources of fuel wood and construction materials for the local communities, and for production of charcoal for the urban markets. Figure 4 shows the expansion of cropland and settlement at the expense of densely vegetated areas.

The other peculiar phenomenon observed was the increase in the Lake Hawassa water body and the decline to eventual disappearance of Lake Cheleleka. The result of classification exhibited that in 1973 Lake Cheleleka and Lake Hawassa covered an area of 11.3 and 91.9 km^2, respectively. During 1985, 1995, and 2011, Lake Hawassa expanded to 93.2, 94.9, and 95.2 km^2 correspondingly, while Lake Cheleleka declined to 8.3 km^2 in 1985, and further diminished to 5.1 km^2 in 1995. In 2011, Lake Cheleleka was found totally desiccated and transformed into mud-flat and grass dominated swamp.

Thus, a combined effect indicated a slight decline in water body mainly owing to the continuous decrease in spatial coverage of Lake Cheleleka.

The desiccation of Lake Cheleleka and the receding process going on in the swampy area due to climate change are really challenging the conservation of biodiversity in the study area. In contrast, Lake Hawassa slightly increased its territory by 3.2 km^2 between 1973 and 2011 which calls for further research to explain the causes. W.W.D.S.E. (2001), cited in Yemane (2004) suggested that the rise in lake level was due to the increase in run-off as a result of excessive deforestation.

Swampy area continuously receded from 1985 to 2011 which accounted for 5.4 % (77.3 km^2) and 4.5 % (64.2 km^2), respectively.

Bare land cover continuously increased from 1973 to 1995, but a decline was observed from 1995 to 2011. This interruption in its continuous rise was mainly attributable to intensification of agricultural activities.

The time 1995 and 2011 witnessed an increase in built-up area. The built-up area which was 0.6 %

Fig. 4 The expansion of agricultural land (**a**) and settlement (**b**) replacing densely vegetated areas (photo by the author, 2012)

(8.6 km^2) in 1995 grew to 1.7 % (24.6 km^2) in 2011. This was manifested by the expansion of residential, industrial and other infrastructures including occupation of public lands by squatters.

It is presumed that favorable economic condition and rapid construction process have contributed to the 12.66 % dynamic annual rate of expansion in built-up areas from 1973–2011. About 70 % of the land converted to built-up areas came from cropland. A study revealed that one to two million hectares of cropland are being taken out of production every year in developing countries to meet the land demand for housing, industry, infrastructure, and recreation (Lambin et al. 2003).

The spatial coverage of grassland constituted 71.8 km^2 (5.0 %) in 1973, however the proportion of grassland cover decreased to 4.6 % (65.8 km^2) in 2011.

The classification result also indicated that in 1973 scrub occupied 6.6 % (95.2 km^2) of the total study area, but its area continuously regressed through the rest of study periods. Part of this land cover is Senkelle Wild Life Sanctuary housing Swayne's Hartebeest (*Alcelaphus buselaphus swaynei*), the endangered antelope native to Ethiopia.

Clearing of the area for farming, construction materials, and firewood by encroaching settlers was the main cause of reduction for scrub land. From a socioeconomic perspective, altering the natural setting of this area may result not only in degradation of the ecosystem, but also a decline in the number of visitors and subsequent reduction of income from tourism both at the local and national level.

In addition to estimating magnitude and proportion of changes in land cover classes, areas that have changed and not changed were quantified for each temporal interval. To create change maps (Fig. 5), two classified image data were overlaid in ERDAS Imagine with matrix function. The output image data were recoded and the not changed classes were colored

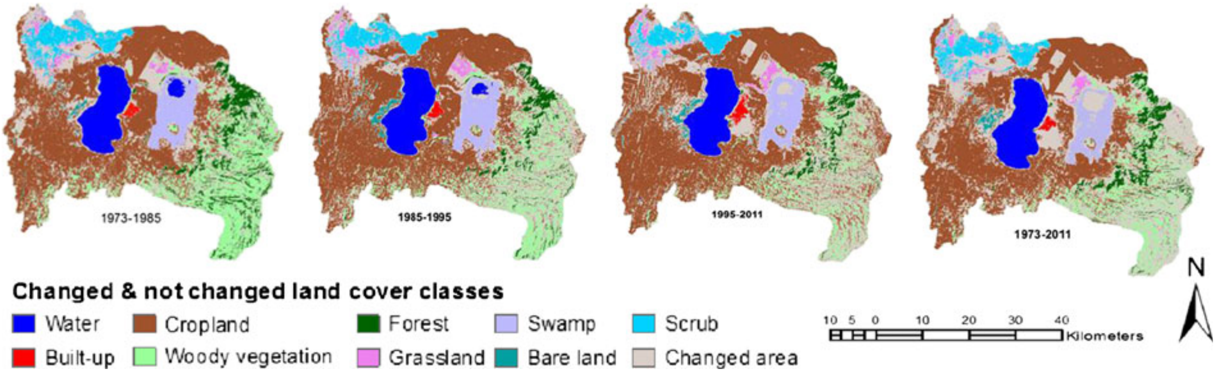


Fig. 5 Change maps showing not changed areas of nine land cover classes and one category of changed area between two dates

Table 8 Magnitudes of not changed and changed areas of land cover classes between two dates

Change categories	Land cover classes	Areas of unchanged and changed land cover classes (km^2)			
		1973–1985	1985–1995	1995–2011	1973–2011
Not changed	Water	99.4	97.4	93.2	91.5
Not changed	Built-up	3.9	5.3	7.5	4.0
Not changed	Cropland	527.4	580.2	608.2	506.4
Not changed	Woody veget.	181.0	129.6	86.6	103.2
Not changed	Forest	79.8	46.5	41.2	54.5
Not changed	Grassland	19.2	24.3	23.3	17.0
Not changed	Swamp	62.3	64.7	57.1	52.0
Not changed	Bare land	5.5	12.7	10.5	7.7
Not changed	Scrub	60.4	49.8	42.3	50.7
Change from	All classes (CA)	(396.2)	(424.6)	(465.2)	(548.0)
Total	–	1,434.9	1,435.0	1,435.2	1,434.9

in the same way as the colors used for the nine individual classes. Changes to other land cover classes were too many and it was not convenient to distinguish the different classes by color. Therefore, changed areas (CA) from all land cover classes were grouped into one category. Table 8 represents areas of the nine land cover classes that remained unchanged and one category of CA that comprises changes in all land cover classes between two dates.

Attributable to unequal distribution of change across each temporal interval, we have estimated percentage of areas not changed and changed (Fig. 6) compared to the whole area between the two dates. The result revealed that the percentage of changed areas of all land cover classes (27.6–38.2 %) were comparable with the not changed areas of cropland (35.3–42.4 %) in all temporal intervals.

Conclusion

The use of a hybrid method and partitioning of images into several units for classification of Lake Hawassa watershed have shown a clear potential in achieving the required classification results. The limitation in using the historical image from 1973 was overcome by using aerial photographs and a topographic map which facilitated to achieve comparable results with that of TM images. The inaccuracies observed from some land cover categories

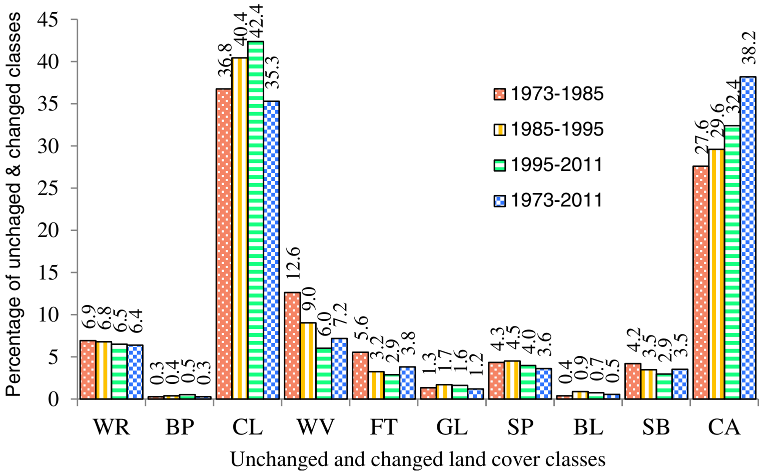


Fig. 6 Percentages of not changed and changed areas of land cover classes. *CA* changed areas, explanations of the other abbreviations are given in Table 3

were mainly attributable to difficulties in discerning actual cover types due to the high heterogeneity of the land cover.

The study area had experienced rapid changes in land cover for the last four decades, the most dominant change being conversion to cropland. The method used proved the possibility of clearly analyzing the expansion of cropland and built-up area, and decline in forest cover and woody vegetation. The most dynamic temporal interval for urbanization was 1995–2011 where built-up areas grew by 185.40 % with significant contributors such as residential areas, industrial zones and development of new institutions including military camp. The conversion of vegetation cover into other land cover classes has caused environmental degradation exemplified by the vanishing of Lake Cheleleka, which is a great loss for biodiversity. Investigating the causes for the slight expansion of Lake Hawassa and the total desiccation of Lake Cheleleka at the end of study period could be a topic for future research.

The change mapping results achieved not only improved the understanding of the on-going land cover change dynamics, but also gave an indication about actions to be taken in resource management and sustainable development. Any planned intervention to mitigate land cover changes should, therefore, be geared towards the underlying factors. Investigation of the underlying driving forces of land cover change is the other future topic of research.

It has also been observed from the classified remote sensing data that natural resources have significantly diminished and are expected to continue. Thus, this study is expected to provide a baseline for understanding LULC changes for all development practitioners and land resource managers and to help explore possible land management scenarios that will benefit all inhabitants.

Acknowledgments This work is funded by Norwegian Agency for Development Cooperation as part of capacity building at Hawassa University, Ethiopia. We gratefully acknowledge the financial support. Authors are also thankful to the two anonymous reviewers for their valuable comments.

References

Abd El-Kawy, O. R., Rød, J. K., Ismail, H. A., & Suliman, A. S. (2010). Land use and land cover change detection in the western Nile delta of Egypt using remote sensing data. *Applied Geography, 31*, 483–494.

Abinet, A., Getachew, A., & Tadesse, A. (2011). *Hawassa City Administration, 2002EC/2009GC socio economic profile*. Hawassa: Finance & Economic Development Data Collection and Dissemination Work Process.

Anderson, J. R., Hardy, E. E., Roach, J. T., & Witmer, R. E. (1976). A land use and land cover classification system for use with remote sensor data. USGS Professional Paper 964, USA.

Aplin, P. (2004). Remote sensing: land cover. *Progress in Physical Geography, 28*(2), 283–293.

Bedru, S. M. (2010). Remote sensing & GIS for land Cover/land use change detection and analysis in the semi-natural ecosystems and agriculture landscapes of the central Ethiopian Rift Valley. Thesis / Dissertation. Rhombos-Verlag, Berlin, Germany

Brink, A. B., & Eva, H. D. (2009). Monitoring 25 years of land cover change dynamics in Africa: a sample based remote sensing approach. *Applied Geography, 29*, 501–512.

Congalton, R. G. (1991). A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sens Environment, 37*, 35–46.

Congalton, R. G. (2001). Accuracy assessment and validation of remotely sensed and other spatial information. *International Journal of Wildland Fire, 10*, 321–328.

Congalton, R. G., & Green, K. (2009). *Assessing the accuracy of remotely sensed data: principles and practices* (2nd ed.). Boca Raton: Taylor & Francis.

Coppin, P., Jonckheere, K., Nackaerts, K., & Muys, B. (2004). Digital change detection methods in ecosystem monitoring: a review. *International Journal of Remote Sensing, 25*(9), 1565–1596.

Das, T. (2009). Land use and land cover change detection: an object oriented approach. MSc Thesis. Munster, Germany

Demelash, A. (2008). Assessment of non-point source pollution in Lake Awassa Watershed using the annualized agricultural non-point source (AnnAGNPS) model. MSc Thesis. Addis Ababa University, Ethiopia.

Dessie, G., & Christiansson, C. (2008). Forest decline and its causes in the south-central rift valley of Ethiopia: human impact over a one hundred year perspective. *Ambio, 37*(4), 263–271.

Dewan, A. M., & Yamaguchi, Y. (2009). Land use and land cover change in greater Dhaka, Bangladesh: using remote sensing to promote sustainable urbanization. *Applied Geography, 29*, 390–401.

ERDAS. (2005). ERDAS Field Guide: Leica Geosystems Geospatial Imaging LLC, Norcross, GA

FAO. (1997). Food and Agriculture Organization of the United Nations. *Estimating Biomass and Biomass Change in Tropical Forests*. http://www.fao.org/docrep/W4095E/W4095E00.htm. Accessed June, 2010.

FCSG. (2010). Forest Cover Shrinking Globally. *Proceedings of the National Academy of Sciences (PNAS)*, issue 26–30. http://www.redorbit.com/news/science/1855654/forest_cover_shrinking_globally/?print=true. Accessed August, 2011.

Foody, G. M. (2002). Status of land cover classification accuracy assessment. *Remote Sensing of Environment, 80*, 185–201.

Hussien, A., Descheemaeker, K., Steenhuis, T. S., & Pandey, S. (2011). Comparison of land use and land cover changes, drivers and impacts for a moisture-sufficient and drought-prone region in the Ethiopian Highlands. *Experimental Agriculture, 47*(S1), 71–83 C.

Jensen, J. R. (2005). *Introductory digital image processing: a remote sensing perspective* (3rd ed.). Upper Saddle River: Pearson Prentice Hall.

Lambin, E. F., Geist, H. J., & Lepers, E. (2003). Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environment and Resources, 28*, 205–241.

Lillesand, T. M., & Kiefer, R. W. (2000). *Remote sensing and image interpretation* (4th ed.). USA: Wiley.

Liu, J., & Taylor, W. W. (2002). *Integrating landscape ecology into natural resources management*. UK: Cambridge University Press.

Liu, W., Gopal, S., & Woodcock, C. E. (2004). Uncertainty and confidence in land cover classification using a hybrid classification approach. *Photogrammetric Engineering & Remote Sensing, 70*(8), 963–971.

Lo, C. P., & Yeung, A. W. (2002). *Concepts and techniques of geographic information systems*. Upper Saddle River: Prentice-Hall.

Lu, D., & Weng, Q. (2007). A survey of image classification methods and techniques for improving classification performance. *International Journal of Remote Sensing, 28*(5), 823–870.

Mather, P. M. (1987). *Computer processing of remotely-sensed images: an introduction*. St. Edmunds: St. Edmundsbury Press.

Million, B. (2001). *Forestry Outlook Studies in Africa*, Ethiopia.

Okeke, F., & Karnieli, A. (2006). Methods for fuzzy classification and accuracy assessment of historical aerial photographs for vegetation change analyses. Part I: algorithm development. *International Journal of Remote Sensing, 27*(1–2), 153–176.

Rembold, F., Carnicelli, S., Nori, M., & Ferrari, G. A. (2000). Use of aerial photographs, Landsat TM imagery and multidisciplinary field survey for land-cover change analysis in the lakes region, Ethiopia. *JAG*, 2(3/4).

Rogan, J., & Chen, D. (2004). Remote sensing technology for mapping and monitoring land-cover and land-use change. *Progress in Planning, 61*, 301–325.

Rozenstein, O., & Karnieli, A. (2011). Comparison of methods for land-use classification incorporating remote sensing and GIS inputs. *Applied Geography, 31*, 533–544.

Samimi, C., & Kraus, T. (2004). Biomass estimation using Landsat-TM and -ETM+. Towards a regional model for Southern Africa? *GeoJournal, 59*, 177–187.

Seto, K. C., Woodcock, C. E., Song, C., Huang, X., Lu, J., & Kaufmann, R. K. (2002). Monitoring land-use change in the Pearl River Delta using Landsat TM. *International Journal of Remote Sensing, 23*(10), 1985–2004.

Tenalem, A., & Yemane, G. (2006). Application of a spreadsheet hydrological model for computing the long-term water balance of Lake Awassa, Ethiopia. *Hydrological Sciences Journal, 51*(3), 418–431.

Vitousek, P. M., Mooney, H. A., Lubchenco, J., & Melillo, J. M. (1997). Human domination of earth's ecosystems. *Science, 277*(5325), 494–499.

WCED. (1987). *World Commission on Environment and Development. Our common future*. Oxford: Oxford University Press.

Wilkinson, L. (1998). *SYSTAT 8.0 Statistics*, USA

Wilson, E. O., & Peter, F. M. (1988). *Biodiversity*. National Academy Press, Washington, D. C. http://www.nap.edu/catalog/989.html. Accessed January 8, 2013.

Yemane, G. (2004). Assessment of the water balance of Lake Awassa Catchment, Ethiopia. MSc Thesis. International Institute for Geo-Information and Earth Observation, Enschde, The Netherlands

Zubair, A. O. (2006). Change detection in land use and Land cover using remote sensing data and GIS: A case study of Ilorin and its environs in Kwara State. MSc Thesis. University of Ibadan, Nigeria

Paper II

Wondrade, N., Dick, Ø. B., & Tveite, H. (2014). Landscape mapping to quantify degree-of-freedom, degree-of-sprawl, and degree-of-goodness of urban growth in Hawassa, Ethiopia. *Environment and Natural Resources Research*, 4(4), 223-237.

This page is intentionally left blank

ISSN 1927-0488 (Print)
ISSN 1927-0496 (Online)

Environment and Natural Resources Research

Vol. 2, No. 3 October 2012

CANADIAN CENTER OF SCIENCE AND EDUCATION

Copyrights

Environment and Natural Resources Research; Vol. 4, No. 4; 2014
ISSN 1927-0488 E-ISSN 1927-0496
Published by Canadian Center of Science and Education

Landscape Mapping to Quantify Degree-of-Freedom, Degree-of-Sprawl, and Degree-of-Goodness of Urban Growth in Hawassa, Ethiopia

Nigatu Wondrade[1, 2], Øystein B. Dick[1] & Håvard Tveite[1]

[1] Norwegian University of Life Sciences (NMBU), Department of Mathematical Sciences and Technology, P. O. Box 5003, N-1432, Ås, Norway

[2] Department of Biosystems & Environmental Engineering, Institute of Technology, Hawassa University, P. O. Box 5, Hawassa, Ethiopia

Correspondence: Nigatu Wondrade, Norwegian University of Life Sciences, Department of Mathematical Sciences and Technology, P. O. Box 5003, N-1432, Ås, Norway. Tel: 47-6496-6394, 251-934-751-455. E-mail: nigatwond@yahoo.com, nigatu.tedo@nmbu.no

Received: September 3, 2014 Accepted: October 17, 2014 Online Published: October 27, 2014

doi:10.5539/enrr.v4n4p223 URL: http://dx.doi.org/10.5539/enrr.v4n4p223

Abstract

In the rapidly urbanizing African continent, monitoring, mapping and modeling of urban growth is an indispensable task to understand the magnitude and rate of the ongoing changes. Remote sensing data have been found useful in mapping urban areas and as a source of data for modeling and analysis of spatio-temporal trajectories of cities. In this study, remote sensing data from different sensors extending over a period of 24 years (1987-2011) were used to classify and extract areas of the established land use land cover classes in Hawassa City, Ethiopia. Among those classes, built-up areas were used to quantify urban growth and sprawl. The result of the mapping indicated that the built-up area had increased by 234.5% between 1987 and 2011. The area under investigation was sub-divided into eight equal zones within a circle to apply analytical models. To analyze the pattern, process and overall growth status of Hawassa City, Pearson's Chi-square statistics, Shannon's entropy, and degree-of-goodness models were employed. The result revealed that the degree-of-freedom was high indicating the disparity between observed and expected urban growth. The entropy values both in temporal intervals and zones were found higher than half-way mark of $log_e(n)\ or\ log_e(m)$ respectively showing the tendency of sprawl. Except the South Zone, the city had not experienced "goodness" during the entire study period. This study has provided new evidence about the urban growth in the study area that could be used by city managers.

Keywords: Hawassa, GIS, remote sensing, urban growth, urban sprawl

1. Introduction and Background

Urban growth is an important global environmental issue that affects both developed and developing countries (Grey, Luckman, & Holland, 2003). Africa is one of the continents where the most explosive urban growth (30-35%) is underway, at a roughly 4% per annum. Consequently, Africa is expected to be about 54% urban by 2025 (World Resources [WR], 1996).

Between 1990 and 2025, the number of people living in urban areas is also expected to be more than five billion and from all of this growth, a staggering 90%, will occur in the developing countries (ibid).

Though there are about eight cities in Ethiopia that are all highly populated, Hawassa is special in that it is the youngest and a multi-ethnic city in South Ethiopia. The high rate of population growth and urban expansion, particularly in the last two decades, attracted our attention.

The population of Hawassa increased from 41 138 in 1987 to 313 564 in 2011 (Central Statistical Agency [CSA], 1988 & 2011). This puts Hawassa in the medium-sized city category with a population between 100 000 and 500 000 (Zanganeh et al., 2011). Rural-to-urban migration and natural growth are the causes for the population growth in Hawassa (ALLREFER, 1991; Aynalem, 2011), though the late merging of the nearby villages as it developed also contributed to some extent.

According to the Central Statistical Agency of Ethiopia (2011), urban area refers to all capitals of regions, zones and *"weredas"*/districts, and localities with urban *"kebeles"* whose inhabitants are primarily engaged in non-agricultural activities. Hawassa is the capital of Southern Nations Nationalities and Peoples Regional State (SNNPRS) and one of the fastest growing cities in Ethiopia (Hurni, Bantider, Herweg, Portner, & Veit, 2007; Wondrade, Dick, & Tveite, 2014). The definition of urban area given by CSA associates urban growth mainly with non-agricultural activities and this definition lacks spatial and population dimensions. Bhatta, Saraswati, & Bandyopadhyay (2010a) defined urban growth as a spatial and demographic process which occurs when the population distribution changes from being largely hamlet and village based to being predominantly town and city dwelling. Changes in urban areas are dynamic and require regular monitoring to understand the overall changes for proper planning and allocation of resources. Effective planning policy and appropriate resource management can only be accomplished through informed decisions, but even basic information on urban extent and change is often outdated, inaccurate, or simply does not exist (Grey et al., 2003) and this is common in developing countries.

We have witnessed that the recent rapid urban growth in the area has created pollution of water resources (Abebe & Geheb, 2003), reduction of agricultural land, shortage of shelter, and opening a lee way for invasion of public land by squatters. In the last 10 years, more attention has been paid to urban land use land cover (LULC) changes due to the fact that urban ecosystems are strongly affected by anthropogenic activities and have close relations with the life of almost half of the world's population (Xiao et al., 2006). To sustain such rapid changes in urban growth, development planning is indispensable. This, in turn, demands proper monitoring of the changing environment and this research was initiated to address such demands. The most effective way to monitor LULC changes and analyze the dynamics of urban spatial growth is through the use of remote sensing data. That is why we directed our efforts, in this study, to use of remote sensing data in combination with Global Positioning System (GPS) data to classify and extract LULC data. However, change detection from classified images alone was not enough to quantify the degree of sprawl (dispersion) or compactness of the urban growth. Thus, the remote sensing community has developed analytical models, using Chi-square statistics (Almeida et al., 2005), Shannon's entropy (Yeh & Li, 2001), and degree-of-goodness (Paul & Dasgupta, 2013) to quantify the spatial patterns and processes of urban growth over time.

Literature review found that several studies were conducted to quantify urban growth and sprawl covering pattern (Sudhira, Ramachandra, & Jagadish, 2004; Ji, Ma, Twibell, & Underhill, 2006; Jat, Garg, & Khare, 2008; Sarvestani, Ibrahim, & Kanaroglou, 2011), process (Galster et al., 2001; Bhatta et al., 2010b; Bhatta, 2012), and an overall analysis (Bhatta et al., 2010a) that combines both pattern and process. Bhatta (2012) specifically indicated that urban change detection focus has shifted from detection to quantification of change, measurement of pattern, and analysis of pattern and process of urban growth and sprawl. In this study, we also used pattern, process, and an overall analysis to quantify urban growth status. Urban growth as a pattern refers to the spatial configuration of built-up areas in each temporal instant while the process reveals the changes in spatial structure of cities over time. Thus, urban growth analysis that takes into account both pattern and process will help us to understand the changes in built-up area in space and time, including the presence or absence of sprawl. Sprawl, as Galster et al. (2001) described, is a metaphor rich in ambiguity that bears one name for many conditions. This has emanated from the lack of agreement among scholars on its definition (Johnson, 2001). For the current study, we consider urban sprawl as uncontrolled, scattered sub-urban development that increases traffic problems, depletes local resources, and destroys open space (Ji et al., 2006).

