Temporal and spatial changes in land use patterns and biodiversity in relation to farm productivity at multiple scales in Tigray, Ethiopia

Promotor:	**Prof. dr. ir. A.H.C. van Bruggen** Hoogleraar Biologische Bedrijfssystemen Wageningen Universiteit
Co-promotoren:	**Dr. ir. W.A.H. Rossing** Universitair hoofddocent bij de leerstoelgroep Biologische Bedrijfssystemen Wageningen Universiteit
	Dr. ir. L. Kooistra Universitair docent bij het Laboratorium voor Geo-informatiekunde en Remote Sensing Wageningen Universiteit
Promotiecommissie:	**Prof. dr. ir. H. van Keulen** Wageningen Universiteit
	Prof. dr. ir. A. Veldkamp Wageningen Universiteit
	Prof. dr. S.M. de Jong Universiteit Utrecht
	Dr. ir . C.J.M. Almekinders Wageningen Universiteit

Dit onderzoek is uitgevoerd binnen de C.T. de Wit onderzoekschool Production Ecology and Resource Conservation (PE&RC).

Temporal and spatial changes in land use patterns and biodiversity in relation to farm productivity at multiple scales in Tigray, Ethiopia

Kiros Meles Hadgu

Proefschrift
ter verkrijging van de graad van doctor
op gezag van de rector magnificus
van Wageningen Universiteit
Prof. dr. M. J. Kropff
in het openbaar te verdedigen
op woensdag 12 november 2008
des namiddags te vier uur in de Aula

Hadgu, Kiros Meles (2008)

Temporal and spatial changes in land use patterns and biodiversity in relation to farm productivity at multiple scales in Tigray, Ethiopia

PhD Thesis Wageningen University, Wageningen, The Netherlands
With summaries in English and Dutch

ISBN 978-90-8585-212-4

Dedicated to my beloved wife Sebli
and handsome son Noel

In memory of my late father
Meles Hadgu Adhana

Abstract

Loss of biodiversity, including agro-biodiversity affects smallholders in dry-land regions by decreasing the buffering capacity of the agro-ecosystem and increasing proneness to yield variability including crop failure due to weather extremes. Loss of biodiversity is associated with land use/land cover (LULC) changes that are related to a range of biophysical and socio-economic drivers. This thesis is focused on the Tigray region in northern Ethiopia which has experienced severe loss of biodiversity over the last decades at the regional scale, while loss of genetic variation of crops at the farm and field scale are ongoing as a result of agricultural technology adoption processes. The overall goal of this thesis research was to identify and analyse factors affecting loss of agro-biodiversity in Tigray, Ethiopia, and relate agro-biodiversity loss to LULC changes, soil erosion, farming practices and agricultural productivity. A multi-scale approach was adopted. At the regional scale, LULC changes over the last decades were investigated using a time-series of remotely sensed data to assess changes in biodiversity. At the farm scale, changes in farming practices and land use between 2000 and 2005 were described along with their effects on agro-biodiversity. These changes were related to biophysical and socio-economic drivers. Finally, at the field scale, the consequences of the presence of *Acacia albida* trees for productivity were assessed. A survey among 151 farms in Tigray indicated that higher numbers of species of trees and shrubs, along with cultivation of land races was associated with traditional farming practices of smallholders in 2000 and 2005. Classified maps from remotely sensed data indicated that significant changes in LULC were accompanied by loss of biodiversity and intensification of agricultural production. At the same time, overall caloric yields were highest and soil erosion lowest in sparsely cultivated areas with high biodiversity, where traditional farming practices still dominate. At the farm scale, it was shown that *A. albida* trees contribute significantly to soil fertility and barley yield. Results of this project may assist policy development on agro-biodiversity restoration by providing information on long-term historical trends, insight into their drivers, and consequences for food security among resource poor smallholders in the region.