In Africa, more than 10 years ago, spatial analysis capabilities were limited (Karanja, Heipke, & Konecny, 2002). Literature review also has not found any research output related to urban growth analysis in the study area and probably this could be the first documentation of the changes in urban dynamics in Hawassa. Generally, the advent of remote sensing data and associated software packages has created an opportunity to quantify LULC data and to model urban growth/sprawl using selected spatial models. The main objective of this study was, therefore, twofold. First, we aimed to detect and quantify LULC classes and output cover maps. Our second aim was to examine the spatio-temporal growth status of Hawassa City for the time interval between 1987 and 2011. The specific objectives include: (1) to classify and extract the proportion and magnitude of built-up areas, (2) to identify and utilize spatial models for quantifying urban growth and sprawl i.e., (i) to quantify the rate of urban growth, (ii) to test the relationship between observed and expected growth (degree-of-freedom), (iii) to analyze whether the growth was sprawling or not using Shannon's entropy, and (iv) to estimate the overall degree-of-goodness and produce a detailed report of urban growth status for further use. We hope that this study will give an insight in the past and present urban growth situation in Hawassa and even be used as a basis for future growth analysis by all people who have a stake in the city.

2. Materials and Methods

2.1 Study Area Description

Hawassa, formerly known as Awassa, is the capital city of SNNPRS, Ethiopia. It is located 275 km south of Addis Ababa along the main highway leading to Nairobi, Kenya via Moyale. This study area (Figure 1) lies between $6^o55' - 7^o06'N$ Latitude and $38^o25' - 38^o33'E$ Longitude and the altitude ranges from 1656 to 2137 m above sea level. The Hawassa City Administration covers an area of 16 062 hectares (ha) and is sub-divided into eight Sub-Cities and 32 “Kebeles”. The research area has a favorable climate with an annual mean minimum and maximum temperature of 13.0^{o}C and 29.2^{o}C respectively and 975.9 mm mean yearly precipitation estimated for ten years using meteorological data.

Hawassa obtained its beauty and name from the Lake Hawassa situated in the Main Ethiopian Rift Valley. However, the availability of water and grazing land had been a major source of conflict among the pastoral community inhabited in this area. The Hawassa city was founded relatively recently (1960) succeeding Yirgalem to become a capital of the former Sidama Province (Zeleke & Serkalem, 2006; Assefa, Alemu, & Abinet, 2011). Then, in late 1970s, it was decided to establish Hawassa as the seat of former four administrative regions in the south, namely Arsi, Bale, Gamo Gofa, and Sidama. However, significant growths including built-up areas have been observed since 1994, when Hawassa became the capital of SNNPRS and the Sidama Zone. The population of Hawassa in 1960 was estimated between 2 500 and 3 000 (Zeleke & Serkalem, 2006). The population of Hawassa projected for 2012 based on the 2007 Census of Ethiopia has grown to 315 459 (Bureau of Finance & Economic Development [BOFED], 2011). The city is now housing a number of industries and institutions attracting people not only within the region, but also all over the country. Accordingly, the demand for housing and other amenities is higher than ever.

Comparing the yearly built-up growth rate (9.8%) estimated from the remote sensing data and yearly population growth rate (27.6%) for 1987-2011, the urban growth would be expected to much greater to cope with the housing demands of the growing population.

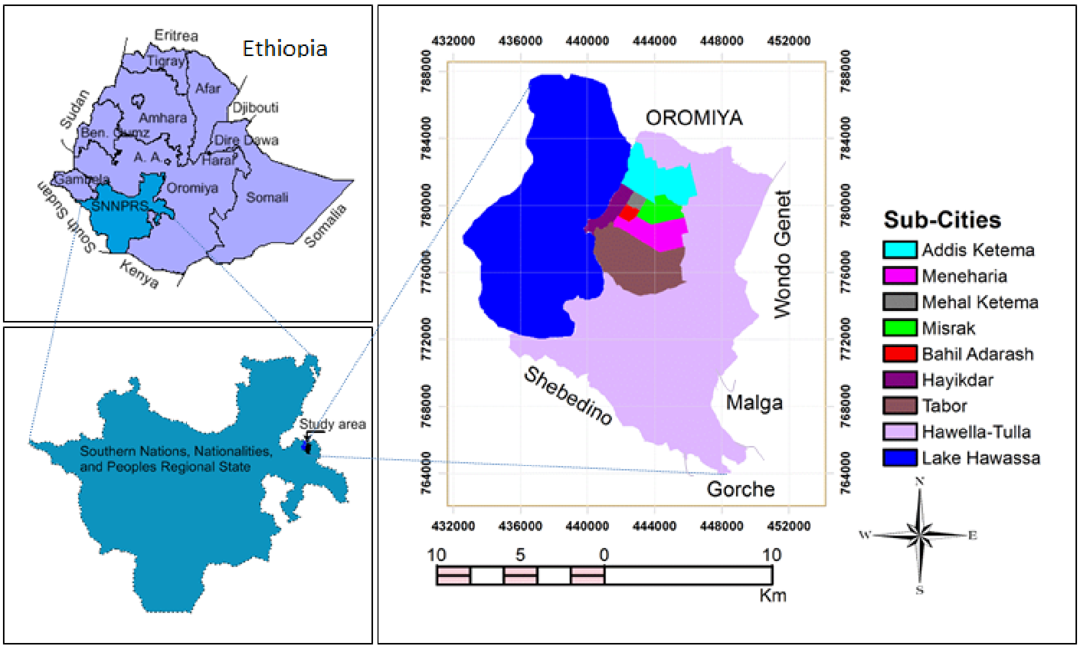


Figure 1. Map showing the study area with sub-cities and neighboring districts

2.2 Image Data Sets and Ancillary Data

High resolution image data such as IKONOS and QuickBird are the most suitable for urban landscape mapping. But, due to budget constraints and at some points their unavailability, this study used SPOT and Landsat imagery to extract built-up areas.

Landsat image data was downloaded from the Website, Global Visualization Viewer at http://glovis.usgs.gov, while the SPOT image data were procured from *e-geos*, an Italian Space Agency and Telespazio Company. The main characteristics of the imagery are described in Table 1. The dates of imagery have been selected in order to estimate LULC changes of 12 years temporal intervals. The three image data sets used were obtained geometrically corrected and projected to the standard Universal Transverse Mercator (UTM) coordinate system (WGS 84 datum, Zone 37N).

Some additional ancillary data were used to assist image interpretation and optimum information extraction from the remotely sensed data.

Table 1. The main characteristics of the utilized satellite images

Acquisition Date	Satellite and Sensor	Spatial resolution (m)	Spectral bands considered
20 January 1987	SPOT1-HRV2	20x20	1, 2, 3
25 January 1999	Landsat5-TM	30x30[a]	1, 2, 3, 4, 5, 7
22 March 2011	SPOT4-HRVIR2	20x20	1, 2, 3, 4

[a] Processed spatial resolution.

These include: a topographical map with scale 1:50 000 obtained from the Ethiopian Mapping Agency, QuickBird image data supplied by e-geos Company, and ground-truth data collected in the field using a hand held GPS device. The topographical map from 1988 was used to select training pixels for classification and reference points for accuracy assessment for the SPOT-1987 data. There were no topographical maps and aerial photographs within the same year as that of the image from 1999 to be used as an ancillary data. This is a common problem in developing countries. Therefore, the classification and thematic map accuracy assessment for the 1999 image data was performed using high resolution QuickBird image data from 2003. Classification and accuracy assessment for the image in 2011 was entirely performed using training pixels and reference points surveyed during the field work.

2.3 Classification Scheme

Once all the images were available, target LULC categories were established to perform classification. To create a closer correspondence between the thematic maps, seven categories were considered: built-up, water, agricultural land, vegetation, grassland, swamp, and bare land. Built-up area covers all developed areas including residential, commercial, industrial, and transportation infrastructures. Water body is open lake, river, and oxidation ponds. Agricultural land encompasses land with crop, ploughed, and fallow land. Vegetation class is a land covered by forest patches, woodland, shrubs, scattered trees mixed with grass, and perennial crops. Grassland involves area dominated by herbaceous vegetation. Swamp corresponds to areas where the water table is near or above the land surface. The existence of herbaceous vegetation is also evident in swampy area. Bare land is an area with no or scant vegetation, quarries, beachside, and exposed rocks.

2.4 Image Pre-Processing

The images considered for analysis were obtained geometrically and radiometrically corrected by the providers. However, owing to the different standards and references used by the image data set suppliers, images were co-registered to overcome the problem of mismatching when overlaying. It is important to mention that the thermal band in Landsat was excluded when stacking all the reflective bands into a single multi-band image. This is because of its coarse resolution and uncertainties that may crop up when resampling to higher resolution to match the other bands. The QuickBird image was first co-registered with the topographical map and, then all the three images were co-registered with respect to QuickBird. The transformation process was performed using ground control points (GCP) collected by GPS and it was achieved with a Total Root Mean Square Error (RMSE) of ≈ 1.04 which is slightly above the conventional requirement of less than one pixel (Mas, 1999; Rozenstein & Karnieli, 2011). To retain the original pixel values and avoid the loss in spatial detail, resampling of Landsat image data to match with spatial resolution of SPOT image was performed using nearest-neighbor resampling method. This will permit images from different sensors to match when overlaying and allow the comparison of LULC types. A vector file was then imported into ERDAS Imagine to subset each image to include only the study area for classification.

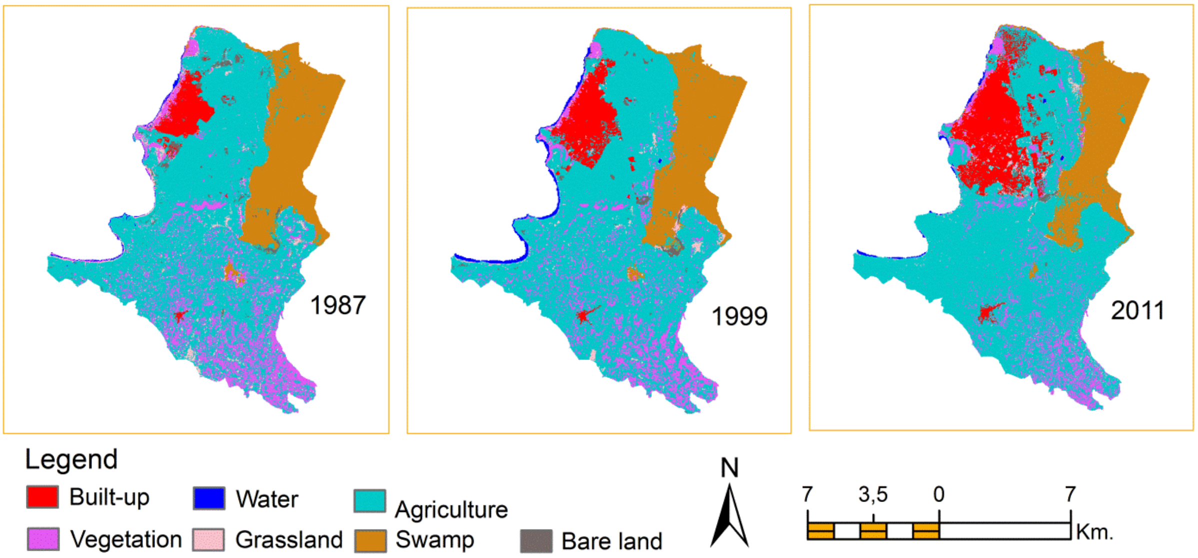


Figure 2. Thematic maps of the study area

2.5 Image Classification

Classification of a heterogeneous urban surface with a complex combination of features is a challenging task, particularly when using coarse spatial resolution images. This was also our experience, and it was not possible to separate all the LULC classes. To overcome these limitations, the image data sets were sub-divided into several landscape units to discern the LULC classes. Accordingly, based on visual inspection and ancillary data, images from 1987, 1999, and 2011 were sub-divided into 24, 45, and 29 segments respectively to enhance classification.

Each segment was first classified using unsupervised *Iterative Self-Organizing Data Analysis Technique* (*ISODATA*) (ERDAS, 2010), allowing a large number of classes (30) to later be aggregated into the pre-defined LULC classes. Even within these relatively small segments, some misclassifications were observed. The major misclassification was between built-up area and agricultural land. This problem was attributable to the fact that building roofs, some pavements, and agricultural lands were captured by sensors with similar spectral signatures. It was also recognized that some quarries and gravel pits, the effects of anthropogenic activities, were confused with built-up areas and agricultural land. Perennial crop fields were also other sources of misclassification with vegetation cover and crop land.

In order to avoid an over/under estimation of built-up area which is the main focus of this study, the unsupervised classification was followed by the supervised maximum likelihood classification method. This permits further definition of LULC classes generated by unsupervised method (ERDAS, 2010) and yields optimum results.

An average of 105 training pixels representing the pre-defined LULC categories was selected in each image to delineate training polygons to perform supervised classification. The training pixels for SPOT-1987 and Landsat-1999 were selected from ancillary data while training pixels for the image in 2011 were collected in the field using GPS device. The training pixels were converted into vector files in a GIS environment and overlaid with the satellite image to delineate training polygons for each category. Misclassifications in the set of classes generated during unsupervised classification were refined by supervised method using the polygons delimited around the created training pixels.

Classification of all segments was performed by a hybrid method using ERDAS Imagine 2011 and the classified segments were recoded and mosaicked to form the whole. To smooth the classified images from mixed and salt-and-pepper effect which are common problems when using medium spatial resolution image data (Sarvestani et al., 2011), a majority filter with an operating window size of 3x3 was applied (Mather, 1987; Lillesand & Keifer, 2000). The classified images (Figure 2) were then exported to ArcGIS 10.1 for map presentation.

2.6 Accuracy Assessment

An accuracy assessment of the thematic maps was conducted using the reference points collected independent of the training data. Owing to significant variation in class sizes and importance, a stratified random sampling scheme was pursued to collect 256, 270, and 280 reference points to assess the accuracy of the maps from 1987, 1999, and

2011 respectively. Reference points to assess the maps from 1987 and 1999 were collected from ancillary data while these points for the map in 2011 were collected during field work using GPS. The number of reference pixels is an important factor in determining the accuracy of the classification and it has been described that a minimum of 30 samples per map class are required to adequately populate an error matrix (Congalton, 2001). The accuracy assessment was run in ERDAS Imagine 2011 to create confusion matrices for each map and accuracy measures are presented in Table 2. The overall accuracies were found above 85%, a cutoff adopted as acceptable results (Congalton & Green, 2009). The accuracies for built-up area were all above 86%. The magnitude and proportion of each land cover class with the attained accuracy is given in Table 3.

Table 2. Accuracy assessment results of the classified image data

LULC Class	1987		1999		2011	
	PA (%)	UA (%)	PA (%)	UA (%)	PA (%)	UA (%)
Built-up	88.6	88.6	92.5	90.2	86.7	86.7
Water	93.3	93.3	95.0	95.0	95.2	95.2
Agriculture	84.2	86.5	87.5	85.4	83.5	84.5
Vegetation	83.7	80.0	86.7	86.7	85.7	83.7
Grassland	79.0	75.0	80.0	75.0	86.7	76.5
Swamp	87.5	91.3	90.0	95.7	90.4	92.2
Bare land	80.0	76.2	80.0	84.2	80.0	84.2
Overall accuracy		*85.2*		*88.2*		*86.4*
Overall kappa statistics		*81.8*		*85.4*		*83.3*

Note: PA and UA stand for producer's accuracy and user's accuracy respectively.

To apply the selected models for urban growth analysis, the center point of Hawassa City was first identified. There were several locations such as, "Addis Ababa Sefer", "Harar Sefer", "Korem Sefer", "Mehal Ketema" etc., where people began to settle. But the City Center, formerly known as "Piazza" is the place where peak movement of people and business was observed (Zeleke and Serkalem, 2006). The identified center point lies between the city center building and "Sidama Bahil Adarash" or Hall. Taking this point as a center, a circle with a radius of 16 684 m was drawn, inscribing the city with built-up areas. The circle with an area of 874.46 km^2 (87 445.78 ha) was then divided into eight equal pie sections, here after referred to as zones (109.31 km^2 or 10 930.72 ha each) as North (N), North East (NE), East (E), South East (SE), South (S), South West (SW), West (W), and North West (NW) as depicted in Figure 3. A vector file with the eight subdivisions was imported into ERDAS imagine to subset the classified images for the three study points in time. The built-up areas in different directions at equal distance from the city center were then extracted in order to analyze the growth status of the city.

Table 3. Magnitude and proportion of LULC types

LULC Class	1987		1999		2011	
	(ha)	(%)	(ha)	(%)	(ha)	(%)
Built-up	600.9	3.7	1014.9	6.3	2009.8	12.5
Water	62.6	0.4	206.2	1.3	76.4	0.5
Agriculture	9632.1	60.0	9929.7	61.8	10017.4	62.3
Vegetation	2239.7	13.9	1718.0	10.7	1163.8	7.3
Grassland	340.4	2.1	195.6	1.2	167.5	1.0
Swamp	3017.2	18.8	2834.4	17.7	2600.3	16.2
Bare land	170.9	1.1	154.4	1.0	34.5	0.2
Total[b]	*16063.8*	*100.0*	*16053.2*	*100.00*	*16069.7*	*100.00*

[b] The variation in total area is due to the difference in spatial resolution and segmentation of the images.

2.7 Zoning Built-Up Spread Pattern for Analysis

Urban growth is a dynamic phenomenon which changes over time and Hawassa city has now eight sub-cities. The jurisdictional boundary of the city is much larger than the built-up area and most of the developed areas are concentrated in the seven sub-cities which cover only 24% of the city. The expansion of the city is more skewed to North-East, East, South-East, and South leaving all corners with no built-up coverage. Considering a sub-division based on administrative boundaries was not found feasible as the largest sub-city with 76% coverage was the least developed area. The extracted built-up areas of the respective zones from each temporal instant are given in Table 4 for analyzing degree-of-freedom, sprawl, and degree-of-goodness in urban growth.

3. Results and Discussion

3.1 Built-Up Area Extent and Urban Growth

Understanding a dynamic phenomenon, such as urban growth/sprawl, requires LULC change analysis, urban sprawl pattern identification and computation of landscape metrics (Jat et al., 2008).

The accuracy assessment results (Table 2) for all the available images indicated that built-up areas were classified with an accuracy of above 86%. Envisaging the growing demand of land for built-up area, the city boundary was redefined to exceed the built-up area where the total agricultural land is still the most dominant LULC category. Due to the heterogeneity of urban land cover and the coarse spatial resolution of the image data utilized, spectral confusion was observed during classification. Particularly, this was noticeable in grassland cover which was difficult to discern from vegetation and agricultural land.

Some unexpected misclassifications were also seen between built-up areas and agricultural land, attributable to very similar spectral signatures. It is also worth mentioning that certain locations with built-up cover in 1987 were seen as vegetation or agricultural land in 1999 and later. This was because of inundation of the surrounding area by Lake Hawassa that entailed the demolition of houses and evacuation of the area. Most conversions to built-up areas come from agricultural land- 33% and 47% during the 1987-1999 and 1999-2011 temporal intervals respectively. On the other hand the increase in agricultural land, though it is small, indicated that there were still conversions to agricultural land within the boundary of the city administration.

The generated maps and field observations showed that the expansion of built-up area was concentrated in the N, NE, E, SE, and S parts due to the presence of geographical barriers in the other zones. The study area is limited to the North by another state (Oromiya), to the West by Lake Hawassa, to the East by Swamp and to the South West by hills which are not suitable for urban development. Thus, the areas left for urban expansion were the North-South line along the highway and the entire Eastern and Southern part. Infill of the open spaces has also taken place in areas initially reserved for green parks, impairing the environmental and aesthetical quality of the city.

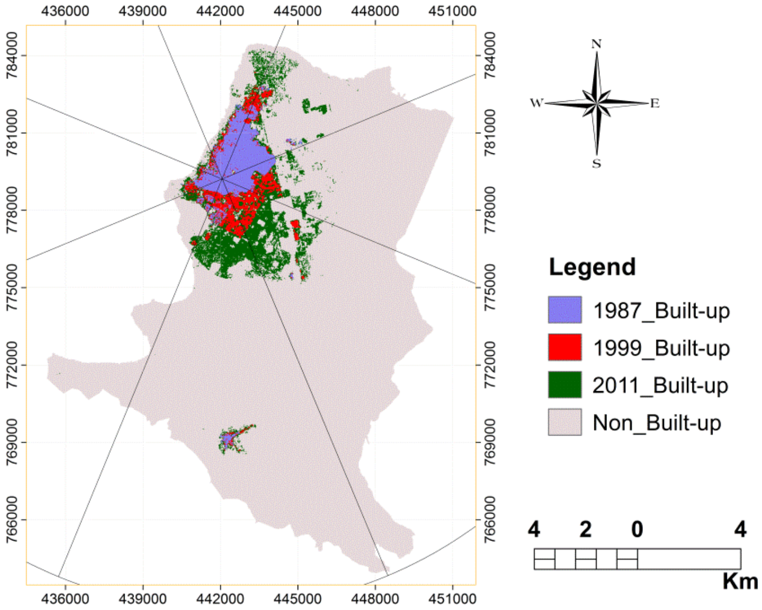


Figure 3. Overlay of classified images showing the built-up and non-built-up areas

The built-up areas for every zone in each year are presented in Table 4 along with a radar chart (Figure 4). It is worth to note that for the radar chart, 16 equal zones were used instead of eight for better visualization of the urban expansion. The chart displays an overlay of built-up areas in each temporal interval and the trends of change over time. It is also evident from the chart that the expansion of built-up areas to the left of N-S line was more or less static due to the natural barriers (lake and hills). As shown in Figure 3, the pattern of observed urban growth varies from one urban place to another and high density growth pattern dominates the area around the center point. The observed pattern explains the spatial distribution of built-up areas in each temporal instant and the process represents the change in spatial distribution of the developed areas.

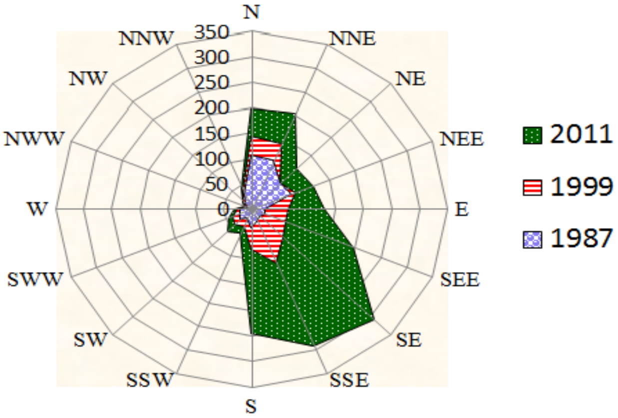


Figure 4. Radar chart showing built-up area expansion (in ha) for the three years

The observed growth in built-up area (Table 5) was computed for the two temporal intervals, 1987-1999 and 1999-2011. We can see the spatial pattern of built-up areas from the classified images, but to quantify and explain the variations in the patterns of urban growth statistically, we need to apply selected quantitative models.

Table 4. Built-up areas in each zone and each temporal instant (ha)

	N	NE	E	SE	S	SW	W	NW	The City[c]
1987	137.84	176.56	95.88	43.32	60.92	45.80	40.00	20.00	620.32
1999	186.36	210.20	146.12	142.44	189.36	77.36	59.64	30.52	1042.00
2011	247.96	317.12	246.60	495.40	527.72	109.12	71.08	33.40	2048.40

[c] *Subdividing the area into eight pie sections entailed minor changes in built-up areas*

Table 5. Observed growth in built-up areas (ha)

	N	NE	E	SE	S	SW	W	NW	Row total
1987-1999	48.52	33.64	50.24	99.12	128.44	31.56	19.64	10.52	421.68
1999-2011	61.60	106.92	100.48	352.96	338.36	31.76	11.44	2.88	1006.40
Column total	110.12	140.56	150.72	452.08	466.80	63.32	31.08	13.40	1428.08

The percentage of an area covered by impervious surfaces is a straight forward measure of urban growth (Barnes, Morgan, Roberge, & Lowe, 2002). The percentage of built-up area, as a measure of urban growth rate, was calculated for 12 years each (Table 6). The result reveals that the general trend of percentage growth rate was rising though there were decreasing rates in some zones. The highest and the lowest growth rates observed were 247.80% and 9.44% respectively (Table 6). Though the overall growth rate was increasing, that was not enough evidence to say the city was developing in the expected pattern or not which calls for further investigation.

Table 6. Percentage built-up growth rate

	N	NE	E	SE	S	SW	W	NW	The city
1987-1999	35.20	19.05	52.40	228.81	210.83	68.91	49.10	52.60	67.98
1999-2011	33.05	50.87	68.77	247.80	178.69	41.05	19.18	9.44	96.58

3.2 Pearson's Chi-Square Statistics and Urban Growth

Different from industrialized nations, some cities in developing countries lack proper planning policies and projected expectations (Paul & Dasgupta, 2013). In the absence of such policies, it was useful to apply Pearson's chi-square statistics to estimate the theoretical expected urban growth. Pearson's Chi-square statistics (degree-of-freedom) takes into account the checking of freedom amongst pairs of variables selected to explain the same category of land cover change (Almeida et al., 2005; Bhatta et al., 2010a; Bhatta, 2012). To perform the chi-square test, predefined expected values should be available but that is not the case in Hawassa city. Therefore, to compare the observed growth and expected growth, the theoretical expected urban growth was computed statistically using Equation (1). Let the Table 5 be matrix M with elements M_{ij}, where $i = 1, 2, \ldots, n$ (specific temporal intervals, rows of the table) and $j = 1, 2, \ldots, m$ (specific zones, columns of the table). The expected built-up growth for each variable was calculated by the products of marginal totals, divided by the grand total (ibid). Thus, the expected growth (M_{ij}^E) for the i^{th} row and j^{th} column is:

$$M_{ij}^E = \frac{M_i^s \ x \ M_j^s}{M_g} \tag{1}$$

$$where\ M_i^s = row\ total$$

$$M_j^s = column\ total, and$$

$$M_g\ = grand\ total = \sum_{i=1}^{n}\sum_{j=1}^{m} M_{ij}$$

Then the degree-of-freedom, degree of deviation for the observed urban growth over the expected (Table 8), was computed using the Pearson's expression: *(observed-expected)* ^{2}*/expected*.

The Pearson's chi-square statistics for each temporal interval (X_i^2) (Table 9) was then calculated using the observed (Table 5) and expected (Table 7) built-up growth as:

$$X_i^2 = \sum_{j=1}^{m} \frac{(M_j - M_j^E)^2}{M_j^E} \tag{2}$$

where X_i^2=degree-of-freedom for i^{th} temporal interval, M_j =observed built-up area in j^{th} column for a specific row, and M_j^E =expected built-up area in j^{th} column for a specific row.

Table 7. Expected growth of built-up area (ha)

	N	NE	E	SE	S	SW	W	NW
1987-1999	32.52	41.50	44.50	133.49	137.84	18.70	9.18	3.96
1999-2011	77.60	99.06	106.22	318.59	328.96	44.62	21.90	9.44

Similarly, substituting j (column) by i (row) and m (number of columns) by n (number of rows) in Equation (2) will yield the degree-of-freedom for each zone (X_j^2) (Table 10). The overall degree-of-freedom (X^2) was also estimated using Equation (3) and shown in Table 15.

$$X^2 = \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{\left(M_{ij} - M_{ij}^E\right)^2}{M_{ij}^E} \tag{3}$$

From Equation (2), we found that chi-square has a lower limit of zero when the observed value is exactly the same as the expected value. It is evident that the degree-of-freedom for each temporal interval (Table 9) was found very high which explains the high variation between the observed and expected urban growth. Table 10 also revealed that the degree-of-freedom in the East and South zones was low portraying the similarity in observed and expected urban growth. Higher overall degree-of-freedom indicates lack of consistent planned development in the city under investigation over time (Bhatta et al., 2010a; Bhatta, 2012), and it cannot be considered as sprawl, but as disparity in observed and expected growth in pattern and /or process.

Table 8. Difference between observed and expected built-up growth (ha)

	N	NE	E	SE	S	SW	W	NW
1987-1999	16.00	-7.86	5.74	-34.37	-9.40	12.86	10.46	6.56
1999-2011	-16.00	7.86	-5.74	34.37	9.40	-12.86	-10.46	-6.56

Table 9. Degree-of-freedom for urban growth in each temporal interval

Temporal interval	Freedom (X_i^2)
1987-1999	51.26
1999-2011	21.48

Table 10. Degree-of-freedom for urban growth in each zone

Zone	N	NE	E	SE	S	SW	W	NW
Freedom (X_j^2)	11.18	2.11	1.05	12.56	0.91	12.56	16.93	15.45

3.3 Shannon's Entropy and Urban Growth

Shannon's entropy is a widely applied method in studies of urban sprawl and it measures the degree of spatial concentration or dispersion of a geographical variable, observed built-up growth rates in zones (Yeh & Li, 2001; Li & Yeh, 2004; Sudhira et al., 2004; Almeida et al., 2005; Kumar, Pathan, & Bhanderi, 2007; Bhatta et al., 2010; Sarvestani et al., 2011). Shannon's entropy for each temporal interval (H_i) was calculated, from Table 6, as:

$$H_i = -\sum_{j=1}^{m} P_j log_e(P_j) \tag{4}$$

where (P_j) =proportion of the variable in the j^{th} column (i.e., proportion of built-up growth rate in j^{th} zone, calculated from Table 6) as: *(built-up growth rate in j^{th} zone/sum of built-up growth rates for all zones)*, m=total number of zones=8.

The entropy values range from 0 to $log_e(m)$ and its magnitude explains the degree of sprawl with values closer to 0 indicating a compact built-up growth distribution. Conversely, an evenly dispersed distribution among the zones will yield a value closer to $log_e(m)$.

When the entropy values are much higher than the half-way mark of $log_e(m)$, the city is said to be sprawled where as if such values goes below the half-way mark of $log_e(m)$, then it is non-sprawling (Bhatta et al., 2010a). It has to be noted that there was no reliable method found to define a threshold value that can determine whether a city is sprawled or not.

Table 11. Shannon's entropy of each temporal interval

Temporal interval	Entropy (H_i)	$log_e(m)$	$log_e(m)/2$
1987-1999	1.76	2.08	1.04
1999-2011	1.65	2.08	1.04

The result (Table 11) indicated that the entropy values are higher than the half-way mark of $log_e(m)$ asserting the city was sprawled. Comparing the entropy values of the temporal intervals, we found that there was a tendency of decrease in sprawl. This result corroborates the findings of Richardson, Bae, and Baxamusa (2000) and Bhatta et al. (2010a) that cities in developing countries are becoming more compact in spite of the beginnings of decentralization.

Similarly, entropy for each zone (H_j) given in Equation (5) was estimated by substituting i with j and m with n in Equation (4):

$$H_j = -\sum_{i=1}^{n} P_i log_e(P_i) \tag{5}$$

where P_i =proportion of the variable in the i^{th} row (i.e., proportion of built-up growth rate in i^{th} temporal interval, calculated from Table 6 as: *(built-up growth rate in i^{th} temporal interval/sum of built-up growth rates for all temporal intervals)*, n=total number of temporal intervals.

Table 12. Shannon's entropy for each zone

Zone	N	NE	E	SE	S	SW	W	NW
Entropy (H_j)	0.69	0.59	0.68	0.69	0.69	0.66	0.59	0.43
$log_e(n)$	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69
$log_e(n)/2$	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35

Table 12 indicated that the entropy values for each zone are all higher than the half-way mark of $log_e(n)$. This shows that the Hawassa City has a general tendency of sprawling. The lowest sprawl was observed in NW zone where the expansion of built-up area is limited by a natural barrier, the Lake. The sprawling effects in the N and NE for temporal instant in 2011 are mainly attributable to illegal settlements. These illegal settlements account for about 19.8% and 14.5% of built-up areas in the N and NE zones respectively.

The overall sprawl (H) can also be computed as given by Equation (6):

$$H = -\sum_{i=1}^{n}\sum_{j=1}^{m} P_{ij} log_e(P_{ij}) \tag{6}$$

where P_{ij} =proportion of the variable in the i^{th} row and j^{th} column (i.e., proportion of built-up growth rate in i^{th} temporal interval and j^{th} zone, calculated from Table 6 as: *(built-up growth rate in i^{th} temporal interval and j^{th} zone/the grand total of all variables)*.

The result of the overall sprawl calculated was 2.4 and found higher than the half-way mark of $log_e(nxm)$ i.e. 1.39. The upper limit of the overall sprawl is considered to be $log_e(nxm) = 2.77.$ which portrays that Hawassa City has an overall sprawled pattern.

3.4 Degree-of- Goodness and Urban Growth

Chi-square and entropy were used to measure degree-of-freedom and sprawl respectively. However, these are not enough to decide "goodness" of the urban growth. This is exemplified by the South zone where the observed and expected growth rates (X_j^2) are relatively related, but still the extent of sprawl (H_j) is one of the highest. Therefore, this requires determining the degree-of-goodness of the urban growth. The degree-of-goodness actually refers to the degree to which observed growth relates to the planned growth and the magnitude of compactness as opposed to sprawl (Bhatta, 2012).

The degree-of-goodness for each temporal interval (G_i) was calculated as:

$$G_i = log_e\left[\frac{1}{X_i^2\left(\frac{H_i}{log_e(m)}\right)}\right] \tag{7}$$

where (G_i) =degree-of-goodness, (X_i^2)=degree-of-freedom, and (H_i) =entropy all for the i^{th} temporal interval, and m =total number of zones=8. The result is given in Table 13.

Similarly, the degree-of-goodness for each zone (G_j) (Table 14) was computed by substituting i with j and m with n in Equation (7).

To compare the degree-of-goodness of the city, an overall degree-of-goodness was also estimated using Equation (8):

$$G = log_e\left[\frac{1}{X^2\left(\frac{H}{log_e(nxm)}\right)}\right] \tag{8}$$

where X^2 is an overall freedom and H is an overall sprawl (Table 15)

Table 13. Degree-of-goodness for urban growth in each temporal interval

Temporal interval	Goodness (G_i)
1987-1999	-3.77
1999-2011	-2.84

Table 14. Degree-of-goodness for urban growth in each zone

Zone	N	NE	E	SE	S	SW	W	NW
Goodness (G_j)	-2.41	-0.58	**-0.03**	-2.53	**0.10**	-2.48	-2.67	-2.25

The magnitude and algebraic signs of the degree-of-goodness are direct indications of whether the urban growths investigated in the temporal intervals or zones are “good” or “bad”. Positive values indicate “goodness” while negative values indicate “badness” of the urban growth. Higher magnitude in degree-of-goodness also shows the badness of the urban growth. Based on the analysis (Table 13), the study area has not experienced goodness during the entire study period, the worst being during the 1987-1999. The analysis for the zones also indicated that, except for South, the values of degree-of-goodness of all zones were with negative sign. The worst is again the West zone, but the overall degree-of-goodness is even much worse. This finding is also in line with the findings of Bhatta et al. (2010a). However, the review of literature did not find any research output that explored urban growth status in this study area.

Table 15. Overall degree-of-freedom, entropy, and degree-of-goodness

Degree-of-freedom (X^2)	Entropy (H)	Degree-of-goodness (G)
72.74	2.40	-4.14

This study considered a circular area equidistant from the city center, assuming that the expansion of urban growth will be equal in every direction from the center. However, uneven growth was observed caused by terrain variables. This effect was particularly visible from the left side of N-S line where the expansion of built-up area was impeded mainly by Lake Hawassa.

The utilized models could be applied for less or more zonal divisions that include both built-up and non-built-up areas. Dividing the area into a higher number of zones will statistically yield more reliable results. But this may reduce the expected values of built-up areas, variables, to less than five which are not recommended in Chi-square statistics (Larson & Farber, 2009). We can also agree with the arguments of Bhatta et al. (2010a) which stipulate that it would be better if the three measures ($X^2, H, and\ G$) were calculated on the basis of percentage of built-up area within a zone by excluding non-developable land. However, quantifying non-developable land from remote sensing data will not be practical due to lack of basic information regarding non-developable land and this could be one limitation of the models used in this study.

Since these kinds of urban growth analyses were not available for the study area, it is presumed that the employed methods and the achieved results will be useful for local planning authorities to recognize and manage urban growth. The results will particularly be useful to understand the current growth status of the city and establish investment goals that will enable to work towards planned development and service provision in the future. When repetitive Landsat and SPOT images of the same scene overtime are available, it is also possible to apply the methods used in this paper for regional planning. Because the utilization of remote sensing techniques and analytical models permits us quantify urban growth, understand the rate and trends of growth which would help in regional planning for better supply of infrastructure and other communication networks.

4. Conclusion

Built-up area was extracted from temporal remote sensing data and used to analyze the status of urban growth and sprawl. Quantifying urban growth and sprawl was performed using Chi-square statistics, Shannon’s entropy and a model to characterize the degree-of-goodness. Such relatively simplified analytical models can easily be applied by city managers and planners who are not necessarily scientists. The approaches followed by sub-dividing the area into different zones have produced a detailed report on urban growth status which will be useful to device mitigation strategies not only for the whole area as an entity, but will also enable the development of different planning policies for each zone with diverse effects.

It was very remarkable, but not unexpected, to see the gap between the rate of urban growth and population growth. Census results revealed that from 1987 to 2011, the population of Hawassa City increased from 41 138 to 313 546 (662.2%) which is a rate close to three times the growth of built-up area (234.5%) for the same period. Recognizing that all the built-up areas were not occupied by residential buildings, one can imagine the high number of occupants per house and the low mean living space available per person. However, this is another topic which requires further investigation to address the problems.

The study area is experiencing more dispersed urban growth at the expense of agricultural land where vertical expansion was rarely practiced during previous years. The major conversion to built-up area is from agricultural land and one of the limitations to the vertical expansion is the location disadvantage that it is found in an active seismic zone.

In conclusion, regular monitoring of urban growth status using multi-resolution and multi-temporal remote sensing data is highly desirable. This coupled with proper planning and sound land law will be useful to prevent illegal settlement and undesirable urban expansion that hinders the provision of basic services.

Acknowledgements

This research was funded by Norwegian Agency for Development Cooperation as part of capacity building at the Hawassa University and we are grateful for the provided financial support. We also would like to extend our gratitude to the University of Life Sciences, Hawassa University and all those who have supported us during data collection.

References

Abebe, Y. D., & Geheb, K. (Eds.). (2003). *Wetlands of Ethiopia. Proceedings of a seminar on the resources and status of Ethiopia's Wetlands, vi, 116*. Nairobi, IUCN-EARO Publication service.

Almeida, C. M., Montero, A. M. V., Mara, G., Soares-Filho, B. S., Cerqueira, G. C. .… Batty, M. (2005). GIS and remote sensing as tools for the simulation of urban land-use change. *International Journal of Remote Sensing, 26*, 759–774. http://dx.doi.org/10.1080/0143116051233131685

Assefa, G., Alemu, T., & Abinet, A. (2011). Hawassa city administration finance & economic development data collection and dissemination work-process. *Socio-economic Profile - 2003EC, p-9*.

Aynalem, A. (2011). *Migration and urbanization*. Retrieved from http://www.EthiopianDemographyAndHealth.org

Barnes, K. B., Morgan, J. M., Roberge, M. C., & Lowe, S. (2002). *Sprawl development: Its patterns, consequences, and measurement. Towson University*. Retrieved from http://pages.towson.edu/morgan/files/Sprawl_Development.pdf

Bhatta, B., Saraswati, S., & Bandyopadhyay, D. (2010a). Quantifying the degree-of-freedom, degree-of-sprawl, and degree-of-goodness of urban growth from remote sensing data. *Applied Geography, 30*, 96-111. http://dx.doi.org/10.1016/j.apgeog.2009.08.001

Bhatta, B., Saraswati, S., & Bandyopadhyay, D. (2010b). Urban sprawl measurement from remote sensing data. *Applied Geography, 30*, 731–740. http://dx.doi.org/10.1016/j.apgeog.2010.02.002

Bhatta, B. (2012). *Urban growth analysis and remote sensing*. Springer briefs in Geography, Kolkata. http://dx.doi.org/10.1007/978-94-007-4698-5

BOFED. (2011). *Bureau of Finance & Economic Development*. Regional statistical abstract, Hawassa.

Congalton, R. G. (2001). Accuracy assessment and validation of remotely sensed and other spatial information. *International Journal of Wildland Fire, 10*, 321–328. http://dx.doi.org/10.1071/WF01031

Congalton, R. G., & Green, K. (2009). *Assessing the accuracy of remotely sensed data: Principles and practices* (2nd Ed.). Taylor & Francis Group, Boca Raton, FL.

CSA. (1988). *Central Statistical Agency*. Projected Population & Housing Census of Ethiopia, Addis Ababa.

CSA. (2011). *Central Statistical Agency*. Projected Population & Housing Census of Ethiopia, Addis Ababa.

ERDAS. (2010). *ERDAS Field Guide*. Erdas, Inc., Norcross, GA.

Galster, G., Hanson, R., Ratcliffe, M. R., Wolman, H., Coleman, S., & Freihage, J. (2001). Wrestling sprawl to the ground: Defining and measuring an elusive concept. *Housing Policy Debate, 12*, 681. http://dx.doi.org/10.1080/10511482.2001.9521426

Grey, W. M. F., Luckman, A. J., & Holland, D. (2003). Mapping urban change in the UK using satellite radar interferometry. *Remote Sensing of Environment, 87*, 16-22. http://dx.doi.org/10.1016/S0034-4257(03)00142-1

Hurni, H., Amare, B., Herweg, K., Portner, B., & Veit, H., (Eds.). (2007). Landscape transformation and sustainable development in Ethiopia. *Background information from a study tour through Ethiopia*, 4-20 September 2006, Compiled by the participants. Center for development and environment, University of Bern, Bern.

Jat, M. K., Garg, P. K., & Khare, D. (2008). Monitoring and modelling of urban sprawl using remote sensing and GIS techniques. *International Journal of Applied Earth Observation and Geoinformation, 10*, 26–43. http://dx.doi.org/10.1016/j.jag.2007.04.002

Ji, W., Ma, J., Twibell, R. W., & Underhill, K. (2006). Characterizing urban sprawl using multi-stage remote sensing images and landscape metrics. *Computers, Environment and Urban Systems, 30*, 861-879. http://dx.doi.org/10.1016/j.compenvurbsys.2005.09.002

Johnson, M. P. (2001). Environmental impacts of urban sprawl: a survey of the literature and proposed research agenda. *Environmental Planning, 33*, 717-73. http://dx.doi.org/10.1016/a3327

Karanja, F. N., Heipke, C., & Konecny, G. (2002). *Use of knowledge based systems for the detection & monitoring of unplanned developments* (Unpublished doctoral dissertation). University of Hannover, Hannover, Germany.

Kumar, J. A. V., Pathan, S. K., & Bhanderi, R. J. (2007). Spatio-temporal analysis for monitoring urban growth-a case study of Indore city. *Journal of the Indian Society of Remote Sensing, 35*(1).

Larson, R., & Farber, B. (2009). Elementary statistics, picturing the world (4th ed.). Pearson Prentice Hall, New Jersey, NJ.

Li, X., & Yeh, A. G. (2004). Analyzing spatial restructuring of land use patterns in a fast growing region using remote sensing and GIS. *Landscape and Urban Planning, 69*, 335–354. http://dx.doi.org/10.1016/j.landurbplan.2003.10.033

Lillesand, T. M., & Kiefer, R. W. (2000). *Remote sensing and image interpretation* (4th Ed.). John Wiley & Sons Inc., USA.

Mas, J. F. (1999). Monitoring land-cover changes: A comparison of change detection techniques. *Int. J. Remote Sensing, 20*, 139-152. http://dx.doi.org/10.1080/014311699213659

Mather, P. M. (1987). *Computer processing of remotely-sensed images: An introduction*. St. Edmundsbury Press Ltd., St. Edmunds, Suffolk.

Paul, S., & Dasgupta, A. (2013). Spatio-temporal analysis to quantify urban sprawl using geoinformatics. *International Journal of Advances in Remote Sensing and GIS, 1*, 3.

Richardson, H. W., Bae, C. C., & Baxamusa, M. H. (2000). Compact cities in developing countries: Assessment and implications. In M. Jenks & R. Burgess (Eds.), *Compact cities: Sustainable urban forms for developing countries*. Spon Press, London & New York.

Rozenstein, O., & Karineli, A. (2011). Comparison of methods for land-use classification incorporating remote sensing and GIS inputs. *Applied Geography, 31*, 533-544. http://dx.doi.org/10.1016/j.apgeog.2010.11.006

Sarvestani, M. S., Ibrahim, A. L., & Kanaroglou, P. (2011). Three decades of urban growth in the city of Shiraz, Iran: A remote sensing and geographic information systems application. *Cities, 28*, 320–329. http://dx.doi.org/10.1016/j.cities.2011.03.002

Sudhira, H. S., Ramachandra, T. V., & Jagadish, K. S. (2004). Urban sprawl: Metrics, dynamics and modelling using GIS. *International Journal of Applied Earth Observation and Geoinformation, 5*, 29–39. http://dx.doi.org/10.1016/j.jag.2003.08.002

Wondrade, N., Dick, Ø. B., & Tveite, H. (2014). GIS based mapping of land cover changes utilizing multi-temporal remotely sensed image data in Lake Hawassa Watershed, Ethiopia. *Environmental Monitoring and Assessment, 186*, 1765-1780. http://dx.doi.org/10.1007/s10661-013-3491-x

World Resources. (1996). *A guide to the global environment: The urban environment 1996-97*. Oxford University Press, Oxford.

Xiao, J., Shen, Y., Ge, J., Tateishi, R., Tang, C., Lilang, Y., & Huang, Z. (2006). Evaluating urban expansion and land use change in Shijiazhuang, China, using GIS and remote sensing. *Landscape and Urban Planning, 75*, 69-80. http://dx.doi.org/10.1016/j.landurbplan.2004.12.005

Yeh, A. G., & Li, X. (2001). Measurement and monitoring of urban Sprawl in a rapidly growing region using Entropy. *Photogrammetric Engineering & Remote Sensing, 67*, 83-90.

Zanganeh Shahraki, S., Sauri, D., Serra, P., Modugno, S., Seifolddini, F., & Pourahmad, A. (2011). Urban sprawl pattern and land-use change detection in Yazd. *Habitat International, 35*, 521-528. http://dx.doi.org/10.1016/j.habitatint.2011.02.004

Zeleke, K., & Serkalem, A. (2006). *History of Hawassa, 1960-2006*. Tony Printing Services, Hawassa.

ALLREFER. (1991). *Urbanization*. Retrieved February 27, 2013, from http://reference.allrefer.com/country-guide-study/ethiopia/ethiopia55.html

Notes

Note 1. Kebele is the smallest administrative unit in Ethiopia, in this case, having an area ranging from 20ha to 2760ha.

Note 2. The terms Hawassa, Hawassa City, and Hawassa City Administration have been used synonymously.

Note 3. The terms built-up, urban and developed area are used interchangeably.

Copyrights

Paper III

Wondrade, N., Dick, Ø. B., & Tveite, H. (2015). Estimating above ground biomass and carbon stock in Lake Hawassa Watershed, Ethiopia by integrating remote sensing and allometric equations. *Forest Research*, 4, 151, doi: 10.4172/2168-9776.1000151.

This page is intentionally left blank

Forest Research: Open Access

www.omicsonline.org

ISSN: 2168-9776

Forest Research

Wondrade, et al., Forest Res 2015, 4:3
http://dx.doi.org/10.4172/2168-9776.1000151

Research Article Open Access

Estimating above Ground Biomass and Carbon Stock in the Lake Hawassa Watershed, Ethiopia by Integrating Remote Sensing and Allometric Equations

Wondrade N[1, 2, *], **Dick OB**[1] **and Tveite H**[1]

[1]*Norwegian University of Life Sciences (NMBU), Department of Mathematical Sciences and Technology (IMT), P. O. Box 5003, As, N-1432 Norway*

[2]*Department of Biosystem & Environmental Engineering, Institute of Technology, Hawassa University, P. O. Box 5, Hawassa, Ethiopia*

[*]**Corresponding author:** Nigatu Wondrade, Norwegian University of Life Ssciences (NMBU), Department of Mathematical Sciences and Technology (IMT), P. O. Box 5003, As, N-1432 Norway, Tel: 4767231641; E-mail: nigatwond@yahoo.com, nigatu.tedo@nmbu.no

Received date: Jun 29, 2015; **Accepted date:** Aug 07, 2015; **Published date:** Aug 10, 2015

Abstract

With the increasing concentration of carbon dioxide in the Earth's atmosphere as the result of deforestation, there is a pressing need to estimate biomass and carbon pools in tropical forests. This is, particularly, essential in Africa where reliable biomass data is lacking. The present study was aimed at classifying land use land cover, estimating above ground biomass using remote sensing data and allometric equations, and determining the importance value of species in Lake Hawassa Watershed. Pantropic allometric equations were used that relate tree variables obtained by non-destructive measurements to the oven dry biomass. Local species specific biomass equations were also used to compare the results. The results indicated that the natural forest had lower mean above ground biomass (200.9 Mg/ha) than the plantation forest (223.6 Mg/ha). The pantropic allometric equations overestimated the above ground biomass by about 13.0% and 20.5% for natural and plantation forests, respectively, compared to the local equations. This variation is likely to be the main source of uncertainty for biomass computed using generalized equations. The species sampled ranged from 1 to 22 per plot and the overall mean stand density was 785 stems/ha. *Cupressus lucitanica* (60.09%), *Grevillea robusta* (28.65%), and *Eucalyptus citriodora* (20.87%) were the species with the highest importance value. The majority of tree species belonged to the diameter at breast height class of 5–25 cm accounting for 79.1% and 73.3% in plantation and natural forests, respectively. The total above ground biomass of the forest in the study area in 2011 was estimated at 1.72 Megatons. Although using generalized allometric equations demonstrated variations in above ground biomass estimates compared to the local species specific equations, results from this research effort can be used in absence of area specific models.