Table of Contents

Chapter 1	General introduction	1
Chapter 2	Detection of land use/land cover changes by remote sensing and associated drivers for the period 1964 – 2005 in the highlands of Tigray, Ethiopia	17
Chapter 3	Biodiversity and sustainability in agricultural landscapes in Tigray, northern Ethiopia	47
Chapter 4	Spatial variation in biodiversity, soil degradation and productivity in agricultural landscapes in the highlands of Tigray, northern Ethiopia	77
Chapter 5	Assessing the effect of *Acacia albida* based land use systems on barley yield at field and regional scale in the highlands of Tigray, northern Ethiopia.	105
Chapter 6	Synthesis and conclusions	133
	Summary	151
	Samenvatting	155
	Acknowledgement	159
	Curriculum Vitae	163
	Publication list	165
	Educational certificate of the Graduate School PE&RC	167
	Funding	169
	Appendix: colour figures	170

Chapter 1

General introduction

1 Background

There is an increasing concern about biodiversity loss and its consequences for ecosystem functions which provide ecosystem services for human well being (Chapin III et al., 2000; MEA, 2005). Evidence is increasing that biodiversity and ecosystem functions have a positive relationship (Balvanera et al., 2006). However, biodiversity and ecosystem functions are declining because of increased demand for food production and inappropriate natural resource use policies (MEA, 2003a). The consequence of this could be severe environmental degradation and low agricultural productivity, especially in sub-Saharan African countries, which are facing food insecurity problems. Soil erosion and soil fertility depletion caused by human-induced and natural drivers are, among the most important factors contributing to the deterioration of agricultural productivity in sub-Saharan Africa (Sanchez, 2002). In an effort to cope with declining productivity and to satisfy their daily needs amidst rising grain prices and wide-spread poverty, people of the region have resorted to over-exploitation of natural resources and have changed the land cover dramatically (Amalu, 2002; Lambin et al., 2000).

To improve the deteriorating agricultural productivity and ensure food security, a better understanding of the contribution of biodiversity to ecosystem services and the relationships between land use/land cover, biodiversity, and sustainability is necessary. A brief overview of biodiversity, sustainability and land use/land cover is therefore given in the following sections.

2 Biodiversity and ecological functions

Biodiversity includes the variation in ecosystems, habitats, communities, species and intra-specific genetic make-up (Kawanabe, 1996). The diversity of life is of crucial value, giving greater resilience to ecosystems, communities and populations of organisms (Ramakrishnan, 1996). Diverse ecosystems are important for the ecological services they provide and for individual species within those ecosystems. The diversity of vegetation and associated organisms contributes to the formation and maintenance of soil structure and the retention of moisture and nutrient levels, and promotes the recycling of nutrients. Loss of biological diversity through clearing of vegetation has contributed to the leaching of nutrients, decrease of organic matter and accelerated erosion of topsoil resulting in reduced productive capacity of the land (Hölzel et al., 2002). Biodiversity contributes also to natural pest and disease control. Thus, in addition to its intrinsic value, biodiversity may be studied from a functional perspective.

3 Agro-biodiversity and productivity

Co-evolution of agricultural and natural ecosystems has created agricultural biodiversity, which is an important part of biodiversity for human survival (Wood and Lenné, 1999). Biodiversity in agricultural landscapes involves planned agricultural biodiversity (biodiversity of crops and livestock deliberately kept on farms), and associated natural biodiversity (naturally growing plants, soil microbes and fauna, weeds, herbivores, carnivores etc., which exist in the agro-ecosystem) (Vandermeer and Perfecto, 1995). Diversity of crops both in time and space is a traditional strategy to promote diversity in income sources, production stability, reduced insect and disease incidence, efficient use of labor, intensification of production with limited resources and maximization of returns under low levels of technology (Francis, 1986). In addition, diverse genotypes of a single crop can provide the opportunity to more effectively exploit different microhabitats in the spatial heterogeneity prevalent in farmers' fields. Therefore, more efficient use of resources may take place, production may be increased, and the land can be in production for a long time (Altieri, 1994 and 1999). Moreover, diversified crops provide insurance against crop failure, especially in areas subject to degradation and drought (Yachi and Loreau, 1999).