Keywords: Above ground biomass; Allometric equations; Forest inventory; Importance value index; Remote sensing

Introduction

Ethiopia is a country rich in biodiversity with a wide range of ecological physiographic heterogeneity, having arid lowlands in the east to rainforest in the west and high-altitude afro-alpine vegetation in the central highlands [1]. Ethiopia's flora is estimated to range from 6500 to 7000 species of higher plants of which 12% are endemic [2]. This diversity, including that of Lake Hawassa Watershed is, however, threatened by environmental degradation and deforestation as a result of population growth [3]. The population density of the Lake Hawassa Watershed was about 588 persons/ km^2 [4].

Human driven influence on woodlands and forests is high and complex. According to Thomas and Bekele [5], 75% of urban and 82% of rural Ethiopia's energy consumption depends on traditional fuel (charcoal and fuel wood) extracted from forests. Consequently, the current size of forest in Ethiopia has become small (less than 3%, though there is no consensus on the figure), which once covered about 40% of the country [6].

Carbon is stored by trees and the removal of these trees or deforestation adds CO_2 to the atmosphere when the carbon contained in the forest biomass is burnt or decomposed [7]. The forest not only provides the local people with many resources that are essential for their livelihood, but also contributes to the environmental stability by preventing soil degradation. Besides, forests, as both carbon sources and sinks, can play a major role in combating global climate change.

African landmass is primarily tropical with a wide variety of vegetation communities [8,9]. An earlier work in the tropics by Chave et al. [10] has shown that one ha of tropical forest may shelter as many as 300 different tree species. Because of this diversity, it is practically difficult to develop allometric equations for all species present in the ecosystem. The literature review also didn't find allometric equations developed to estimate above ground biomass (AGB) of the tree species inventoried.

Though destructive sampling methods were initially used to estimate living tree biomass [7], several studies [11-13] have used allometric equations as an alternative method for biomass estimation. In the current study, AGB was also estimated using generalized allometric equations developed for similar biophysical environment.

Generally, in Ethiopia, there is limited number of reports on biomass studies, and the existing studies have focused on small diameter ranges and on few species from Eucalyptus and Acacia genera. In their earlier study, Fantu et al. [14] developed allometric equations for the three Eucalyptus species using destructive sampling method while Zewdie et al. [15] applied the tree variables, diameter at stump height (DSH) and height to develop allometric equations for Eucalyptus globulus coppice - shoot age ranging from one to nine years. In the former study, the Eucalyptus trees harvested were part of a plantation forest in Degaga and Kofele districts in the northern part of our study site, while in the latter the samples were harvested in a plantation forest located around Addis Ababa, at an altitude of 2300-3200 m above sea level. Due to the age limits of sampled trees (between 9 and 14 years old) and variations in biophysical environment, the developed equations were not found suitable to apply for our study site. In their reports, Woldemariam et al. [16] summarized the results of above ground live biomass and carbon stock of the Harana tropical rain forest in the Bale zone, not to be much far away from our study site, using generalized allometric equations. Eshete and Stahl [17] studied the amount of biomass accumulated in the five Acacia species that belong to the natural setting. The land-use types of Harana were Afromontane forest managed for Coffee production and unmanaged natural forest for which the AGB were estimated at 341.2 and 418.2 Mg/ha, respectively. Whereas the study site of the Acacia species is situated within the Ethiopian Rift Valley, far north (≈80 km) from our study site and it was highly disturbed woodland due to its proximity to large cities and the main road. The biophysical environment of the two sites was different from the Lake Hawassa Watershed. Besides, variation existed in management practices between the two sites and our study area. In a similar scenario, Negash et al. [18] developed allometric equations in the Rift Valley Escarpment, found adjacent to our study site for estimating the AGB of Coffea arabica, which is native to Ethiopia, while Abate et al. [19] reported the AGB for Munessa-Shashemene forest. These areas have similar biophysical environment with our study site. However, Coffea arabica in the current study area was sampled from a natural forest different from the other study area where the Coffee plants were sampled in an agroforestry system. Consequently, owing to the difference in management practices and degree of disturbances, it was not possible to use the equations developed for Coffea arabica to estimate AGB of the same species in our site. The Munessa-Shashemene forest site has not only similar biophysical environment with our study area which is critical for the model transfer [20], but also part of this site falls in the district where our study site is located. Therefore, the allometric equations developed for *Croton macrostachyus* (in natural forest) and *Cupressus lucitanica* (in plantation forest) were used to validate the AGB estimated in the current study.

The review indicated that no study has fully addressed the AGB and above ground carbon (AGC) distribution of all species in our study site. Thus, given the large potential storage of carbon in tropical forest, it is worthwhile to direct our effort to estimate AGB/carbon stock. This was performed utilizing the technique of remote sensing combined with field measurements [21-23] which have become common in forest investigation providing realistic and cost effective way of estimating AGB and carbon stock.

The specific objectives of the present study were to (i) analyze satellite image data and delineate forest cover for the base year (2011), (ii) explore and identify the existing tropical forest allometric equations that best estimate the tree based AGB and extrapolate it to the entire study area, (iii) estimate the potential AGB/carbon accumulated in the Lake Hawassa Watershed, and (iv) evaluate the diversity and dominance of species in the ecosystem. Certainly, the analysis performed and the estimated AGB are useful to understand and manage forest resources in the area.

Materials and Methods

Study area description

The study area is located in the Lake Hawassa Watershed ecosystem (latitude 6°49′ to 7°14′ N and longitude 38°16′ to 38°44′ E) covering an area of 143973.4 ha (Figure 1). Out of this, 8130.5 ha were covered with forest in 2011. It extends in both Southern Nations Nationalities and People's Regional State (SNNPRS) and Oromiya Regional State, Ethiopia. The selected site is a mosaic of parts from eight districts from which much of the area (77.6%) falls in the SNNPRS.

The study area accommodates both plantation and natural forests. Wondo Genet area, in particular, is a home for various tree species and harbors a number of wild animals. The dominant tree species in the plantation forest were *Cupressus lucitanica*, *Grevillea robusta*, *Eucalyptus citriodora*, *Juniperus procera*, and *Pinus patula*. Tree species dominant in the natural forest were *Celtis Africana*, *Podocarpus gracilior*, *Croton macrostachyus*, *Albizia gummifera*, *Teclea nobilis*, and *Cordia Africana*.

This area was selected for the study because of its ecological and economic importance. It is one of the few remaining patches of forest in the region near two big cities (Hawassa and Shashemene), and it contains a number of tree species including the major lumber plantations such as *Cupressus lucitanica*, *Podocarpus gracilior*, *Aningeria adolfi-friederici*, and *Pinus patula*.

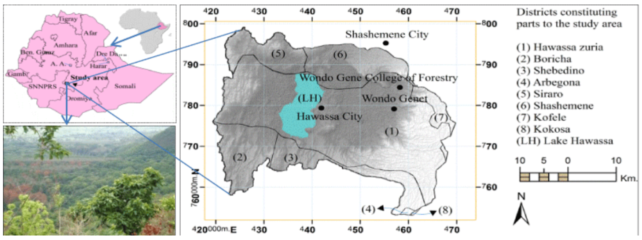


Figure 1: Maps showing the study area in the Rift Valley floor.

The Wondo Genet area is endowed with rich water resources, fertile soil, and wild life. Topographically the study area comprises hills, rugged surfaces, depressions, and flat plains with an altitude ranging between 1571 and 2962 m above sea level. The Watershed is classified as tropical sub-humid type (Moist Weyna Dega) agro climatic zone [24,25], receiving considerable amount of precipitation averaging 1134 mm on an annual basis and temperatures between 12.5°C and 27.2°C [26]. The rainfall pattern of the forest site (Wondo Genet) is bimodal with the main rainy season between July and September, and short rainy season from February to April [27]. The raw rainfall and temperature data used (1984-2003) were from Wondo Genet and Hawassa meteorological stations, respectively. The temperature data from Hawassa station was used due to the absence of recorded data at Wondo Genet station.

The forest areas considered for AGB estimation were predominantly open to dense canopy (30-80%), most of which are found at the south and south-eastern foothills of Abaro Mountain. In areas with higher precipitation, trees were taller, forests were more dense and with fairly-closed canopy. Such areas occur in the Abaro and Wondo Genet sample plots. The natural forest in some hillsides and their foot slopes had dense undergrowth while understory vegetation in some plantation forest and easily accessible sites were little due to a freely roaming animal population. There were signs of illegal cutting of trees and ring-barking causing more tree mortality. In areas which were once harvested, there were regenerating sites with juvenile trees and coppices often in plantation forest.

Most of the forest areas were surrounded by agricultural lands and built-up areas. As a result, the forests were under intense pressure from anthropogenic activities to open-up new farmland, settlements, illegal tree felling for firewood, and construction materials, causing a serious ecosystem degradation and disturbance of the wild life.

Classification of satellite image to delineate forest cover

Remote sensing has long been identified as an effective and efficient tool in forestry studies [28,29] and several researches [21-23] have been conducted to estimate forest biomass and carbon stocks using remote sensing data combined with field measurements. Land cover interpretation and vegetation status of the study area was analyzed using a Landsat TM image from January 10, 2011. The image was downloaded from Global Visualization Viewer at http://glovis.usgs.gov website. This image was segmented into a series of non-overlapping and homogeneous landscape units and land cover classification was performed using a hybrid method with the goal to improve its accuracy. The classified segments were then mosaicked and partitioned into eight parts representing components of districts (Figure 2) that constitute the study area. The digital analysis and delineation of forest class was performed using ERDAS Imagine 2011 and maps were prepared in ArcGIS 10.1. A more detailed description of the image processing and the classification techniques can be found in Wondrade et al. [30].

Forest inventory

The tallying of woody plants in sample plots included the measurement of stem diameter at breast height (DBH), diameter at stump height (DSH), and total height (H). Since it was impractical to measure the height and diameter of all trees in the entire area, H and DBH of trees in the randomly selected plots were measured to represent all trees in the entire forest.

The field survey was conducted during the dry season of January and February, 2012. Sampling of trees in the two forest types was undertaken by a random method within the forest strata in an attempt to sample a broad range of representative trees in the watershed. But in the field, difficulty to access some sample plots on steep slopes limited the strict adherence to the sampling plan.

Four plots were dropped after taking the measurements for being on the boundary and measurements in eight other plots located in the south eastern part of the study area were constrained by natural barriers and security problems during the field work. A total of 48 rectangular plots of 1225 m^2 each were set-out, of which 10 plots were in natural forest and 38 in plantation forest. The size of the rectangular plots was 35 m x 35 m. The sample plot size (0.1225 ha) was determined based on the requirement described by Reid and Stephen [31], who recommended to use sample plot size of 0.2-0.02 ha for a forest with stocking rate (trees/ha) ranging from 100-1000. In another study by Chave et al. [32], it was suggested that a total sampling size of 5 ha allows a land scape scale estimation of the AGB with an error of ± 10%.

Hand held Global Positioning System (GPS) device, measuring tape, colored measuring rope, compass, and pegs were used to set-up sample plots. In each plot, DBH and H of all individual trees with DBH ≥ 5 cm were marked, measured, and identified. Trees with DBH<5 cm were not measured since they normally contribute a small amount of biomass [29]. DBH was measured from a conventional height of 1.3 m [33-35] from the ground level using tree caliper and diameter tape. Individual tree height in each plot was systematically measured using a clinometer and a graduated pole for low trees. When used correctly, the Suunto Clinometer has an accuracy of ± 0.5 m for a 20 m tall tree, i.e., about 2.5% [36].

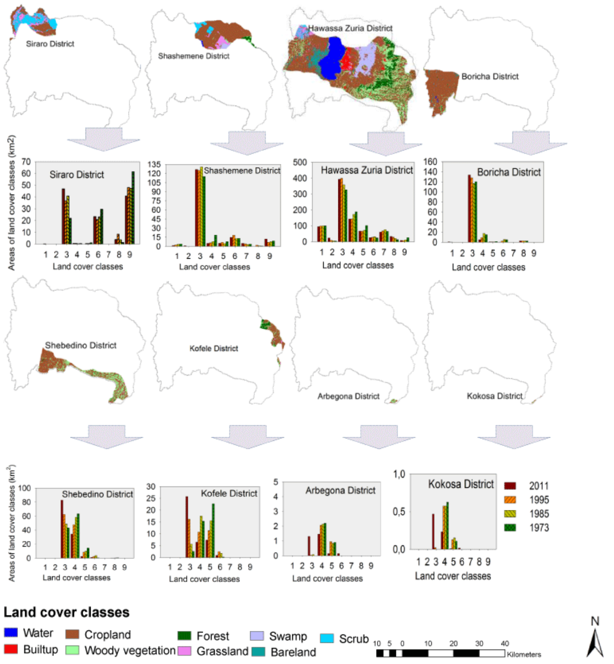


Figure 2: Land cover classes and the corresponding areas (km^2) in each district. 1: Water, 2: Built-up, 3: Cropland, 4: Woody vegetation, 5: Forest, 6: Grassland, 7: Swamp, 8: Bare land, and 9=Scrub. Classified maps for 1973, 1985, and 1995 can be found in Wondrade et al. [30].

Tree species identification

All trees within the sample plots were recorded and identified. Both vernacular and scientific names of tree species were first identified by the support of local people and forest technicians immediately in the forest. For those tree species that could not be identified outright in the field, sample leaves, (seeds, fruits, and flowers when available) were coded and collected in a botanical press for later verification. Species identification of such plants was performed using books published by Bekele-Tessema [37] and Kelecha [38], and Arboretum at Wondo Genet College of Forestry. Despite considerable efforts to identify tree species, we were not able to identify botanical names of two plants identified with local names as Dinbicho in Sidamigna and Muka kara in Oromgna languages, respectively.

Allometric equations

The study area falls under the tropical moist zone where species' richness is prevalent. In such highly diverse tropical forest, it is difficult to develop species-specific regression models, as used in the temperate zone [39]. This is because generation of local species-specific equations by destructive method is prohibitively costly, time taking, and may not be feasible in conservation areas. On the other hand, the most common method of estimating biomass from forest is through allometric equations [7,13]. However, very few allometric equations exist for Sub-Saharan Africa [12]. Therefore, the possibility of using existing mixed species allometric equations established for forests in other continents that best describe the relationship of biomass and tree variables was explored. After literature review, several equations were collated, but used the pantropic allometric equations developed by

Brown [40] and Chave et al. [10] for plantation and natural forest, respectively. These models are also widely used and recommended for estimating carbon stocks in tropical forests [24,41].

Brown's equation was based on volume/ha data and the biomass density were calculated by taking into account the biomass of the other above ground living tree components. It has the following functional form:

$$AGB \text{ density } (\text{t ha}^{-1}) = \text{VOB} \times \text{WD} \times \text{BEF} \ (1)$$

Where, VOB=inventoried volume over bark of free bole (first main branch), WD=volume-weighted average wood density (ton of oven-dry biomass per m^3 green volume), BEF=biomass expansion factor (ratio of above ground oven-dry biomass of trees to oven-dry biomass of inventoried volume), and t ha-1= ton per hectare.

Volume weighted average wood density was calculated as:

$$WD = \left\{ \left(\frac{v_1}{v_t}\right) \times \text{WD}_1 + \left(\frac{v_2}{v_t}\right) \times \text{WD}_2 + \cdot\cdot\cdot + \left(\frac{v_n}{v_t}\right) \times \text{WD}_n \right\}$$

(2)

Where, V_1, V_2,………V_n= estimated volume of species 1,2,….,n; V_t = total volume

WD_1, WD_2, …., WD_n = wood density of species 1, 2,…., n

Available in previous studies [42,43] and 0.580 g/cm^3, the arithmetic mean for tropical Africa [32,44], when wood density of species or species itself is unknown.

The volume of trees in each sample plot was calculated using equations developed and used by several authors [40,45,46] which has the following general form:

$$VOB = \text{BA} \times \text{H} \times \text{FF} \ (3)$$

Where,

$$BA = \pi \times \left(\frac{DBH}{2 \times 100}\right)^2 = \text{ basal area } (\text{m}^2)$$

H = the measured tree height (m),

DBH = the measured diameter at breast height (cm) and

FF = tree form factor

Tree form factors vary not only between species, but also with age, site, composition, and crown size [47]. They take a value of 0.33 for cone shaped trees and 1 when no tapering. In our volume calculation, 0.42 was used, because diameters were actually measured at 1.3 m above the ground and most trees carry a bit more volume than the cone form would suggest.

Research outputs based on data across the tropics has shown that tropical broadleaved forest biomass expansion factors (BEF) are significantly related to stem wood biomass (SWB) and BEFs can be calculated according to the following model [48,49]:

$$BEF = Exp\{3.213 - 0.506 \times \ln(\text{SWB})\}$$

For SWB < 190 t/ha (4)

= 1.74 for SWB ≥ 190 t/ha (5)

Where SWB=biomass of inventoried volume (t/ha), calculated as the product of VOB/ha (m^3/ha) and wood density (t/m^3), ln=natural logarithm, and Exp{}=e raised to the power of{}. No model for calculating BEF for coniferous forests was available to do the type of analysis performed for the broadleaved forests. Therefore, an estimated mean value of 1.3 presented in ref. [40] was used.

The best pan-tropic model for moist forest based on DBH and wood density [10,33] was applied to the current data to estimate AGB of natural forest.

$$TAGB = \text{WD} \times \text{Exp}\{-1.499 + 2.148 \ln(\text{DBH}))^2 - 0.0281 (\ln(\text{DBH}))^3\} \quad (6)$$

WD is species specific wood density in g/cm^3 and available from the same source given in equation (2) and mean wood density of 0.570 g/cm^3 for unknown species and for those species with an unknown wood density.

The equation of Chave et al. [10] was developed based on a much wider sampling size that involved ca. 2410 trees with DBH ≥ 5 cm directly harvested in 27 study sites across the tropics. Although this model includes the diameter range from 5-156 cm, it excludes Africa in its sample data. However, some other studies [12,50], indicated that Chave's model is less biased and has immediate applicability to Africa.

Estimation of total above ground biomass and carbon stock.

The available above ground tree biomass was estimated by applying allometric equations to the inventoried individual tree and extrapolated to the entire area. The allometric equations convert forest structural variables (DBH, H, and WD) into biomass and carbon [13,33]. For plantation forest, the volume of individual trees in each sampling plot, wood density, and biomass expansion factors were used to derive AGB density. In Natural forest, AGB of each tree was estimated using DBH and wood density. The AGB content of the individual trees in a sample plot were then summed to get the total AGB density in that sample plot. The mean AGB density was computed for each forest type and these were then averaged to obtain the total mean AGB density for the entire sample plots. This total mean expressed in t/ha was later multiplied by the total forest cover (ha) in each district to obtain the AGB in tons, the summation of which gives the AGB of the forests in the entire study area.

The forest carbon stocks are widely estimated from the allometric equations for biomass. Generally, the carbon concentration of different parts of a tree is assumed to be 50% of its dry biomass [8,51,52]. Therefore, the estimated AGB in each district was converted to AGC stock using the conversion factor of 0.5 and the carbon stock values were expressed in tons and megatons.

Importance value index of tree species

To investigate the species composition in the Lake Hawassa Watershed ecosystem, the importance value indices were calculated for tree species. Tree species were coded using three letters from the genus, while the last two letters identify the species as used in the woody biomass inventory manual of Ethiopia [53]. The importance value indices (IVI) indicating the importance of species in an ecosystem were calculated using the following relationships [54,55].

IVI = Relative density + Relative dominance + Relative frequency (7)

Where

$$Relative\ density = (Density\ /\ Total\ density\ of\ all\ species) \times 100$$

Density = Number of individuals / Sum of all plot areas,

$$Relative \text{ dominance } = (Density\ /\ Total \text{ dominance } for\ all\ species) \times 100$$

Dominance = Basal area of each species/ Sum of all plot area,

$$Relative\text{ frequency } = (Density\ /\ Total\text{ frequency }for\ all\ species) \times 100$$

Frequency = No. of plots which have at least 1 individual/ Total no. of plots sampled

Results and Discussion

Classification and accuracy

The classification of LULC from image data was aimed at extracting forest cover paying equal attention also to other classes. The magnitude of LULC classes and an overall accuracy are given in Table 1. In this process, plantation and natural forests with tree canopies of 30% and above were classified as forest leaving out other tree formations that were mixed with shrubs and grasses.

LULC class	Water	Built-up	Cropland	Woody vegetation	Forest	Grass land	Swamp	Bare land	Scrub
Area (ha)	9596.8	2465.6	81102.6	19557.3	8130.5	6608.3	6429.7	3998.0	6084.5
An overall accuracy=85% and the total area=143973.4 ha.									

Table 1: Spatial coverage of land cover classes for the base year 2011.

Forest structure

A total of 4617 trees belonging to 35 families, 51 genera, and 58 species were recorded in the stratified sample plots. Species' composition calculated using IVI (Table 2), indicated that *Cupressus lucitanica* was the most important species accounting for 60.09% followed by *Grevillea robusta* (28.65%) and *Eucalyptus citriodora* (20.87%). The abundance of *Cupressus lucitanica* (62%) was also reported [19] for the contiguous Munessa-Shashemene forest.

Species code	**Scientific name**	**Vernacular name**	**RDen (%)**	**RDom (%)**	**RFre (%)**	**(IVI 300)**
CUPLU	*Cupressus lucitanica*	Ye-ferenj Tsid (Am.)	20.51	31.02	8.56	60.09
GRERO	*Grevillea robusta*	Grevillea (En.)	12.63	12.42	3.60	28.65
EUCCI	*Eucaluptus citriodora*	Shito-barzaf (Am.)	10.57	8.50	1.80	20.87
JUNPR	*Juniperus procera*	Tsid (Am.)	8.75	6.49	2.25	17.49
EUCCA	*Eucaluptus camaldulensis*	Key-barzaf (Am.)	7.62	3.39	1.80	12.81
EUCGL	*Eucaluptus globulus*	Nech-barzaf (Am.)	6.52	3.83	1.35	11.70
CELAF	*Celtis africana*	Kawoot (Am.)	2.84	4.48	4.05	11.37
PODGR	*Podocarpus gracilior*	Zigba (Am.)	5.63	1.91	3.15	10.69
CROMA	*Croton macrostachyus*	Bisana (Am.)	0.95	1.28	6.76	8.99
PINPA	*Pinus patula*	Patula (Am.)	1.80	4.71	1.35	7.86
ALBGU	*Albizia gummifera*	Sassa (Am.)	0.69	1.25	4.50	6.45
TECNO	*Teclea nobilis*	Lela (Or./Sd.)	1.95	1.06	3.15	6.16
CORAF	*Cordia africana*	Wanza (Am.)	1.49	2.31	1.80	5.61
CAUEQ	*Casuarina equisetifolia*	Shewshewe (Am.)	1.21	2.35	0.90	4.47
ACOSC	*Acokanthera schimperi*	Keraru (Or./Sd.)	2.06	0.53	1.35	3.94
CAOMA	*Cassipourea malosana*	Tilo (Or.)	1.04	0.67	1.80	3.51
ANIAD	*Aningeria adolfi-friederici*	Kerero (Am.)	0.32	0.92	2.25	3.50
MACKI	*Macaranga kilimandscharica*	Shakere (Wl.)	0.50	0.21	2.70	3.41
XMUKX	*No scientific name found*	Muka kara (Or.)	0.54	0.11	2.70	3.35

ACASY	*Acacia seyal*	Wach'u (Am./Or.)	0.48	1.01	1.80	3.29
CHIMI	*Chionanthus mildbraedii*	Sigheda-dhaltu (Or.)	1.06	0.37	1.80	3.23
POLFU	*Polyscias ferruginea*	Yezinjoro wenber (Am.)	0.22	0.65	2.25	3.12
MILFE	*Millettia ferruginea*	Birbra (Am.)	0.43	0.70	1.80	2.94
JACAC	*Jacaranda acutifolia*	Jacaranda (Am.)	1.62	0.85	0.45	2.93
FARAN	*Fagaropsis angolensis*	Sisa (Or.)	0.28	0.31	2.25	2.85
PYGAF	*Pygeum africanum*	Tikur-inchet (Am.)	0.97	0.94	0.90	2.82
EKECA	*Ekebergia capensis*	Oloncho (Wl.)	0.26	0.27	2.25	2.78
EUCGR	*Eucaluptus grandis*	Key barzaf (Am.)	0.63	1.68	0.45	2.76
PITVI	*Pittosporum viridiflorum*	Ara (Or.)	0.35	0.11	2.25	2.71
DIPDA	*Diphasia dainellii*	Hadesa (Or.)	0.37	0.05	2.25	2.67
CALCI	*Calistemon citrinus*	Bottle-brush (En.)	0.78	0.73	0.90	2.41
BESAB	*Bersama abyssinica*	Teberako (Sd.)	0.37	0.07	1.80	2.24
SPANI	*Spathodea nilotica*	Ye-chaka nebelbal (Am.)	0.26	1.50	0.45	2.21
MASLA	*Measa lanceolata*	Gobacho (Sd.)	0.24	0.06	1.80	2.10
VERAU	*Vernonia auriculifera*	Reji (Or./Sd.)	0.87	0.09	0.90	1.85
OLEHO	*Olea hochstetteri*	Damot-weyra (Am.)	0.24	0.19	1.35	1.78
DRAST	*Dracaena steudneri*	Tonkicho (Sd.)	0.22	0.17	1.35	1.73
PAVAB	*Pavetta abyssinica*	Muka buna (Or.)	0.30	0.04	1.35	1.70
PSIGU	*Psidium guajava*	Zeytun (Am.)	0.19	0.08	1.35	1.62
MAYOV	*Maytenus ovatus*	Kombolcha (Or.)	0.19	0.02	1.35	1.57
MIMKU	*Mimusops kummel*	Kolati (Or.); Ishe (Am.)	0.06	0.02	1.35	1.44
ACAAL	*Acacia albida*	Grar (Am.)	0.28	0.66	0.45	1.39
ACAAB	*Acacia abyssinica*	Bazra-grar (Am.)	0.28	0.54	0.45	1.28
FICSU	*Ficus sur*	Shola (Am.)	0.24	0.58	0.45	1.27
ERIJA	*Eriobotrya japonica*	Woshmela (Am.)	0.13	0.08	0.90	1.11
SYZGU	*Syzygium guineense*	Dokma (Am.)	0.06	0.13	0.90	1.10
PERAM	*Persea americana*	Avocado (Am.)	0.04	0.14	0.90	1.09
BUDPO	*Buddleja polystachya*	Bulchano (Sd.)	0.09	0.04	0.90	1.02
FICVA	*Ficus vasta*	Warka (Am.)	0.06	0.05	0.90	1.02
FLAIN	*Flacourtia indica*	Huda (Or.)	0.04	0.04	0.90	0.98
NUXCO	*Nuxia congesta*	Bitana (Or.)	0.04	0.01	0.90	0.95
XDINX	*No scientific name found*	Dinbicho (Sd.)	0.04	0.00	0.90	0.95
COFAA	*Coffea arabica*	Buna (Am.)	0.04	0.00	0.90	0.95
VERAM	*Vernonia amygdalina*	Grawa (Am.)	0.35	0.07	0.45	0.86
DELRE	*Delonix regia*	Yediredawa-zaf (Am.)	0.09	0.27	0.45	0.81
EHRCY	*Ehretia cymosa*	Uraga (Or.)	0.06	0.05	0.45	0.56
RHUNA	*Rhus natalensis*	Tatesa (Or.)	0.06	0.01	0.45	0.52

PSYOR	*Psychotria orophila*	Digita (Am.)	0.04	0.00	0.45	0.50
	Total		100.00	100.00	100.00	300.00

Table 2: Importance value indices of tree species in the study area.

Note: Relative density (RDen), Relative dominance (RDom), Relative frequency (RFre). Vernacular names of identified tree species in some of the local languages and in English: Amargna (Am.), Oromgna (Or.), Sidamigna (Sd.), Wolaytgna (Wl.), English (En.). The first three letters of the vernacular names were taken for trees with unknown genus and species to begin and end with a letter 'X'.

The stem density of plantation forest (800/ha) was higher than the density of natural forest (730/ha), while the overall stand density was 785 stems/ha. Basal area and volume of plantation forest were 25.0 m^2/ha and 251.9 m^3/ha, respectively. The tree species with the highest basal area and volume were *Cupressus lucitanica*, *Grevillea robusta* and *Eucalyptus citriodora*. These species accounted for 43.7% of the total tree plants. *Eucalyptus grandis*, having the highest mean height, stood 9th and 12th in terms of volume and basal area, respectively. However, *Spathodea nilotica*, a species with the highest mean DBH, was 13th both in volume and basal area.

The spatial distribution and species' composition of the sampled trees revealed that species had variations in their abundance, frequency, and density across the study site. The pattern of forest structure also indicated that about one-fifth of the species had individual trees above the medium stage (20 cm ≤ DBH < 50 cm). Moreover, the mean height of about one-third of the tree species sampled (20 species) were less than 10 m indicating the infrequency of matured trees. The uneven population structure and insignificant number of matured trees can mainly be explained as an indication of human intervention in the forest and selective removal of such trees for timber production.

The majority of tree species both in plantation and natural forest belonged to the DBH class of 5-25 cm accounting for 79.1% and 73.3%, respectively. The number of species in the sampled forests ranged from 1 to 22 per plot, the highest being in the natural forest. Cupressaceae was the most dominant tree family as given in Figure 3b, while Flacourtiaceae and Lauraceae were the least abundant.

The high prevalence of trees with small DBH class in both forest types (Figure 3a) was an indication of disturbance where mature stems are affected by anthropogenic activities and tree mortality as observed during the field inventory. Such disturbance was reported [56] in the Harenna forest, Bale zone in the eastern part of our study area with a relatively similar altitude of 1500-2700 meters above sea level. The change in land use has also been one of the factors that have contributed to the deforestation as reported by Abate et al. [19] for one of the adjoining forest blocks in the area.

Previous studies [55,56] suggested that the patterns of plant population structure represented by an uninterrupted reversed J distribution indicate the presence of individual trees at all sizes implying a healthy and stable regeneration process. However, the observed DBH and Height distributions in the current study area were different from reversed J distribution which can also be attributed to the intense previous and current human interventions.

AGB and carbon estimation

The 48 plots contained trees with mean DBH of 17.4 cm (range 5-75.4), mean height 18.2 m (range 2-57 m), and WD of 0.570 g/cm^3 (range 0.400-0.784). The mean AGB density per plot was estimated at 200.9 Mg/ha (range 87.7-308.6) for natural forest, whereas the estimated mean AGB density for plantation forest was 223.6 Mg/ha (range 51.9-401.7). The mean AGC density per plot was estimated at 100.5 Mg/ha and 111.8 Mg/ha for natural and plantation forests, respectively. It is evident from the figures that the plot level and mean values of AGB density reflected variability within and among the forest types. The amount of biomass and carbon stored in forest varies based on several factors including forest types, age, management practices, and level of human and natural disturbances [15,57,58].

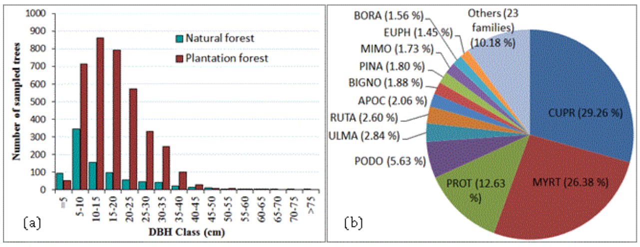


Figure 3: Distribution of sampled trees by DBH class (a) and by Family (b). Tree families with the highest occurrence both in natural and plantation forests: CUPR: Cupressaceae; MYRT: Myrtaceae; PROT: Proteaceae; PODO: Podocarpaceae; ULMA: Ulmaceae; RUTA: Rutaceae; APOC: Apocynaceae; BIGNO: Bignoniaceae; PINA: Pinaceae; MIMO: Mimosoideae; BORA: Boraginaceae; EUPH: Euphorbiaceae and others.

The result revealed that large fractions of AGB and Carbon were stored in small (5-20 cm) and medium (20-50 cm) DBH classes where the number of mature trees were limited (Figure 4).

The sample plot with the highest AGB in the natural forest had 538.8 stems/ha compared to the plot with the lowest AGB having a stand density of 579.6 stems/ha indicating the presence of more biomass in less number of trees with larger size. Therefore, the major variation in the AGB is explained by the large DBH sizes and age differences. Four trees with DBH between 60.5 and 75.4 cm, in the plot with the highest AGB, contributed about 59.1% of the total biomass.

The results of AGB in the plantation forest revealed that the stand density of trees was not the main contributor for the increased AGB. This was exemplified by the plot with the highest and lowest AGB. The stand density of trees in the plot with the lowest AGB was 1 314 stems/ha, while the plot with the highest AGB had 278 stems/ha. The average DBH and height of trees sampled in the plot with the highest AGB were large enough (34.1 cm and 38.5 m, respectively) compared to the average DBH and height of trees (9.8 cm and 17.8 m, respectively) in the plot with the lowest AGB. This shows that the main factors for the variation of the AGB in plantation forest were the differences in DBH and height of individual trees in the sample plots.

Thus, the overall mean AGB of the two forest types (212.3 Mg/ha) was used to estimate the biomass of the entire study area (Table 3). The mean AGC in the natural and plantation forests were estimated to be 100.5 and 111.8 Mg/ha, respectively.

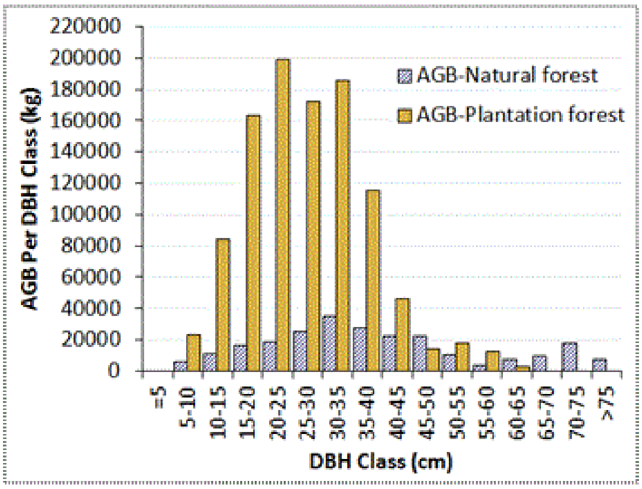


Figure 4: AGB and DBH class distribution of the inventoried trees in both forest types.

The absence of forest cover in Siraro district indicated the presence of heavy anthropogenic activities and active LULC changes on the border between the two regional states. This finding is consistent with the work of Dessie and Kleman [57], who reported the complete replacement of forest cover at the border by agricultural land in the same area.

Comparison of AGB and carbon with the available estimates

The total mean AGB density estimated for this study area was considerably lower than the range of forest AGB reported (245-513 Mg/ha) for the same life zone in countries such as Cameroon, Malaysia, and French Guiana [59]. Though all the sites fall in tropical moist forests, the large variation in AGB is likely due to differences in the type of forest, size of sampled plants and wood density of the inventoried forests. However, the current mean AGB density for plantation forest (223.6 Mg/ha) was within the range of mean AGB density estimated for *Cupressus lucitanica* (217 Mg/ha) and *Eucalyptus globulus* (255 Mg/ha) [19] in plantation forest adjacent to our study site.

Regional State	District	Geographic area (ha)	Forest cover (ha)	Total AGB^3 (ton)
SNNP SNNP SNNP SNNP	Hawassa Zuria	84512.2	6550.6	1390683.9
	Boricha	14286.3	72.7	15438.5
	Shebedino	12116.3	236.7	50251.4
	Arbegona	306.1	14.8	3133.5
Oromiya Oromiya Oromiya Oromiya	Siraro	11518.0	0.0	0.0
	Shashemene	17124.2	521.4	110686.9
	Kofele	4038.2	733.7	155760.3
	Kokosa	72.1	0.7	152.9
Total	.	143973.4	8130.5	1726107.3
		Mt=Megaton		1.726 Mt

Table 3: The estimated mean AGB of forest in the Lake Hawassa Watershed. Total AGB^3 is the product of forest cover and the mean AGB of all plots (212.3 t/ha).

The comparison of AGB from the pantropic allometric equations was made against local species specific equations with DBH ranging from 10 to 30 cm and 19 to 47 cm for *Croton macrostachyus* and *Cupressus lucitanica*, respectively (Table 4). In both cases, the pan tropic equations overestimated the AGB compared to the local equations for the specified DBH classes. The equations (ii), (iii) and (iv) overestimated the AGB on average by about 13.0, 19.5, and 42.0%, respectively, for the natural forest, whereas equations (vi), (iii), and (iv) overestimated by about 20.5, 59.0, and 82.8%, respectively, for plantation forest. It is evident from the figures that equation (ii) corresponding to natural forest and equation (vi) which was used for the plantation forest were found the best models giving results close to the local species specific equations. This was one of the reasons why we selected the two equations to estimate AGB and AGC in the current study area.

a. AGB (kg) of trees from *Croton macrostachyus* (Natural forest)				
DBH (cm)	**Equation (i)**	**Equation (ii)**	**Equation (iii)**	**Equation (iv)**
15	96.3	102.5	111.9	130.0
18	164.1	166.0	177.4	212.7
21.5	243.2	265.1	278.2	336.3
28	390.1	528.0	542.7	643.4
b. AGB (kg) of trees from *Cupressus lucitanica* (Plantation forest)				
DBH (cm)	**Equation (v)**	**Equation (vi)**	**Equation (iii)**	**Equation (iv)**
25	302.2	359.3	407.4	489.2
30	438.7	517.4	646.1	758.2
35	575.1	654.0	954.4	1086.8
40	711.6	936.3	1337.9	1475.1

Table 4: Comparison of AGB estimated using local and pan tropic allometric equations.

(i) - (vi) represent allometric equations used to compare AGB of trees with the specified DBH range

(i) AGB=22.601 × DBH-242.74; Abate et al. [19]

AGB= WD × Exp {-1.499+2.148 × ln(DBH)+0.207 × (ln(DBH))2-0.0281 × (ln(DBH))3}; Chave et al. [10]

(iii) AGB=Exp (−2.134+2.530 × ln(DBH)); Brown [40]

(iv) AGB= (38.4908-11.7883 × DBH+1.1926DBH2); Brown et al. [59]

(v) AGB=27.293 × DBH-380.14; Abate et al. [19]

(vi) AGB density: VOB × WD × BEF, converted to biomass; Brown [40]

Note: (i) and (v) are local species specific equations.

The higher percent variation observed in the plantation forest can be attributed to (1) inaccuracies in height measurement of trees caused by dense canopy, (2) the fact that the original data base used for developing the volume weighted equations was based on closed forests different from the present study site which contains open to closed canopy, and (3) probably the current plantation forest was not purely composed of broadleaf trees, rather, in some plots, with a mix of limited number of conifer trees. On the other hand, most conifer trees such as *Pinus patula, Cupressus lucitanica, and Juniperus procera* were with similar branching and leaf structure within species. Consequently, the variation in BEF of conifer trees will be less than that of broadleaf trees and can influence the result of AGB and carbon stock if BEF of broadleaf is applied. It was also observed that, tree branches near settlements and along routes was trimmed for fencing, fuel wood, and roofing materials which were believed to have contributed to the low AGB estimates using the local equations. This was exemplified by the proportion of biomass of tree components of the species used for comparison where by ≥ 90% of the AGB was allocated to stem wood and the remaining tree components (branches and foliage) accounted only for ≤ 10% [19]. In the absence of precise data, we believe that this will give first estimates of the AGB and AGC for the inventoried forests. Due to lack of other site specific equations, it was not possible to compare AGB for other species.

Chave's equation was developed with very high coefficient of determination (R2 ≥ 99%) for many different forest types across various tropical countries and in the current study; it also demonstrated a comparable result (13.0%) with the area specific equation.

Generally, the reasons why we selected the two equations include: (1) the use of more variables, rather than only DBH, that can lead to an important improvement of biomass estimation [7], (2) equations published by Chave et al. [10] were less biased and more precise than other equations according to a research finding [12] in the tropical forest of Africa, (3) their mathematical simplicity, (4) similarity in biophysical environment where the equations were developed, and (5) the comparative closeness of the AGB with that estimated by the local species specific equations for the available range of DBH. Thus, the equations used can be applied in other tropical moist forests as long as the study area has similar biophysical environment and for the range of tree variables for which the equations were developed.

Uncertainty and errors

Though the allometric equations of Brown and Chave were the best equations found in literature for moist tropical forest worldwide [12,60], they were not without limitations. In estimating AGB of plantation forest, the volume of trees was computed using H, DBH, and form factor as variables. The uncertainty in measuring such tree variables might have contributed to the overestimation of AGB/carbon. Here, it has to be noted that uncertainty in measuring the height of small trees was less since such tree heights were measured directly using graduated poles. The absence of very large diameter trees (100 cm or more) and small number of harvested samples (<10) used to develop the site specific equation that were considered for comparison could also be one source of uncertainty in AGB estimation.

Special plants having the stature of trees, but having different branching and leaf structure such as Dracaena steudneri, may contribute to the AGB and carbon stock of the tropical forest. However, applying the same allometric equations to estimate AGB and carbon accumulation of such plants may be another explanation for the variation of the results.

The use of coarse resolution remotely sensed data where a pixel of forest may also contain a mixture of information may affect accurate estimation of AGB and carbon storage when extrapolated to the entire study area. This was exemplified by the accuracies achieved during image classification. The overall accuracy of the classified image from 2011 was 85%, while the producer's and user's accuracies of forest classification were 87.1% and 88.5%, respectively.

Conclusion

The growing population of the current study area is largely reliant on fuel wood for its energy consumption and livelihood benefits leading to immense depletion of the available forest resources. This is also expected to continue in the future unless the available forest cover is regularly inventoried and sustained to serve the coming generation. Moreover, the preservation of forest resources may contribute to the mitigation of global climate change which has elevated the need for assessment of biomass.

This paper endeavored to quantify the AGB and carbon using the generalized allometric equations developed for tropical moist forests. The abundance of tree species in tropical forest coupled with practical and cost constraints have prompted the use of existing pantropic allometric equations. The best tree allometric equations found in the literature were the equations of Brown [40] and Chave et al. [10]. The application of the selected models is important for the assessment of forest biomass and created a base line for tracking changes in the carbon storage considering the current study as one temporal instant.

The generalized equations, when compared to the available site specific equations, have generally shown the tendency to overestimate the AGB in the order of 20.5% and 13% in plantation and natural forests, respectively. This could be due to the uncertainties in model transfer and measurement of tree variables. It should be noted that using one species specific allometric equation for each forest type for validation may not be enough. In order to minimize the uncertainty in estimating AGB and validate the results achieved using the generalized equations, further research should consider developing local species specific allometric equations in the future.

Given the lack of data on biomass, the current study provided valuable estimates of AGB and AGC storage and fills the data gap in an area under-represented by existing literature.

Acknowledgements

This study was supported by Norwegian Agency for Development Cooperation (NORAD) as part of capacity building at Hawassa University, Ethiopia. We gratefully acknowledge the financial support provided by NORAD and Hawassa University to undertake this research. The authors are thankful to the forest technicians both at Hawassa College of Agriculture and Wondo Genet College of Forestry, for providing assistance in tree species identification and measurement. We also would like to express our sincere appreciation to all the crew members whose active involvement made the forest inventory possible.

References

1. Bekele-Tessema A, Birnie A, Tengnas B (1993) Useful trees and Shrubs for Ethiopia. In: Rimmerfors P (ed). SIDA's Regional Soil Conservation Unit, Nairobi.

2. Lemma A (2005) Site action plan for the conservation and sustainable use of the Lake Awassa biodiversity. Institute of Biodiversity Conservation, Addis Ababa.
3. Ango TG, Bewket W (2007) Changes and prospects for sustainable forest management in Wondo Genet area, Southern Ethiopia. Ethiopian Journal of Development Research 29: 27-64.
4. Thomas I, Bekele M (2003) Role of planted forests and trees outside forests in sustainable forest management in the Republic of Ethiopia. In working papers of the planted forests and trees. Forest Resource Division, FAO, Rome.
5. Eshetu AA (2014) Forest resource management systems in Ethiopia: Historical perspective. International Journal of Biodiversity and Conservation 6: 121-131.
6. Bautista AAL, Groen TA, Weir JC (2012) Biomass/carbon estimation and mapping in the subtropical forest in Chitwan, Nepal: A comparison between VHR GeoEye satellite images and airborne LiDAR data. MSc Thesis, University of Twente.
7. Gatson G, Brown S, Lorenzini M, Singh D (1998) State and change in carbon pools in the forests of tropical Africa. Global Change Biology 4: 97-114.
8. Brown S, Gatson G (1995) Use of forest inventories and geographic information systems to estimate biomass density of tropical forests: Application to tropical Africa. Environmental Monitoring and Assessment 38: 157-168.
9. Chave J, Andalo C, Brown S, Cairns MA, Chambers JQ, et al. (2005) Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145: 87-99.
10. Ahmedin AM, Bam S, Siraj KT, Raju AJS (2013) Assessment of biomass and carbon sequestration potentials of standing Pongamia pinnata in Andhra University, Visakhapatnam, India. Bioscience Discovery 4:143-148.
11. Henry M, Besnard A, Asante WA, Eshun J, Abu-Bredu S, et al. (2010) Wood density, phytomass variations within and among trees, and allometric equations in a tropical rainforest of Africa. Forest Ecology and Management 260: 1375-1388.
12. Vieira SA, Alves LF, Aidar M, Araujo LS, Baker T, et al. (2008) Estimation of biomass and carbon stocks: the case of the Atlantic Forest. Biota Neotropica 8: 21-29.
13. Fantu W, Nuruddin AA, Haris FA, Ab-Malik AR (2010) Above ground biomass equations for selected Eucalyptus species in Ethiopia. In: Gil L, Tadesse W, Tolosana E, Lopez R (eds) Eucalyptus species management, history, status and trends in Ethiopia. Proceedings from the congress held in Addis Ababa.
14. Zewdie M, Olsson M, Verwijst T (2009) Above-ground biomass production and allometric relations of Eucalyptus globulus Labill. Coppice plantations along a Chrono sequence in the central highlands of Ethiopia. Biomass and Bioenergy 33: 421-428.
15. Woldemariam T, Getu Z, Gonfa T, Andargachew A (2011) Report of the capacity building training on measuring and assessing carbon stocks in the Bale Eco-Region, Delo Mena, Ethiopia.
16. Eshete G, Stahl G (1998) Functions for multi-phase assessment of biomass in acacia woodlands of the Rift Valley of Ethiopia. Forest Ecology and Management 105: 79-90.
17. Negash M, Starr M, Kanninen M, Berhe L (2013) Allometric equations for estimating above ground biomass of Coffea arabica L. grown in the Rift Valley escarpment of Ethiopia. Agroforestry Systems 87: 953-966.
18. Abate A, Muller-Hohenstein K, Aas G (2004) Biomass and nutrient studies of selected tree species of natural and plantation forests: Implications for a sustainable management of the Munessa-Shashemene forest, Ethiopia. PhD Dissertation, University of Bayreuth.
19. Lu D (2006) The potential and challenge of remote sensing-based biomass estimation. International Journal of Remote Sensing 27: 1297-1328.
20. Navar-Chiadez J (2011) The spatial distribution of aboveground biomass in tropical forests of Mexico. Tropical and Subtropical Agroecosystems 13: 149-158.
21. Goetz SJ, Baccini A, Laporte NT, Johns T, Walker W, et al. (2009) Mapping and monitoring carbon stocks with satellite observations: a comparison of methods. Carbon Balance Manag 4: 2.
22. Roy PS, Ravan SA (1996) Biomass estimation using satellite remote sensing data-An investigation on possible approaches for natural forest. Journal of Biosciences 21: 535-561.
23. Intergovernmental Panel on Climate Change (IPCC) (2003) Good practice guidance for land use, land-use change and forestry. In: Penman J, Gytarsky M, Hiraishi T, Krug T, Tanabe K, Wagner F (eds). Institute for Global Environmental Strategies, Hayama.
24. Hurni H (1998) Soil Conservation Programme Ethiopia. In the research report of agro ecological belts of Ethiopia: An explanatory notes on three maps at a scale of 1: 1000000. Center for Development and Environment, University of Bern.
25. Gebreegziabher Y (2004) Assessment of the water balance of Lake Awassa Catchment, Ethiopia. MSc Thesis, International Institute for Geo-Information Science and Earth Observation, Enschede.
26. Getachew F, Abdulkadir A, Lemenih M, Fetene A (2012) Effects of different land uses on soil physical and chemical properties in Wondo Genet area, Ethiopia. New York Science Journal 5: 110-118.
27. Wang K, Xiang W, Guo X, Liu J (2012) Remote sensing of forestry studies: Global Perspectives on Sustainable Forest Management. In: Okia CA (ed) InTech, Slavka Krautzeka.
28. Deo RK (2008) Modelling and mapping of above-ground biomass and carbon sequestration in the cool temperate forest of north-east China. MSc Thesis, International Institute for Geo-Information Science and Earth Observation, Enschede.
29. Wondrade N, Dick OB, Tveite H (2014) GIS based mapping of land cover changes utilizing multi-temporal remotely sensed image data in Lake Hawassa Watershed, Ethiopia. Environmental Monitoring and Assessment 186: 1765-1780.
30. Reid R, Stephen P (2001) Tree and forest management. In the farmers' forest: Multi-purpose forestry for Australian farmers. The University of Melbourne, Melbourne.
31. Chave J, Condit R, Aguilar S, Hernandez A, Lao S, et al. (2004) Error propagation and scaling for tropical forest biomass estimates. Philos Trans R Soc Lond B Biol Sci 359: 409-420.
32. Basuki M, van Laake PE, Skidmore AK, Hussin YA (2009) Allometric equations for estimating the above-ground biomass in tropical lowland Dipterocarp forests. Forest Ecology and Management 257: 1684-1694.
33. Alamgir M, Al-Amin M (2008) Allometric models to estimate biomass organic carbon stock in forest vegetation. Journal of Forestry Research 19 (2): 101-106.
34. Losi CJ, Siccama TG, Condit R, Morales JE (2003) Analysis of alternative methods for estimating carbon stock in young tropical plantations. Forest Ecology and Management 184: 355-368.
35. Brack C (1999) Forest measuring and modelling. http://fennerschoolassociated.anu.edu.au/men-suration/author.htm.
36. Bekele-Tessema A (2007) Useful trees and shrubs of Ethiopia: Identification, propagation and management for 17 Agro climatic Zones. In: Tengnas B, Kelbesa E, Demissew S, Maundu P (eds). World Agroforestry Center, Nairobi.
37. Kelecha WM (1987) A Glossary of Ethiopian Plant Names. (4th edn.) Artistic Printing Press, Addis Ababa.
38. Baishya R, Barik SK, Upadhaya K (2009) Distribution pattern of aboveground biomass in natural and plantation forests of humid tropics in northeast India. Tropical Ecology 50: 295-304.
39. Brown S (1997) Estimating biomass and biomass change of tropical forests: A primer, FAO-Forestry-Paper 134. Forest Resources Assessment Publication, Illinois.
40. Rutishauser E, Noor'an F, Laumonser Y, Halperin J et al. (2013) Generic allometric models including height best estimate forest biomass and carbon stocks in Indonesia. Forest Ecology and Management 307: 219-225.
41. Vreugdenhil D, Payton IJ, Vreugdenhil A, Tilahun T, Nune S, et al. (2011) Establishing a ''carbon baseline" and mechanisms for payments for carbon environmental services discharged by protected areas in Ethiopia. World Institute for Conservation and Environment, USA.
42. Zanne AE, Lopez-Gonzalez G, Coomes DA et al. (2009) Global wood density database. https://www.google-.no/search?q=Wood+density+database+in+-africa&oq=&gws_rd=ssl.