Several traditional agricultural land use systems (e.g., smallholder farming system in tropics) utilize tree-crop interactions for sustainable agricultural production (Buresh and Tian 1998; Kidanu et al., 2004). Diversity-productivity expressed by tree-crop interactions can have positive or negative effects on the functioning of agro-ecosystems (Ong, 1995; Kho, 2000; García-Barrios and Ong, 2004). Trees can explore a relatively large space compared to crop plants, and can have the capacity to capture and use above-and below-ground resources efficiently (Goldberg, 1990; García-Barrios, and Ong, 2004), thereby becoming more resistant to cyclic environmental changes (Ong et al., 1996; Hiremath et al., 2002). They can increase available nutrients for crops by root exudates and leaf drop (Jung, 1970; Belsky et al., 1989; Radersma and Grierson, 2004). Above and belowground resources are partitioned between trees and crops such that relative interspecific competition is lower than relative intraspecific competition, resulting in niche differentiation (Vandermeer, 1989; Malézieux et al., 2008). Thus, there can be a total resource increase in the system or increased resource use efficiency (Cannell et al., 1996; Holmgren et al., 1997; Kho, 2000). System productivity can be increased by reducing nutrient losses through leaching in deep soil, reduced soil erosion, protection against wind (Rao et al., 1998; Malézieux et al., 2008), reducing weed populations (Liebman and Gallandt, 1997; Hauggaard-Nielsen and Jensen, 2005), or capturing nutrients through N-fixation and mycorrhizal associations (Young, 1989; Giller, 2001). Moreover, trees can add considerable amounts of organic matter to the soil, improving soil fertility and physical structure, stabilizing soil structure and reducing erosion (Young, 1997; Roose and Barthès, 2001). Thus, trees and crops are complementary, since enhanced soil fertility in the presence of trees can increase crop productivity in the vicinity of trees (Verinumbe, 1987).

A tree can modify and improve growth of other trees or crops also by changing the biophysical environment (Hunter and Aarssen, 1988; García-Barrios and Ong, 2004). Trees can affect soil water contents either positively (Caldwell and Richards, 1989; Dawson, 1993) or negatively (Smith et al., 1999; Odhiambo et al., 2001), and thereby influence root growth and water and nutrient uptake by crops (Radersma et al., 2004). Although trees can increase the potential soil water-holding capacity, they can also have negative effects on the actual water volume available in the tree-crop-soil system. On the other hand, trees can reduce soil evaporation by shading crops by their canopies and reducing air movement through understories, improve microclimatic conditions by reducing air temperature and wind speed, and reduce water stress in crops (Monteith et al., 1991; Vandenbelt and Williams, 1992; Ong et al., 2000). Tree roots can also use water accumulated deeper in the ground, which can benefit crop growth. Besides, they can use residual available water outside the crop growing season (Ong et al., 1996; García-Barrios and Ong, 2004). However, root length densities of crops can be affected negatively by allelopathy of trees (Ridenour and Callaway, 2001) and/or by an increase in competition (Casper and Jackson, 1997). Nevertheless, integrated tree-crop systems have existed for a long time and may enhance the sustainability of crop production.

4 Sustainability

The term sustainability has been defined in many different ways, encompassing several different dimensions, i.e. ecological, economic and social dimensions. In relation to international development, sustainability has been defined as a form of development that 'meets the needs of the present without compromising the ability of future generations to meet their own needs' (WCED, 1987). To attain sustainable development, resources should not be used in excess of what the ecosystem can continue to provide. Sustainable agriculture has also been defined in various ways, for example 'A way of farming that will continually protect the environment, conserve resources, and enhance the health and safety of farm workers and consumers, while producing needed food and fiber at a profit for farmers' (Gliessman, 2001). Definitions of sustainable agriculture contain several common themes, namely stewardship of both natural and human resources from a systems perspective, implying interdisciplinary approaches to management and development. As sustainability involves long-term conservation and maintenance of natural resources, the state of sustainability cannot be measured. However, we can measure the progress made in terms of clearly defined practical goals towards sustainability (Rigby and Caceres, 2001), which depend on the scale of influence considered to be relevant, the local circumstances, and the wishes of stakeholders. Although we can distinguish ecological, economic and social dimensions of sustainability, the emphasis in this thesis is on its ecological dimension, in particular the relationships among land cover, agro-biodiversity and soil resilience and stability.