43. Berhanu L (2005) Global forest resources assessment: Country reports, Ethiopia. The forest resource assessment programme (FAO), Rome.
44. Vilà M, Carrillo-Gavilán A, Vayreda J, Bugmann H, Fridman J, et al. (2013) Disentangling biodiversity and climatic determinants of wood production. PLoS One 8: e53530.
45. Garzuglia M, Saket M (2003) Wood volume and woody biomass: Review of FRA 2000 estimates. The Forest Resource Assessment Programme (FAO), Rome.
46. Fehrmann L, Aspange (2013) Stem shape. http://wiki.awf.forst.uni-goettingen.de/wiki/index.php/Stems shape.
47. Forest Resources Assessment 1990-Tropical Countries (1993) Food and Agricultural Organization of the United Nations-paper112. Vialedelle Terme di Caracalla, Rome.
48. Brown S, Lugo AE (1992) Above ground biomass estimates for tropical moist forests of the Brazilian Amazon. Interciencia 17: 8-18.
49. Forest Resource Mapping Project under the Japanese grant for the forest preservation programme to the Republic of Malawi (2013) Department of forestry, ministry of environment and climate change management, Lilongwe, Malawi.
50. Marshall AR, Willock S, Platts PJ, Lovett JC, Balmford A, et al. (2012) Measuring and modelling above-ground carbon and tree allometry along a tropical elevation gradient. Biological Conservation 154: 20-33.
51. Smith JE, Heath LS, Woodbury PB (2004) How to estimate forest carbon for large areas from inventory data. Journal of Forestry: 25-31.
52. Parent G, Sutcliffe PJ, Mamo A, Tilimo S, Tellier R, et al. (2000) Woody Biomass Inventory and Strategic Planning Project: Manual for Woody Biomass Inventory. Tecsult International, Addis Ababa.
53. Gebretsadik ZM, Telila AN (2013) Woody plants diversity in disturbed secondary forest and river course vegetation at Eastern base of Abaro Mountain, Wondo Genet, Southern Ethiopia. World Journal of Biology and Biological Sciences 1: 001-009.
54. Girma A, Mosandl R (2012) Structure and potential regeneration of degraded secondary stands in Munessa-Shashemene forest, Ethiopia. Journal of Tropical Forest Science 24: 46-53.
55. Tesfaye G, Teketay D, Fetene M (2002) Regeneration of fourteen tree species in Harenna forest, Southern Ethiopia. Flora 197: 461-474.
56. Dessie G, Kleman J (2007) Pattern and magnitude of deforestation in the South Central Rift Valley Region of Ethiopia. Mountain Research and Development 27 : 162-168.
57. Brown S, Schroeder P, Kern JS (1999) Spatial distribution of biomass in forests of the eastern USA. Forest Ecologt and Management 123: 81-90.
58. Brown S, Gillespie AJR, Lugo AE (1989) Biomass estimation methods for tropical forests with applications to forest inventory data. Forest Science 35: 881-902.
59. Vieilledent G, Vaudry R, Andriamanohisoa SF, Rakotonarivo OS, Randrianasolo HZ, et al. (2012) A universal approach to estimate biomass and carbon stock in tropical forests using generic allometric models. Ecol Appl 22: 572-583.

Paper IV

Wondrade, N., Dick, Ø. B., & Tveite, H. (2015). Analysis of land use land cover conversions and underlying driving forces: The case in Lake Hawassa Watershed, Ethiopia. Submitted to *Kart og Plan* (under review).

This page is intentionally left blank

Analysis of land use land cover conversions and underlying driving forces: The case in the Lake Hawassa Watershed, Ethiopia

Nigatu Wondrade[a,b,]*, Øystein B. Dick[a], Håvard Tveite[a]

[a] Norwegian University of Life Sciences, Department of Mathematical Sciences and Technology, P. O. Box 5003, Ås, N-1432 Norway;

[b] Department of Biosystems & Environmental Engineering, Institute of Technology, Hawassa University, P. O. Box 5, Hawassa, Ethiopia

* Corresponding author: Norwegian University of Life Sciences, Department of Mathematical Sciences and Technology, P. O. Box 5003, N-1432, Ås, Norway.
E-mail: nigatwond@yahoo.com, nigatu.tedo@nmbu.no; Tel.: +251 934751455, +47 6496 6394

Abstract

Lake Hawassa Watershed, in the Main Ethiopian Rift Valley, has experienced significant land use land cover (LULC) conversion over the last four decades. The challenges facing policy makers and resource managers are the insufficient or total lack of data on LULC changes both at local and regional levels. Accurate information about the extent and rates of LULC conversions is needed in order to avoid overuse and damage of the landscape beyond recovery. This research aims at quantifying the spatial and temporal extent of LULC changes and the underlying driving forces (UDFs) over the study period (1973-2011) using remotely sensed data and key informant interviews. A cross-tabulation matrix was used to quantify LULC conversions between successive dates, while key informant interviews identified five major UDFs: demographic, economic, institutional, technological, and biophysical factors. The study area is one of the most densely populated regions in Ethiopia. The result of remote sensing analysis revealed that built-up area expanded at a rate of 12.7% annually between 1973 and 2011 and in absolute terms the increase represents 1.7% of the total area. The highest rate of decline in forest cover occurred during the 1973-1985 temporal interval accounting for (-2.6% yr^{-1}), while the conversion in woody vegetation was the highest (-2.1% yr^{-1}) between 1985 and 1995. Cropland expansion, typical for the current study area, was estimated at 29.4% (183.8km^2) between 1973 and 2011. On the other hand, cropland lost about 18km^2 of its area to built-up between the same temporal instants indicating that the LULC conversions were multi-directional and significant in magnitude. Generally, LULC conversions are continuing to take place in the area, but a slight deceleration was observed in the expansion of cropland which could be explained either for shortage of land for further expansion or that the remaining land is not suitable for development.

Keywords: Land use land cover conversion, underlying driving forces, remote sensing, GIS, Ethiopia

1. Introduction

Ethiopia is known as the cradle of humankind. For thousands of years people have been living in the area, interacting and transforming the natural environment (Brink et al., 2014). Humans have always depended on natural resources for deriving food, freshwater, timber, fiber, and fuel (Guler et al., 2007; Ramankutty and Foley, 1999). However, over the past decades such human interventions have been largely affecting the LULC and its rate of conversion has been higher than in any preceding period in human history. Such human induced changes have caused adverse effects on both society and the environment.

Landscapes in the Lake Hawassa Watershed have undergone extensive LULC conversion. Vegetated areas have been overwhelmingly replaced by crop land. At the same time, some farmyards were converted into vegetation/perennial crops, bare land and built-up areas over the study period. It is not surprising to see the dominance of cropland, as agriculture at subsistence level is the main stay of the economy. More than 85% of Ethiopia’s population depends on agriculture. The country is economically underprivileged, basic resource need outstrips supply and nature is put under pressure by uncontrolled population growth (Wondafrash and Tessema, 2011). Around 2005 (DELTA, 2005) the average cultivable land size per household in the Lake Hawassa Watershed was about 0.58ha.

In the present study area, agricultural production did not keep up with population growth due to factors such as lack of technological know-how and the necessary inputs, land tenure systems, and regime changes following armed conflicts. These factors reduced the stewardship of institutions and individuals to protect natural resources including protected areas from destruction. Empirical evidence of LULC conversions obtained from multi-temporal image analysis can greatly contribute to a better understanding and management of available resources, especially in developing countries where other kinds of background data are limited or totally lacking (Tekle and Hedlund, 2000). However, to devise more appropriate mitigation strategies, studies on LULC conversions should be integrated with investigation of their UDFs.

Landscape changes are considered as one of the main research topics because changes in LULC are major factors in the global environmental processes (Imam, 2011). Since the advent of optical satellite based observation in the 1970s, remote sensing technologies have played a major role in analyzing and documenting changes in LULC at regional and local level.

Numerous case studies at multiple spatio-temporal scales have been conducted in different parts of the world to investigate LULC change dynamics. For instance, Abd El-Kawy et al. (2010), Guler et al. (2007), and Mendoza et al. (2011), analyzed LULC conversions in Egypt, Turkey, and Mexico, respectively using remotely sensed data. In all cases, it was confirmed that expansion in agricultural land, urban areas, and decline in vegetated areas were prevalent with the only exception in Turkey. In Turkey, a slight decrease in agricultural land was reported owing to irrigation practices and shortage of suitable land for further expansion. Other investigations performed within Ethiopia have displayed a similar scenario. The LULC change analysis undertaken (Tekle and Hedlund, 2000; Zeleke and Hurni, 2001) in the northern and northwestern part of Ethiopia, respectively have indicated a wide spread of vegetation clearance, including natural forests and expansion of cultivated land between 1957 and 1995. These are some of the areas with the highest land degradation in the country due to high population pressure and shortage of land. The farming community is compelled to cultivate marginal lands and steep slopes (>30%). Recent studies carried out in the central Rift Valley (*Arsi Negele* district) between 1973 and 2006 (Garedew et al., 2009), and at *Hare* River Watershed in the Southern Rift Valley (Tadele and Forch, 2007) from 1967 to 2004, estimated cropland expansions comparable to the results obtained in the current study. In the *Arsi Negele* district, a site adjacent to our study area, the cropland doubled between 1973 and 2006, while woodland cover declined from 40 to 9%. In the *Hare* River Watershed, farmland and settlement grew from 28.3% in 1975 to 52% in 2004, whereas vegetation cover declined from 28.4 to 16.2% from 1975 to 2004. Though it cannot be ascertained conclusively that these problems are nationwide with the limited number of reports, these are indications that the country's natural resources is at a stake and the biophysical resources need to improve in order to support millions of people.

Remote sensing technologies are suited for capturing LULC conversions (Rogan and Chen, 2004) at a variety of spatial scales with no information on what have caused the changes. Different views exist regarding the relationship between LULC changes and the UDFs in the tropics. Several authors (Castillo-Santiago et al., 2007; Mather and Needle, 2000) have concluded that population pressure is one of the major causes of deforestation and degradation of the land, while Mendoza et al. (2011) associated the main driving forces of LULC change in developing countries to the rapid population growth, poverty, and welfare condition. Rapid socio-economic development (Zhang et al., 2010), fire (Jones et al., 2011), and deforestation, large scale logging, firewood collection and charcoal burning, over grazing, and fire (Jianzhong et al., 2005) have alternately been described as the main drivers of LULC change and forest decline. Probably, deforestation and LULC changes are more explained by multiple factors (demographic, economic, technological, political/policy and institutions, biophysical, and cultural) acting synergistically rather than by a single factor (Burgi et al., 2004; Geist and Lambin, 2002; Lambin et al., 2003). Based on the interviews carried out with key informants in the watershed, the five most prominent UDFs of LULC change (demographic, economic, technological, institutional, and biophysical factors) were identified.

It is challenging to reverse land cover degradation while at the same time meeting the growing demands of people for more goods and better services, particularly in areas with land scarcity that are inhabited by resource-poor farmers. Thus, to sustainably manage natural resources, it is necessary to know the extent of changes and its causative factors. Literature review has not found published documentation on the state of LULC changes and the driving forces in the Hawassa area. That is why this research was undertaken in the Lake Hawassa Watershed to apply remote sensing and field survey techniques for the attainment of the following specific objectives: to (1) quantify the spatial and temporal dimensions of LULC conversions from the classified Landsat images extending over the period of 38 years, (2) conduct key informant interviews and identify the most prominent UDFs of LULC changes, and (3) provide analysis of the identified driving forces with a particular focus on LULC conversions and deforestation. We believe that the analysis performed provides useful information for planning and management of the Watershed.

2. Materials and methods

2.1. Study area description

The study area is located in the center of the Great East African Rift Valley, at times called the Afro-Arabian Rift. It is found 275km South of Addis Ababa, the capital city of Ethiopia, and covers a total of 1435km^2. Its extreme coordinates are 6°49′ and 7°14′ N latitude and 38°16′ and 38°44′ E longitude. The study area includes parts of Southern Nations, Nationalities, and Peoples

Region (SNNPR) (77%) and Oromiya Region (23%). Districts (*Weredas*) partly within the study site include *Hawassa zuria*, *Arbegona*, *Boricha*, *Shebedino*, *Siraro*, *Shashemene*, *Kofele*, *and Kokosa* (Figure 1), the first four being in SNNPR.

Hawassa and Shashemene cities, located at the center and northern edge of the study area, respectively, are the major urban centers and have a combined population of 432 445 (CSA, 2011). Based on the same source, this study area is one of the most densely populated regions in Ethiopia with estimated values ranging from 111 to 677 persons/km^2 for rural inhabitants and 1950 persons/km^2 for the Hawassa City. The average number of people living in the watershed in 1973 was estimated at 44 086 (CSA, 1975), a number which had increased to 1 103 507 by the year 2014 (BoFED, 2014). These figures were estimated based on the population density of provinces and districts for the year 1973 and 2011, respectively since there are no population data at watershed level. The sharp increase of the population in the watershed is an indication of the continuing influx of people to Hawassa, the region's capital city.

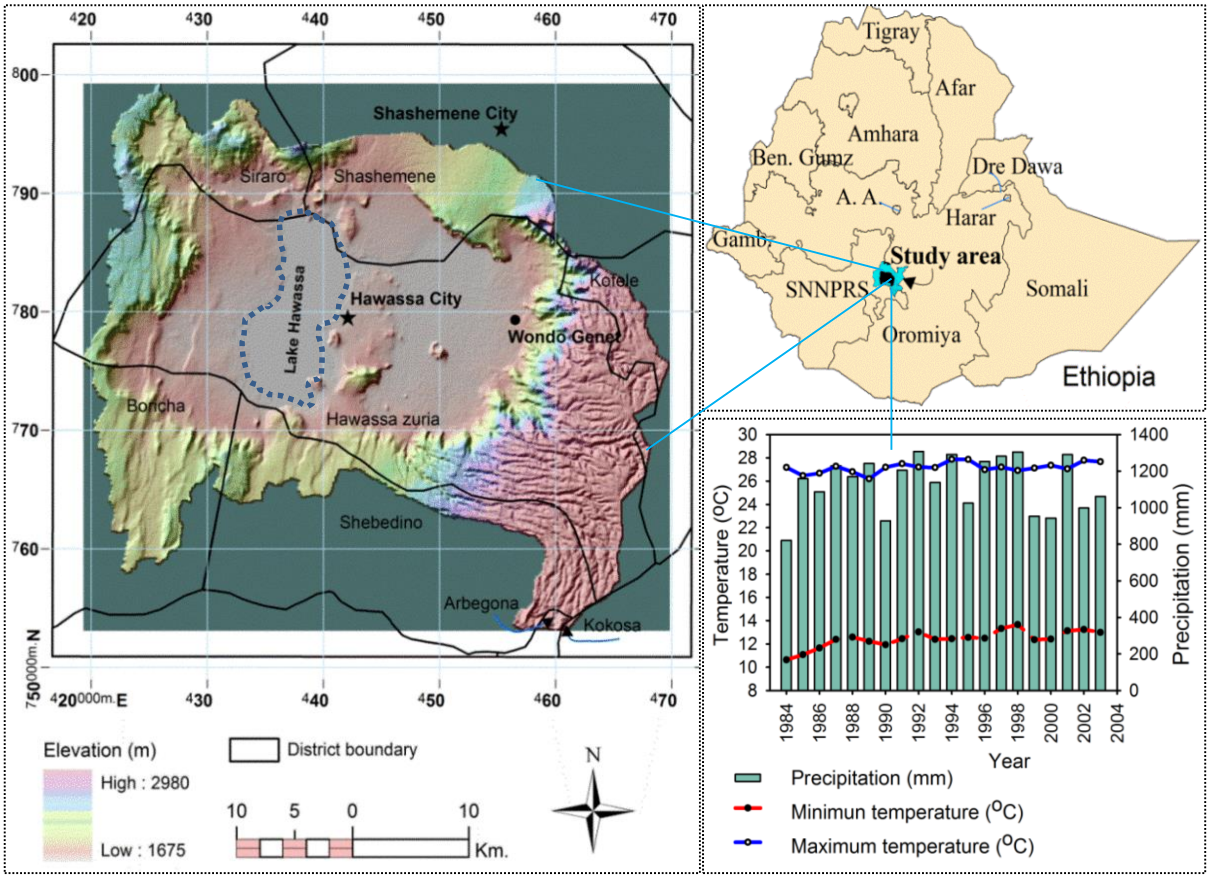


Figure 1. Maps showing location, climatic data, and administrative districts of the study area.

This area was rich in flora and fauna (Lemma, 2005) and has historically supported human related activities, such as agriculture, livestock grazing, fishing, recreation, extraction of wood for construction materials and household fuel. The average annual precipitation varies between 821 and 1307mm, the highest being in Wondo Genet area. The average temperatures generally range between 12.5 and 27.2^{o}C, but are as low as 10.6^{o}C up in the *Abaro* Mountain. Both mean precipitation and temperatures were calculated from 20 years of meteorological data recorded from the stations within the site. According to reports from previous studies (DELTA, 2005; MWUD, 2006), there have been significant LULC changes in the Lake Hawassa Watershed since 1965. The topography of the watershed ranges from flatlands, gentle sloping land to dissected escarpments, and mountainous regions. The study area features altitudes between 1675 and 2980m above sea level and it is characterized by two complex calderas, volcanic features formed by the collapse of lands following volcanic eruptions. The Hawassa caldera is a giant elliptical depression 30-40km wide (Esayas, 2010; Gebreegziabher, 2004) on the Rift Valley floor, while the Korbetti caldera which is found in *Siraro* and partly in *Hawassa zuria* districts, north west of Lake Hawassa, is a nested caldera within the Hawassa caldera. The eastern and north eastern highlands had more vegetation cover than areas at lower altitudes, while the western part of the watershed is poorly vegetated and severely affected by erosion. The soils are formed on volcano-sedimentary rocks and are predominated by sandy loam, loamy sand to sandy loam, heavy clay, and sandy clay loam (Lemma, 2005).

2.2. Data sets and image classification

The main sources of data, in this study, were multi-temporal satellite images and field surveys augmented by census reports, meteorological data, and documented facts. Population data were collected from the Central Statistical Abstracts of Ethiopia and Bureaus of Finance and Economic Development.

The spatial analysis of LULC conversions relied on Landsat Multispectral Scanner (MSS) image from 1973 and Thematic Mapper (TM) images from 1985, 1995, and 2011 along with ancillary data such as topographic maps and aerial photographs. Considerable evidence is available (Loveland, 1999) demonstrating the use of Landsat data for investigating contemporary LULC conversions. The selected TM images have been geometrically corrected and georeferenced by the image provider to the UTM (Universal Transverse Mercator) projection with a processed spatial resolution of 30m. The MSS image was resampled to be comparable to TM images. Topographical maps were used as a reference to register all the Landsat images in ERDAS Imagine and the precision of spatial registration of MSS and TM images was less than one pixel. To aid classification and accuracy assessment, locations were determined using Global Positioning System and visual interpretation. The overall accuracies were between 82.5 and 85%. The user's and producer's accuracies were all reasonable, but as expected there were some difficulties in discerning cropland and grassland covers. Upon completion of classification by applying a hybrid method, multi-date post classification comparison was performed to quantify the spatial distribution of LULC changes. A more comprehensive review of the image analysis and its accuracy assessment can be found in Wondrade et al. (2014).

2.3. Field survey to identify underlying driving forces

The advantage of using remote sensing was that it allows mapping and monitoring of LULC changes. However, this bio-physical approach gives no information on why changes occur (Garedew et al., 2009). A field survey was then combined with multi-date image data analysis in order to identify the UDFs of LULC conversions. In this research setting, key informant interviews were used as a tool to collect information about the driving forces. The interview questions were focused on identification of the major LULC types, changes that have occurred, and the possible UDFs of changes. The interviews were conducted with a total of 27 selected key informants within the Lake Hawassa Watershed. Of this number, 7.4 and 92.6% were female and male, respectively. The survey was conducted in January and February, 2012, involving farmers, forest technicians, GIS experts, forest guards, researchers, and experts from the regional bureau of agriculture, the forestry college, and the city municipality. During the selection of interviewees, purposive sampling focusing on their knowledge of the watershed's natural resources development was used. It was observed that the memory gaps of the young informants were higher for the time span that refers back to 1973 compared to aged respondents. Previous reports, academic theses, and published papers were also used as supplemental sources to identify driving forces.

2.4. Land use land cover conversions

To derive the spatial distribution of LULC conversions in the Lake Hawassa Watershed, cross-tabulation matrices were created through a spatial overlay of successive thematic maps (Figure

2), in ERDAS Imagine. Cross-tabulation matrices are tables with systematic arrays, composed of the LULC classes from the initial year in one axis and the same classes from the subsequent year in the other axis. Each cell of the main diagonal of the matrix contains the surface area (in km^2) of each class that remained unchanged during the time period evaluated, while the remaining cells contain the estimated surface area of a given LULC class that changed to a different class during the same time period (Mendoza et al., 2011). The tables facilitated the determination of the quantity of LULC conversions taking the advantage of ‘’from-to’’ change information for each of the nine established cover classes. Recent studies (IPCC, 2003; Zhou et al., 2008) have shown that remote sensing is the most direct and cost-effective tool that can be used for verification of LULC classes and conversions.

Attributable to unequal length of the temporal intervals (12, 10, and 16) and undoubtedly uneven distribution of LULC conversions within each temporal interval, it was necessary to estimate the average temporal and annual rates of change of LULC type for the purposes of comparison. The annual rates of change were computed by dividing the temporal rates of change by the number of years in the interval (Sleeter and Raumann, 2006; Zhang et al., 2010), which is calculated according to the following formula: $R_a = R_t/\Delta Y$, and $R_t = (A_c - A_p)/A_p * 100$, where $R_a \, and \, R_t$ are the annual and temporal change rates of the target LULC type, respectively; $A_c \, and \, A_p$ are the area of the target LULC type at the current and previous study points in time, respectively; and ΔY is the length of the study period measured in the unit of years. Calculating annual change rates by applying algebraic or geometric progression was not found meaningful owing to uneven distribution of LULC changes across each year and unequal temporal intervals.

3. Results and discussion

3.1. Dynamics of land cover conversions

From the total study area, about 548km^2 (38.2%) has experienced change in LULC for the analyzed 38 year time period. Nearly 396km^2 (27.6%), 425km^2 (29.6%), and 465km^2 (32.4%) of land have been converted into other LULC classes for the 1973-1985, 1985-1995, and 1995-2011 epochs, respectively. In the year 1973 vegetated area, such as forest, woody vegetation, scrub, and grassland represented 10.3%, 21.0%, 6.6%, and 5.0% of the total LULC, respectively.

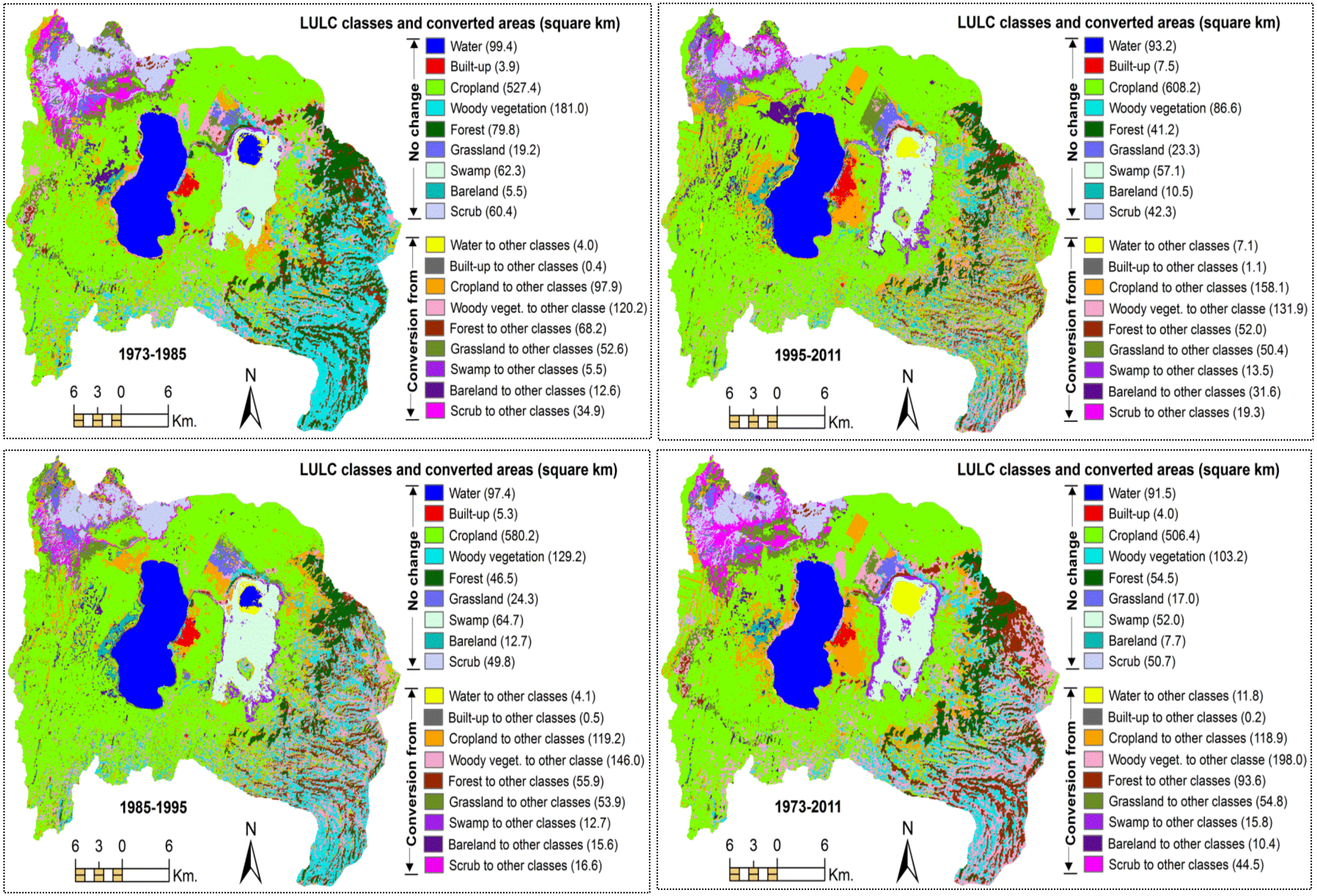


Figure 2. Patterns of LULC conversions between selected dates. Modified based on Wondrade et al. (2014).

However, several drivers had transformed the landscape with a predominant trend of vegetation cover being converted to cropland.

Cropland: This pattern of cropland expansion appears to be typical for the area and was in agreement with the findings of Rembold et al. (2000) in the lakes region, north of our study site, between 1972 and 1994 and that of Fikir et al. (2009) in Eastern Tigray, Ethiopia between 1965 and 2005. As anticipated, the cross-tabulation matrices containing LULC conversions revealed a considerable increase (29.4%) in cropland between 1973 and 2011, the largest in spatial coverage. During 1973-1985, 86.9km^2 from woody vegetation, 41.4km^2 from grassland, 14.1km^2 from forest, and 13.5km^2 from scrub LULC were transitioned to cropland. Likewise, during the interval from 1985 to 1995, 99.8km^2 from woody vegetation, 35.7km^2 from grassland, and 21.8km^2 from forest were converted to cropland.

Cropland also increased significantly during 1995-2011 gaining 101.8km^2 from woody vegetation, 31.2km^2 from grassland, 27.1km^2 from bare land, and 22.2km^2 from forest land cover. On the other hand, cropland lost about 18km^2 of its area to built-up between 1973 and 2011 indicating that the LULC conversions were multi-directional and significant in magnitude. We estimated a yearly rate of change in cropland at 1.0% for the first two periods (Table 1). This was in agreement with reports from (Brink et al., 2014) with a yearly increase rate of arable land and permanent crops (0.9%) in Intergovernmental Authority on Development in East Africa (IGAD) region during 1990-2000. However, the increase in cropland for 2000-2010 was much higher (1.87%) than the rate in our study area (0.3%) for 1995-2011. This slight deceleration in the expansion of cropland could be attributed either to shortage of suitable land for further conversion or that the remaining area is not suitable for development.

Apparently, large area conversion from cropland to woody vegetation was evident in all temporal intervals in the cross-tabulation matrices (Table 2). These were not actually conversions to trees, bushes and other natural vegetation cover, but the conversions were to perennial crops which were challenging to discern from other woody vegetation due to similar spectral signatures of the image data used for classification. On the other hand, woody vegetation lost its area to other classes by 39.9% from 1973 to 1985, 53.0% from 1985 to 1995, and 60.4% from 1995 to 2011. The major conversions of woody vegetation were to cropland in all temporal intervals.

Table 1. Temporal and annual rates of LULC change between two dates.

LULC Classes[c]	(WR)	(BP)	(CL)	(WV)	(FT)	(GL)	(SP)	(BL)	(SB)
LULC Change (1973-1985)									
Difference (km^2)	-1.9	1.6	74.4	-25.3	-45.6	6.4	9.6	10.3	-28.8
Temporal change rate (%)	-1.8	37.0	11.9	-8.4	-30.8	9.0	14.2	56.9	-30.2
Annual change rate (%)	-0.1	3.1	1.0	-0.7	-2.6	0.7	1.2	4.7	-2.5
LULC change (1985-1995)									
Difference (km^2)	-1.2	2.8	66.9	-57.1	-9.3	-4.5	-6.7	13.7	-4.8
Temporal change rate (%)	-1.2	48.5	9.6	-20.7	-9.0	-5.7	-8.6	48.4	-7.2
Annual change rate (%)	-0.1	4.9	1.0	-2.1	-0.9	-0.6	-0.9	4.8	-0.7
LULC change (1995-2011)									
Difference (km^2)	-4.5	16.0	42.4	-23.8	-12.2	-7.9	-6.5	-2.2	-1.2
Temporal change rate (%)	-4.5	185.4	5.5	-10.9	-13.1	-10.7	-9.1	-5.2	-1.9
Annual change rate (%)	-0.3	11.6	0.3	-0.7	-0.8	-0.7	-0.6	-0.3	-0.1
LULC change (1973-2011)									
Difference (km^2)	-7.5	20.4	183.3	-106.3	-67.0	-5.9	-3.5	21.8	-34.7
Temporal change rate (%)	-7.3	480.9	29.4	-35.3	-45.3	-8.3	-5.2	120.9	-36.5
Annual change rate (%)	-0.2	12.7	0.8	-0.9	-1.2	-0.2	-0.1	3.2	-1.0

[c] Note: For the description of abbreviated LULC classes, see Table 2.

Forest: This was the third largest LULC class in 1973 and the major conversions observed were to woody vegetation and cropland throughout the study period, which shows the removal and degradation of forest cover. Forest experienced continuous decline, -30.8% from 1973 to 1985 and -13.1% from 1995 to 2011 period with a -1.2% annual rate of change during the whole study time. The forest cover transitioned to woody vegetation during 1973-1985, 1985-1995, and 1995-2011, were 51.2km^2, 30.6km^2, and 27.5km^2, respectively.

Table 2. Cross-tabulation matrices showing LULC conversions (in km^2) between two dates.

LULC Classes										
	Year 1985									**Total (1973)**
Year 1973	WR	BP	CL	WV	FT	GL	SP	BL	SB	-
Water (WR)	**99.4**	0.0	0.1	0.2	0.1	0.3	3.1	0.0	0.0	103.3
Built-up (BP)	0.0	**3.9**	0.2	0.1	0.0	0.0	0.0	0.0	0.0	4.2
Cropland (CL)	0.2	1.2	**527.4**	38.5	2.9	25.4	9.8	19.1	0.7	625.3
Woody vegetation (WV)	1.5	0.4	86.9	**181.0**	18.7	10.9	1.3	0.5	0.0	301.1
Forest (FT)	0.2	0.0	14.1	51.2	**79.8**	1.0	0.2	0.2	1.3	148.0
Grassland (GL)	0.1	0.2	41.4	3.2	0.2	**19.2**	0.8	2.7	4.0	71.8
Swamp (SP)	0.1	0.0	3.6	1.0	0.5	0.3	**62.3**	0.0	0.0	67.8
Bare land (BL)	0.0	0.1	12.0	0.0	0.0	0.5	0.0	**5.5**	0.0	18.1
Scrub (SB)	0.0	0.0	13.5	0.3	0.3	20.5	0.0	0.3	**60.4**	95.2
Total (1985)	101.5	5.8	699.4	275.6	102.4	78.1	77.3	28.4	66.5	1434.9

	Year 1995									**Total (1985)**
Year 1985	WR	BP	CL	WV	FT	GL	SP	BL	SB	-
Water (WR)	**97.4**	0.0	0.2	0.3	0.1	0.0	3.5	0.0	0.0	101.5
Built-up (BP)	0.0	**5.3**	0.2	0.3	0.0	0.1	0.0	0.0	0.0	5.8
Cropland (CL)	0.8	3.0	**580.2**	50.1	10.4	23.1	2.1	27.0	2.8	699.4
Woody vegetation (WV)	0.3	0.3	99.8	**129.6**	35.0	10.4	0.2	0.1	0.0	275.6
Forest (FT)	0.3	0.0	21.8	30.6	**46.5**	2.9	0.0	0.0	0.2	102.4
Grassland (GL)	1.2	0.0	35.7	6.3	0.8	**24.3**	0.2	1.4	8.3	78.1
Swamp (SP)	0.2	0.0	10.3	1.1	0.2	0.6	**64.7**	0.2	0.0	77.3
Bare land (BL)	0.2	0.1	13.8	0.0	0.0	1.1	0.0	**12.7**	0.6	28.4
Scrub (SB)	0.0	0.0	4.3	0.2	0.2	11.3	0.0	0.7	**49.8**	66.4
Total (1995)	100.3	8.6	766.2	218.5	93.2	73.7	70.7	42.1	61.7	1435.0

	Year 2011									**Total (1995)**
Year 1995	WR	BP	CL	WV	FT	GL	SP	BL	SB	-
Water (WR)	**93.2**	0.0	1.1	0.4	0.2	0.1	5.1	0.2	0.0	100.3
Built-up (BP)	0.1	**7.6**	0.1	0.6	0.1	0.2	0.0	0.0	0.0	8.6
Cropland (CL)	1.0	14.5	**608.2**	72.0	15.1	19.6	1.1	26.4	8.4	766.4
Woody vegetation (WV)	1.0	1.5	101.8	**86.6**	22.6	4.6	0.3	0.1	0.2	218.6
Forest (FT)	0.4	0.1	22.2	27.5	**41.2**	1.5	0.2	0.0	0.3	93.2
Grassland (GL)	0.1	1.0	31.2	5.8	1.6	**23.3**	0.4	1.7	8.7	73.7
Swamp (SP)	0.0	0.0	12.1	0.8	0.1	0.5	**57.1**	0.0	0.0	70.7
Bare land (BL)	0.2	0.1	27.1	1.0	0.1	2.4	0.1	**10.5**	0.6	42.1
Scrub (SB)	0.0	0.0	4.7	0.1	0.0	13.5	0.0	1.0	**42.3**	61.6
Total (2011)	95.8	24.6	808.6	194.7	81.0	65.8	64.2	39.9	60.5	1435.2

	Year 2011									**Total (1973)**
Year 1973	WR	BP	CL	WV	FT	GL	SP	BL	SB	-
Water (WR)	**91.5**	0.0	0.3	0.1	0.1	0.0	11.4	0.0	0.0	*103.3*
Built-up (BP)	0.0	**4.0**	0.0	0.2	0.0	0.0	0.0	0.0	0.0	*4.2*
Cropland (CL)	1.2	17.8	**506.4**	44.0	9.7	13.1	0.5	27.1	5.6	*625.3*
Woody vegetation (WV)	2.4	2.0	168.6	**103.2**	16.1	8.3	0.1	0.6	0.0	*301.2*
Forest (FT)	0.3	0.1	46.6	42.6	**54.5**	2.5	0.1	0.1	1.4	*148.1*
Grassland (GL)	0.3	0.4	44.7	2.6	0.4	**17.0**	0.3	3.2	2.9	*71.8*
Swamp (SP)	0.0	0.0	12.9	1.3	0.1	1.5	**52.0**	0.0	0.0	*67.8*
Bare land (BL)	0.0	0.4	9.4	0.1	0.0	0.5	0.0	**7.7**	0.1	*18.1*
Scrub (SB)	0.0	0.0	19.6	0.9	0.0	22.9	0.0	1.2	**50.7**	*95.2*
Total (2011)	95.8	24.6	808.4	194.7	81.0	65.8	64.2	39.9	60.5	1434.9

From our personal on-site observations and according to key informants, there were signs of forest closure at some locations, but due to low involvement of local people, the borders were violated by encroaching settlers at several sites. Limited area conversions from cropland to forest were observed as the result of farmers' initiative to grow Eucalyptus trees on their farmstead to partially fulfill their wood demands for fuel and housing (Figure 3a).

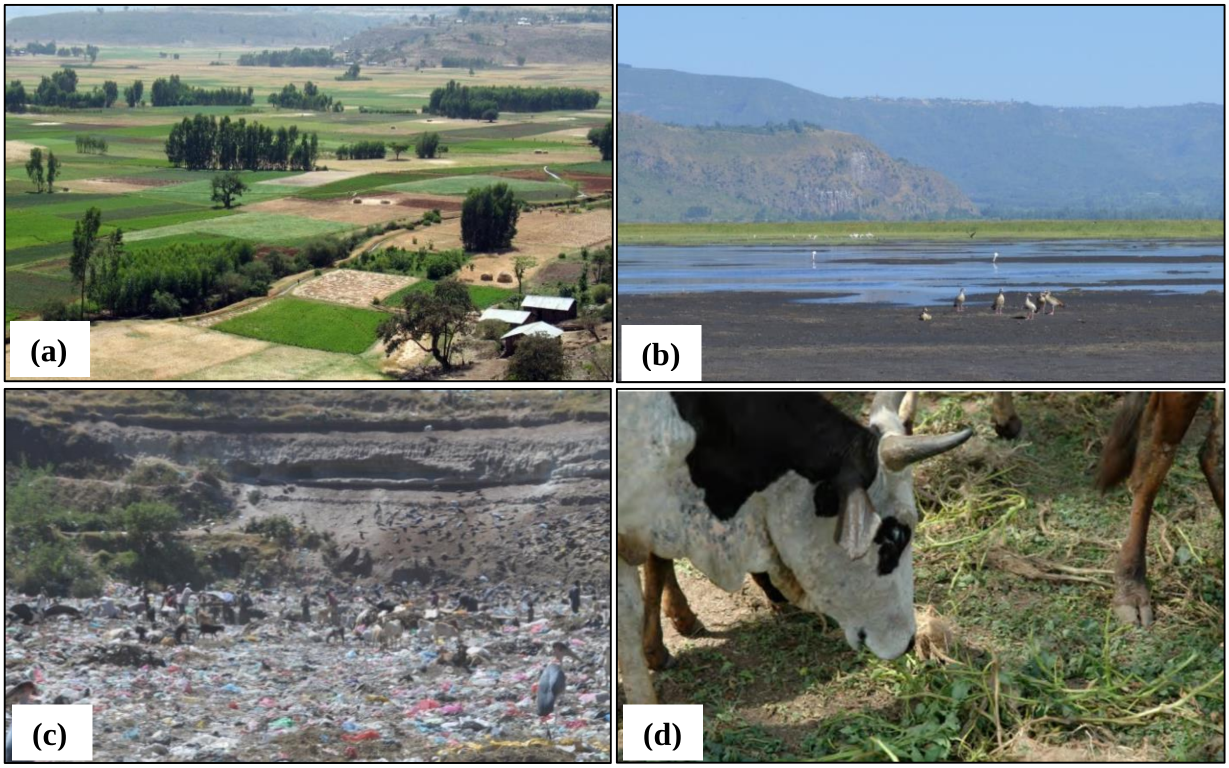


Figure 3. (a) Farmers' initiative to grow Eucalyptus tree on their farmstead (photo by Dessie, 2009), (b) Lake Cheleleka transformed into mudflat and grassland (photo by the author, 2013), (c) Quarrying pit currently used as a disposal site (photo by the author, 2013), and (d) Destruction of vegetation by overgrazing (photo by Bishaw, 2013).

Woody vegetation: In a similar scenario, woody vegetation cover constantly declined, the highest loss being -20.7% between 1985 and 1995. Mid of this interval coincides with the aftermath of the conflict that resulted in regime change in Ethiopia where control over natural resources was loose. Similar reports were published by Gebremariam et al. (2009) that 1991 precipitated in an unprecedented period of environmental destruction until full authority was restored in 1993.

The conversion of woody vegetation to forest in the area signifies the presence of managed forests and the area that once was covered by plantation forest could be changed to woody vegetation in the other temporal interval as grown trees are harvested and left with understories and coppices. Expansion of cropland, extensive livestock browsing, and unwise harvesting of fuel wood were some of the main causes for the deterioration of woodlands.

Built-up: Driven by a constantly accelerating urban population in recent decades, urbanization has become one of the most dynamic processes in the context of global land cover transformations (Bhandari, 2010). Built-up areas increased by 480.9% over the study period and grew at a rate of 37.0%, 48.5%, and 185.4% during the 1973-1985, 1985-1995, and 1995-2011 periods, respectively. These are the highest temporal growth rates recorded in each period, except in the first temporal interval. The largest proportion of land conversions to built-up area were from cropland in all intervals. The promotion of Hawassa City as a political center of the region and improvements in investments particularly since 1995 combined with rapid growth in the construction sector have contributed to the expansion of built-up area. A study conducted (Ayenew and Gebreegziabher, 2006) in the same watershed between 1965 and 1998 corroborated our findings that built-up area has shown similar spatial increase of 185.7%, while (Tekle and Hedlund, 2000) reported 192% of urban settlement increase between 1958 and 1986 in southern Wollo, Ethiopia. Unexpected conversions from built-up to other LULC classes, though it was very small (ca. 0.2km^2), were observed owing to the effect of automatic classification and the coarse resolution of the images utilized.

Water: It is evident from the cross-tabulation matrices that the area occupied by water and swamp decreased by -7.3 and -5.2%, respectively between 1973 and 2011. Though the total coverage of water body had decreased due to the desiccation of Lake Cheleleka, the surface area of Lake Hawassa had increased by ca. 3.5km^2 owing to the loss of vegetation cover and subsequent increase in runoff in the watershed. During the years of abundant rainfall, a rise in the lake levels were recorded, the highest being 3.83m in November 1998 (MWUD, 2006), which caused inundation of the surrounding area. Such lake level rises are presumed to be a threat to Hawassa City, established at its eastern shore.

Grassland: The coverage of grassland decreased by -8.3% between 1973 and 2011, while an increase of 9.0% was noted during the 1973-1985 study period. This variation of temporal change rate in grassland can be accounted for the land management system - that means the land that once was covered by grassland has been converted to cropland (mechanized farm). This switching of farmland to grassland and then back to farm land again was observed in the northern part of the study area. This is demonstrated by the transition of farmland (mechanized farm) to grassland in 1973-1985 when most parts of the state farms were abandoned and then in the next two intervals, grassland lost the majority of its area to cropland as people started to occupy and cultivate those sites. It should also be noted that higher temporal change rates in grassland were observed during the period 1995-2011 (-10.7%) than during the wider interval 1973-2011 (-8.3%). This shows that wider interval change analysis may mask more change processes than short intervals and shows one limitation in LULC conversion analysis. We believe that the opening up of the Landsat archive and the launching of Landsat Data Continuity Mission will provide a good opportunity in future research to analyze land use land cover changes with a more dense time series.

Swamp: The study results indicated an increase (14.2%) in swampy area during 1973-1985, but in the next two intervals, 1985-1995 and 1995-2011, it had continuously decreased by -8.6% and -9.1%, respectively. Between 1973 and 2011, about 19% of the swampy areas were converted into cropland as the result of siltation and continuous evacuation of water from the former lake Cheleleka (Figure 3b). The surface area of Lake Cheleleka was about $12km^2$ in 1972, with an estimated average depth of 5m and a storage volume of $6 \times 10^7 m^3$ (Ayenew, 2004). However, it has now been converted into mud-flat and grassland indicating that the transported sediments have gradually filled the lake bed.

Bare land: This LULC class occupied the smallest area in all the study years next to built-up, but changed with the highest rate (56.9%) in 1973-1985. As the loss of vegetation cover increased, the bare land cover also increased during the first two intervals, but since 1995 when the land for cultivation has become scarce due to population pressure, areas previously left as marginal lands have come under cultivation and two-third of its area turned into cropland. This in turn has aggravated land degradation and yield reduction which causes a demand for more land to cultivate, creating a vicious circle.

Scrub: Scrub was limited to the north-western part of the study area. The major conversions observed were mainly to grassland and cropland over the entire period evaluated. The annual rates of change of scrub were estimated at -2.5%, -0.7%, and -0.1% during 1973-1985, 1985-1995, and 1995-2011 temporal intervals, respectively. This LULC was conserved as Swayne's Hartebeest Sanctuary, but it has frequently been disturbed and still clearing for farming, construction materials, and firewood has continued by encroaching settlers.

3.2. Underlying driving forces analysis

The image analysis has revealed that in many parts of the study area, landscape transformations have taken place at a high rate, but the question of what forces have driven those changes needed further investigation. To understand the changes and associated UDFs, it was necessary to integrate the use of remote sensing which captures the LULC conversions and the experience of key informants who have the knowledge about the watershed's natural resource usage to pinpoint the possible causes of the changes.

Several authors (Burgi et al., 2004; Jones et al., 2011; Zak et al., 2008) support the notion that land cover conversions are influenced by a variety of factors operating on more than one spatial and temporal level and acting not in isolation, but in an interconnected effect of several drivers. The interview results on the driving forces were in agreement with this notion and similar to the framework of Lambin et al. (2003) for tropical regions. Though it is difficult to analyze and represent all driving forces adequately due to their complexity, the assessment result indicated that the LULC conversions in the Lake Hawassa Watershed are mainly driven by a combination of demographic, low agricultural technology, institutional, economic, and biophysical factors.

3.2.1. Demographic factors

Historically, humans have increased agricultural output mainly by bringing more land into production by clearing vegetation cover (Lambin et al., 2003). The clearing of forest and other woody vegetation has taken place in Ethiopia for a long time and it continued at a rate of 141000ha annually between 2000 and 2010 (FAO, 2011). This is mostly converted into cropland resulting in reduced vegetation cover and accelerated soil erosion (Berry, 2003).

According to the Census data (CSA, 1973; BoFED, 2014), the population of Lake Hawassa Watershed increased from 44 086 in 1973 to 1 103 507 in 2014 (Figure 4). Migration was one of the most important demographic factors that contributed to population increase. Based on interview results and own observation, most of the LULC conversions were population induced agricultural land clearance and overstocking of grazing land. Similar interview results (Dessie and Christiansson, 2008) indicated that between 1974 and 1975, when the Revolutionary Derg took power, many farmers from the surrounding villages settled in the Wondo Genet “protected” forest which is part of this study site and in 1991 during the most recent regime change, a large area of government owned forest was extensively felled and converted to farm land. Increase in population, migration, and power vacuum all have the effect of increasing pressure on the existing natural resources. Particularly, population pressure, worsened by low agricultural technology, has significantly contributed to the expansion of agricultural land and excessive extraction of biomass. Earlier works of Nemani and Running (1995) have shown that increase in population and the associated pressures are major driving forces of land cover changes and contributes to natural resource degradation. Increase in population creates surplus labor force and the usual trend for this force has been to break from the extended family and start their own family life. However, this is seldom possible in the area due to shortage of land and thus, the nuclear family stays with the extended family for an elongated period. The recent trends show that this labor force migrates to other undisturbed areas in search of farm land or to the urban areas to look for jobs. Migration to urban areas in turn contributes to the expansion of built-up areas. Urbanization is causing deforestation and permanent soil degradation by replacing previously preserved green areas, parks, and lake side ecosystems. Some of the key informants noted that the combined effect of urbanization and soil degradation has been one of the causes for pollution of water sources through surface run-off.

The demand for fuel is critical in Ethiopia and it is one of the most severe causes of land degradation. A 1989-90 study (Berry, 2003) suggests that nationwide 18 percent of the energy in rural areas is supplied by dung and crop residues. Earlier, such residues were left in the field to serve as organic fertilizer to replenish soil fertility. A similar study conducted in our research area (Yigrem et al., 2008) indicated that 18.2% of the households used animal dung for fuel. Besides, the population increase has led to a shortage of land and fallowing practice is becoming uncommon which in turn reduces soil fertility. It is evident from the image interpretation that 10-27km^2 area was converted from bare land to cropland in every temporal interval, indicating the use of more fragile marginal lands mainly accountable to the increase in population. Population growth has exerted more pressure on vegetated and bare land and this in turn caused an increase in demand for more land and more forest products. As a result, forest resources have been continuously cleared during the study period. Poverty and scarcity of agricultural land, is widely considered as one of the most important precursors of deforestation (Castillo-Santiago et al., 2007).

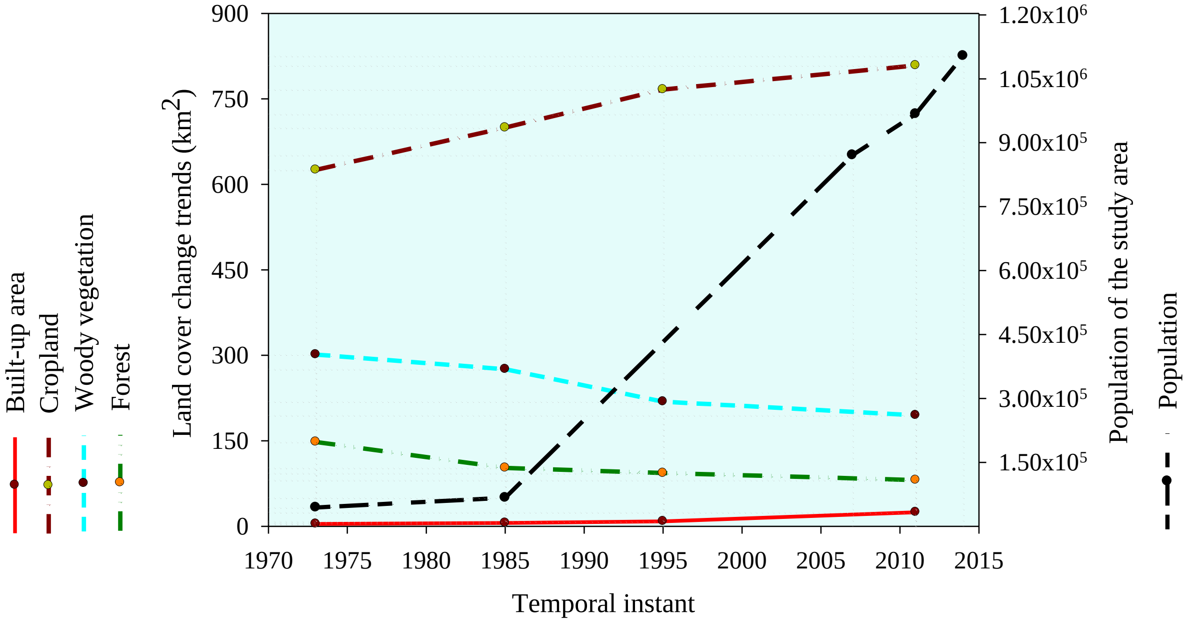


Figure 4. Trends of change in selected LULC classes and human population (1973, 1985, 1995, 2007, 2011 and 2014).

In the current study area, the livestock population has undergone a parallel increase to that of human population. The increase in livestock population has contributed to a fragmentation of arable land and degradation of pasture areas. Arable land per capita declined significantly. In 1994/95, about 61 % of farming households cultivated less than one hectare of land and only 1 % of the farmers' own holdings were greater than 5 hectares (FAO, 2001) and these are likely to be concentrated in the sparsely populated areas with low agricultural potential. Agricultural sample survey by CSA (1985) and BoFED (2014) indicated that the livestock population (cattle, sheep, goat, donkey, horse, and mule) in the current study area increased from 74 810 to 1 136 670. These numbers refer to private peasant holdings only and livestock data of cities were not included due to unreliable sources.

According to respondents, the main source of feed for livestock was natural vegetation available in the field. As the common grazing land areas are gradually transformed into new farms, animals were freely roaming in the remaining pasture, woodland, and even in forested areas. The effects of overgrazing and trampling (Figure 3d) lead to vegetation removal. As confirmed by interviewees, scarcity of pasture for livestock coupled with difference in ethnic background and lack of well-defined boundaries between all forms of land resources are occasionally sources of conflict in the area.

3.2.2. Technological factors

The image analysis revealed that LULC conversion was multi-directional, the primary shift being from vegetated area to cropland. According to respondents, lack of technological know-how and necessary inputs have led the farming community to pursue rain fed horizontal expansion agricultural practices resulting in LULC conversions. Most agricultural practices have a traditional nature of farming system i.e. mixed type comprising cultivation of crops and livestock production on a subsistence basis. This involves the use of wooden traditional farm implements which are extracted from the surrounding forests and woodlands, contributing to the deforestation and LULC conversions.

The main stay of the farming community is agriculture, but the agricultural practices followed were not able to secure self-sufficiency in food, raw materials for agroindustry, and jobs for the growing population. A survey (Deininger et al., 2008) conducted in the SNNP Regional State indicated that 84% of households depend on agriculture and only about 6.1% and 2.5% of households are self-employed and salaried members, respectively. This shows the limited extent of economic diversity and the importance of land as a source of livelihood. According to respondents, farmers rely on horizontally expanding, labor-intensive and rain fed agriculture and sustainable intensification has not been possible due to the lack or high cost of agricultural inputs (fertilizer, seed, and secure land). The Wondo Genet area is endowed with abundant water resources and fertile soil where irrigation could have played a major role in food production.

The long existing state owned Shallo improved seed enterprise which is rain fed and the recently launched private owned G2 irrigated farm, occupying about 3.0% of the study area, were formerly covered by woodland and pasture at the suburb of Hawassa City. However, farmers in the area are still practicing traditional agriculture on limited farmlands. Poor technological applications in the wood sector leading to wasteful logging practices (Geist and Lambin, 2002) are also contributing to the destruction of vegetation cover.

3.2.3. Institutional factors

There are several institutions with legal jurisdiction to administer land resources in Ethiopia. These include: the Ministry of Agriculture and Rural Development (MoARD) at a national level, Regional Agricultural Bureaus, the Environmental Protection Authority, and the Agricultural Research Organization among others. In Oromiya Regional State, authority over forests lies with the Rural Land and Natural Resources Administration Authority, while in SNNPRS jurisdiction falls to the Agriculture and Natural Resources Development Bureau under regional MoARD. Besides, institutions responsible for natural resource management have frequently been restructured to improve the protection of available resources. However, key informants interviews indicated that frequent restructuring and overlapping responsibilities among those institutions accountable for land resource management were considered barriers to halting the severe deforestation and land degradation in the area. Devolving of natural resource management responsibilities to lower administrative units, district level, where serious concerns exist over the capacity of officials to accurately demarcate the location of natural resources was shared by 75% of the respondents. Thus, inadequate capacity of institutions at district level to educate and involve local community in the management and conservation of the natural resources was one of the causes that led to the clearance of land cover and soil degradation.

Another pattern, seen mostly in Africa, comes from insecure ownership related to uncertainties of land tenure. In Ethiopia, ownership of land is with the state and people are entitled to inheritable use right which is in conflict with the goal of ensuring land users’ tenure security. In their reports, Grover and Temesgen (2006) argued that restrictions on land ownership and land sales have caused insufficient land use, discouraged long-term investment in the land and thereby contributed towards increased land degradation. Key informants confirmed that people considered natural resources including forests as village commons and the environmental custodianship was gradually eroded among the newly emerging households. This situation makes the farming community both actor and victim of the land degradation.

From a study conducted by Dessie and Christiansson (2008) and feedback from key informants, it became evident that the power vacuum during the regime changes and weak institutional law enforcement exemplified by encroachment deep into vegetated areas, selective cutting, and illegal logging has also caused LULC conversions in the study area. During the regime changes, institutions often completely lose their stewardship to protect the natural resources. The weak law enforcement is sometimes linked with some level of undesired relationships among those engaged with resource management.

The Rural Land Administration and Land Use Proclamation (FDRE, 2005) was one of the institutional decisions perceived to reduce deforestation and land cover conversions in the region. This proclamation (456/2005) was issued in 2005 with the aim to increase tenure security, improve productivity and avoid expectations of land re-distribution. However, forested areas were not mentioned until it was amended in 2007 and in most instances forests have yet to be mapped and registered. Rural households who knew this loophole in land law were able to clear land and stake a claim before the registration process began. Such was the case in SNNPRS where large areas of forest were cleared prior to the proclamation being issued (Gebremariam et al., 2009).

3.2.4. Economic factors

Agriculture is the predominant economic activity in Ethiopia and it contributes 53% of the GDP, 90% of the export earnings and 85% of the employment and livelihood (Bekele, 2001). Recent state investments in transportation and communication infrastructures improved access to local and regional markets and created opportunity for people to look for alternative livelihoods. An earlier study (Geist and Lambin, 2002) indicated that economic factors are prominent UDFs of tropical deforestation. According to our observation and feedback from key informants, soaring prices of timber and other wood products aggravated by overstocking of saw mill and joinery enterprises in the surrounding towns have negatively contributed to the LULC change in the area. Consumer prices for local and imported timber were reported to have reached USD 307/m^3 (ca. 5 500 Birr) in 2009 for local sawn wood and USD 386/m^3 for imported timber (Bekele, 2011).

The other perspective is the introduction and prioritization of certain high-return crops. Based on earlier reports (Dessie and Christiansson, 2008) and as confirmed by interviewees, the emergence of coffee, haricot beans, and khat (a mild stimulant plant) as economic crops, have intensified changes by promoting economic activities, establishment of new markets, and immigration and settlement, all of which factors have contributed ultimately to agricultural expansion and decline in wood lands.

We realized that forest protection was not a priority for the community, but an opportunity to benefit from forest resources. This is because not all members have knowledge of the impact of forests on the environment. Key informants also recognized that due to the limited off-farm employment opportunity, the majority of households need instant cash from other sources to pay for schooling, health care, and land taxes. This has increased the demand and pressure on natural resources by encouraging people to engage in illegal logging and clearing forest for charcoal burning to earn immediate income.

In connection with expanding built-up areas and associated construction activities, quarrying of building and road filling materials as a source of income has been extensive in the area. These include harvesting of sand, gravel, red ash, clay, surface and sub-surface earth materials. In suburbs of the cities and towns of the study area, people who are exploiting the resource may ask for permission for a given site, but dig anywhere they choose. In some areas the exploiters seldom bother to seek permission from anyone. On site observation and feedback from selected informants indicated that such quarrying activities have been huge sources of income since the 1990s resulting in a wide spread clearance of vegetation and soil degradation. Exposed surfaces due to quarrying are vulnerable to erosion, and regrowth on such surfaces is rare or very slow. Besides, some of the quarrying pits close to Hawassa City are used as waste dumping sites. The quarrying pit in the new settlement area, commonly called "Diaspora", is a living example (Figure 3c). Some respondents interviewed around this site and from the municipality noted that there are many people involved in the flourishing waste disposal business to generate income to support their families.

3.2.5. Biophysical factors

Biophysical attributes such as topography, local climate, soil type and availability of water (Briassoulis, 2000), generally play an important role in LULC conversions. According to accounts from key informants, suitability of land with flat-lying topography and availability of water for a range of use has contributed considerably to the expansion of agricultural land and livestock production. These conditions have served as a pull factor to the increase in the number of inhabitants and has led to cultivation of marginal lands. Areas with steep slopes and reduced vegetation cover are susceptible to erosion when short torrential tropical rain flashes. The result of image analysis and feedback from the interviewees demonstrated that the western part of the watershed was converted to bare land and some areas were exposed to gully formations due to erosion. Respondents also said that human-induced fires have played a significant role in the destruction of forest and dense bush on hillsides and steep areas where it is not easy to access and control the incidents. In the current study area, complete regeneration of vegetated areas was not possible given the increasing human and livestock population, expanding agricultural activities, and proximity to settlements and road networks.

The long term mean monthly rainfall of the watershed varies between January and September. According to summaries drawn by (Gebreegziabher, 2004) using meteorological data within the study area, the mean monthly rain fall in January was 26.7mm while the highest recorded was in September amounting 133.1mm. The rainfall data reveals the occurrences of high seasonal variability and recently irregular changes in the pattern have also been observed affecting the growth and regeneration of vegetation cover.

4. Conclusion

As the regions enclosing the study area do not have documented and harmonized land resource data, assessment of land conversions and driving forces at a local level is an important information layer that could be expanded to a regional level. The availability and analysis of remote sensing data coupled with field survey techniques was found effective to quantify LULC conversions and identify the UDFs of the changes. The result revealed a wide spread clearance of vegetation cover, the primary conversion being to agricultural land. The current study area has undergone a rapid LULC conversion and more than 291km^2 (20.3%) of woody vegetation and forest cover has been permanently converted into other LULC classes over the study period (1973-2011). The quantified LULC conversions and interviews with key informants not only enabled us to identify the changes and UDFs, but also showed us direction about measures to be taken in order to minimize deforestation and land degradation. If the biophysical resources are to improve, mitigation strategies should be developed that are geared towards the UDFs. The need to transform low agricultural technology, enabling local community to influence resource management institutions through policies, and introducing secure land tenure system are some of the factors pinpointed to minimize the extent of resource degradation in the study area. The survey results and census data also indicated that the area is under population pressure and this trend is expected to grow in the future unless proper migration policy coupled with family and land use planning is formulated and implemented.

It is useful to create awareness that the use of coarse spatial and temporal resolution imagery may never completely be free of limitations. Using fine resolution image data in the future research should produce better results for planning and informed decision making in natural resource management. Particularly, analysis of high temporal resolution images will tend to avoid the masking of some sudden changes that have occurred within short temporal intervals.

The findings based on the analysis of the quantified LULC conversions and the response of key informants about the causal factors should provide useful information to planners and natural resource managers to better understand the past and current change dynamics and subsequently manage biophysical resources in the future.

Acknowledgements

The present research was supported by the Norwegian Agency for Development Cooperation (NORAD) through a grant to Hawassa University for capacity building. The authors are grateful for the financial support provided to undertake this research. Key informants are acknowledged for sparing their time to give interviews. The authors would also like to thank the two anonymous reviewers for their thorough review and valuable comments.

References

Abd El-Kawy, O.R., Rød, J.K., Ismail, H.A., Suliman, A.S., 2010. Land use and land cover change detection in the western Nile delta of Egypt using remote sensing data. *Applied Geography*, 31, 483-494.

Ayenew, T., 2004. Environmental implications of changes in the levels of lakes in the Ethiopian Rift since 1970. *Regional Environmental Change*, 4, 192-204.

Ayenew, T., Gebreegziabher, Y., 2006. Application of a spreadsheet hydrological model for computing the long-term water balance of Lake Hawassa, Ethiopia. *Hydrological Sciences Journal*, 51(3), 418-431.

Bekele, M., 2001. Forestry Outlook Studies in Africa. Food and Agriculture Organization, pp. 39. Available at http://www.fao.org/3/a-ab582e.pdf (accessed 16.08.2012).

Bekele, M., 2011. Forest plantations and woodlots in Ethiopia. *African Forest Forum*, 1(12), 1-52.

Berry, L., 2003. Land Degradation in Ethiopia: Its Extent and Impact (Unpublished results), Ethiopia.

Bhandari, S., 2010. Urban Change Monitoring Using GIS and Remote Sensing Tools in Kathmandu Valley, Nepal. MSc Thesis, Erasmus Mundus Consortium.

BoFED, 2014. Bureau of Finance and Economic Development, Hawassa and Shashemene, Ethiopia.

Briassoulis, H., 2000. Factors Influencing Land-Use and Land-Cover Change. UNESCO-EOLSS Sample Chapters. Land Use, Land Cover and Soil Sciences, Vol. I.

Brink, A.B., Bodart, C., Brodsky, L., Defourney, P., Ernst, C., Donney, F., Lupi, A., Tuckova, K., 2014. Anthropogenic pressure in East Africa-Monitoring 20 years of land cover changes by means of medium resolution satellite data. International *Journal of Applied Earth Observation and Geoinformation*, 28, 60-69.

Burgi, M., Hersperger, A.M., Schneeberger, N., 2004. Driving forces of landscape change-current and new directions. *Landscape Ecology*, 19, 857-868.

Castillo-Santiago, M.A., Hellier, A., Tipper, R., de Jong, B.H.J., 2007. Carbon emissions from land-use change: An analysis of causal factors in Chiapas, Mexico. *Mitigation and Adaptation Strategies for Global Change*, 12, 1213-1235.

CSA, Central Statistical Abstract of Ethiopia, 1973. Central Statistical Office, Addis Ababa, Ethiopia.

CSA, Central Statistical Abstract of Ethiopia, 1975. Central Statistical Office, Addis Ababa, Ethiopia.

CSA, Central Statistical Abstract of Ethiopia, 1985. Central Statistical Office, Addis Ababa, Ethiopia.

CSA, Central Statistical Agency, 2011. Central Statistical Authority, Addis Ababa, Ethiopia.

DELTA, Development Management Consultancy Services, 2005. Land Use/Land Cover Change and Erosion Hazard Assessment in Lake Hawassa Catchment (Unpublished results), Hawassa, Ethiopia.

Deininger, K., Ali, D.A., Holden, S., Zevenbergen, J., 2008. Rural land certification in Ethiopia: Process, initial impact, and implications for other African Countries. *World Development*, 36(10), 1786-1812.

Dessie, G., Christiansson, C., 2008. Forest decline and its causes in the South-Central Rift Valley of Ethiopia: Human impact over a one hundred year perspective. *AMBIO: A Journal of the Human Environment*, 37(4), 263-271.

Esayas, Y., 2010. Evaluating the Impact of Land-use Land-cover Change on Soil Erosion and Runoff Using SWAT Model at Tikur Wuha Watershed. MSc Thesis, Addis Ababa University, Addis Ababa, Ethiopia.

FAO, 2001. The Change Drivers. Food and Agriculture Organization of the United Nations, Rome. Available at http://www.fao.org/docrep/004/ab582e/AB582E03.htm FAO Corporate Document Repository (accessed 16.08.2012).

FAO, 2011. State of the World’s Forests. Food and Agricultural Organization of the United Nations, Rome.

FDRE, 2005. Rural Land Administration and Land Use Proclamation. Federal Democratic Republic of Ethiopia, Addis Ababa.

Fikir, A., Nurhussen, T., Nyssen, J., Atkilt, G., Amanuel, Z., Mintesinot, B., Deckers, J., Poesen, J., 2009. The impacts of watershed management on land use and land cover dynamics in Eastern Tigray (Ethiopia). *Resources, Conservation & Recycling*, 53, 192-198.

Garedew, E., Sandewall, M., Soderberg, U., Campbell, B.M., 2009. Land-use and land-cover dynamics in the Central Rift Valley of Ethiopia. *Environmental Management*, 44, 683-694.

Gebreegziabher, Y., 2004. Assessment of the Water Balance of the Lake Hawassa Catchment, Ethiopia. MSc Thesis, International Institute for Geo-Information Science and Earth Observation, Enschede, the Netherlands.

Gebremariam, A.H., Bekele, M., Ridgewell, A., 2009. Small and Medium Forest Enterprises in Ethiopia. Farm-Africa and International Institute for Environment and Development, London, UK.

Geist, H.J., Lambin, E.F., 2002. Proximate causes and underlying driving forces of tropical deforestation. *Biosciences,* 52(2), 143-150.

Grover, D.K., Temesgen, A., 2006. Enhancing Land-Use-Efficiency Through Appropriate Land Policies in Ethiopia (Unpublished results), Ethiopia.

Guler, M., Yomralioglu, T., Reis, S., 2007. Using Landsat data to determine land use/land cover changes in Samsun, Turkey. *Environmental Monitoring and Assessment*, 127, 155-167.

Imam, E., 2011. Uses of geospatial technology in evaluating landscape cover type changes in Chandoli National Park, India. *Computational Ecology and Software,* 1(2), 95-111.

IPCC, 2003. Good Practice Guidance for Land Use, Land-Use Change and Forestry. Global Environmental Strategies for the IPCC, Japan.

Jianzhong, Y., Yili, Z., Wanqi, B., Yanhua, L., Weikai, B., Linshan, L., Du, Z., 2005.Land cover changes based on plant successions: Deforestation, rehabilitation and degradation of forest in the upper Dadu River Watershed. *Science in China Series D Earth Sciences,* 48(12), 2214-2230.

Jones, N., de Graaff, J., Rodrigo, I., Duarte, F., 2011. Historical review of land use changes in Portugal (before and after EU integration in 1986) and their implications for land degradation and conservation, with a focus on Centro and Alentejo regions. *Applied Geography*, 31, 1036-1048.

Lambin, E.F., Geist, H.J., Lepers, E., 2003. Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environment and Resources*, 28, 205-241.

Lemma, A., 2005. Site Action Plan for the Conservation and Sustainable Use of the Lake Hawassa Biodiversity (Unpublished results), Addis Ababa, Ethiopia.

Loveland, T.R., Sohl, T.L., Sayler, K., Gallant, A., Dwyer, J., Vogelmann, J.E., Zylstra, G.J., 1999. Land cover trends: Rates, causes, and consequences of late-twentieth century U.S. land cover change, *EPA Journal*, 1-52.

Mather, A.S., Needle, C.L., 2000. The relationships of population and forest trends. *The Geographical Journal*, 166(1), 2-13.

Mendoza, M.E., Granados, E.L., Geneletti, D., Perez-Salicrup, D.R., Salinas, V., 2011. Analyzing land cover and land use change processes at watershed level: A multi-temporal study in the Lake Cuitzeo Watershed, Mexico (1975-2003). *Applied Geography*, 31, 237-250.

MWUD, Ministry of Works and Urban Development, 2006. Report on Hawassa Integrated Development Plan (Unpublished results), Addis Ababa, Ethiopia.

Nemani, R.R., Running, S.W., 1995. Satellite monitoring of global land cover changes and other impact on climate. *Climate Change*, 31, 395-413.

Ramankutty, N., Foley, J.A., 1999. Estimating historical changes in global land cover: Croplands from 1700 to 1992. *Global Biogeochemical Cycles*, 13(4), 997-1027.

Rembold, F., Carnicelli, S., Nori, M., Ferrari, G.A., 2000. Use of aerial photographs, Landsat TM imagery and multidisciplinary field survey for land-cover change analysis in the lakes region, Ethiopia. JAG, 2(3/4), 181-189.

Rogan, J., Chen, D., 2004. Remote sensing technology for mapping and monitoring land-cover and land-use change. *Progress in Planning*, 61, 301-325.

Sleeter, B.M., Raumann, C.G., 2006. Land-cover trends in the Mojave Basin and range ecoregion. *Science for a Changing World*, 1-15.

Tadele, K., Forch, G., 2007. Impact of land use/cover change on stream flow: The case of Hare River Watershed, Ethiopia. *FWU Water Resources Publication*, 6.

Tekle, K., Hedlund, L., 2000. Land cover changes between 1958 and 1986 in Kalu District, Southern Wello, Ethiopia. *Mountain Research and Development*, 20(1), 42-51.

Wondafrash, M., Tessema, Z., 2011. A Glimpse at Biodiversity Hotspots of Ethiopia. Available at: http://www.ewnhs.org.et/wpcontent/uploads/downloads/2011/03/Biodiversity-Hotspots-of-Ethiopia.pdf (accessed 04.09.2014).

Wondrade, N., Dick, Ø.B., Tveite, H., 2014. GIS based mapping of land cover changes utilizing multi-temporal remotely sensed image data in Lake Hawassa Watershed, Ethiopia. *Environmental Monitoring and Assessment*, 186, 1765-1780.

Yigrem, S., Beyene, F., Tegegne, A., Gebremedhin, B., 2008. Dairy Production, Processing and Marketing Systems of Shashemene-Dilla Area, South Ethiopia. Improving Productivity and Market Success of Ethiopian Farmers Project Working Paper 9. International Livestock Research Institute, Nairobi, Kenya, pp. 62.

Zak, M.R., Cabido, M., Caceres, D., Diaz, S., 2008. What drives accelerated land cover change in central Argentina? Synergistic consequences of climatic, socioeconomic, and technological factors. *Environmental Management*, 42, 181-189.

Zeleke, G., Hurni, H., 2001. Implications of land use and land cover dynamics for mountain resource degradation in the Northern Ethiopian Highlands. *Mountain Research and Development*, 21(2), 184-191.

Zhang, X., Kang, T., Wang, H., Sun, Y., 2010. Analysis on spatial structure of land use change based on remote sensing and geographical information system. *International Journal of Applied Earth Observation and Geoinformation,* 12S, S145-S150.

Zhou, W., Troy, A., Grove, M., 2008. Object-based land cover classification and change analysis in the Baltimore Metropolitan area using multi-temporal high resolution remote sensing data. *Sensors*, 8, 1613-1636.