5 Land cover and land use

Land cover is a biophysical characteristic which refers to the cover of the surface of the earth, whereas land use is the way in which humans exploit the land cover (Riebsame et al., 1994; Lambin et al., 2003). In most tropical regions, the common agricultural land use system is a smallholder farming system with agricultural production in small parcels for subsistence purposes with no or little external inputs. However, the small farm sizes are insufficient to provide for ever-increasing human populations (Shiferaw and Holden, 2000). In response to the increasing demands for food production, agricultural lands are expanding at the expense of natural vegetation and grasslands (Lambin et al., 2000; Hartemink et al., 2008). These changes in land use/land cover (LULC) systems have great impact, among others, on agro-biodiversity, soil degradation and sustainability of agricultural production (Lambin et al., 2003).

Despite the potentially large contribution to loss of ecosystem services, understanding of LULC dynamics and their trends, mainly in tropical regions, is seriously hampered by incomplete availability of quantitative data (Lambin, 1997). In particular, application of GIS and remote sensing techniques in combination with field information can help to analyze and understand LULC development in tropical regions (e.g., Lambin and Ehrlich, 1997; Mertens and Lambin, 1999; Rembold et al., 2000; Trinh et al., 2005; Hartemink et al., 2008). LULC assessment is an important step in planning sustainable land management that can help to minimize agro-biodiversity losses and land degradation, especially in developing countries like Ethiopia (Brandt and Townsend, 2006).

6 Agro-biodiversity, land use systems and productivity in Ethiopia

Ethiopia, with a total land area of 1.1 million km^2 (CSA, 2004), is one of the eight world centres of origin and diversity of agricultural products (Vavilov, 1951). The enormous variety and complexity of habitats, diversified climatic environments and the diverse farming systems and cultural practices have provided an array of micro-environments which in turn have created large differences in the amount and distribution of genetic variation in general and the diversity of crop species in particular (Robin et al., 2000). The country exhibits extraordinary genetic diversity in many crop plants and it is the main centre of genetic diversity of crops such as teff (*Eragrostis tef*), noug (*Guizotia abyssinica*) and rapeseed (*Brassica carinata*). In addition, Ethiopia also has a high genetic diversity in four of the world's most widely grown food crops: wheat (*Triticum* spp.), barley (*Hordeum vulgaris*), sorghum (*Sorghum bicolor*) and beans (*Phaseolus vulgaris*), and in a number of other crop plants of global or local importance. This study focused on one of the centers of diversity in Tigray located in the North of Ethiopia (4° 82' – 5° 10' N and 15° 66' – 15° 28' E). Diversity has been declining in this part of Tigray as a result of profound changes in land use. Policymakers and agricultural organizations are worried about the obvious declines in natural habitat, but insufficient quantitative information is available upon which to base policy decisions.

The study area covers approximately 30 × 40 km and is located at an elevation of 1300 – 2800 metres above sea level (m.a.s.l.) (Figure 1). Climate of the area is semi-arid, with two rainy seasons, the main season beginning in late June and lasting until September, and a minor rainy season between March and April. The average annual rainfall ranges from 740 mm at 1500 m.a.s.l. to 900 mm at 2000 m.a.s.l. (Deurloo and Haileselassie, 1994). Wide variation in rainfall from year to year is characteristic of the area. Soils are predominantly Cambisols, Fluvisols, Xerosols, Vertisols and Luvisols (Sarraute and Vonder, 1994). The study area is considered as one of the most densely populated areas in Ethiopia (Feoli et al., 2002). Because of the ever-increasing population pressure and the widespread poverty, land use and land cover are changing dramatically, but the changes have not been documented properly. The selected area is therefore a suitable model to study LULC changes in relation to soil degradation and changes in agro-biodiversity and -productivity.

Most of the land in Tigray is used for agriculture, but the intensity varies from very low in areas dominated by shrubs and trees, to moderately intensive with a mix of agriculture and natural habitat, to pure agriculture. Traditionally, the typical agricultural practice in the study area has been a mixed crop-livestock smallholder farming system where cereal crops are planted in mixture and in rotation with pulses. Crops have traditionally been planted in between more or less densely spaced trees and shrubs, but in recent years, trees have been removed, especially close to towns. Agricultural production depends on rainfall and productivity is typically low. Variation in productivity exists and may be related to the widespread degradation of the natural environment, but this relationship has been insufficiently explored.

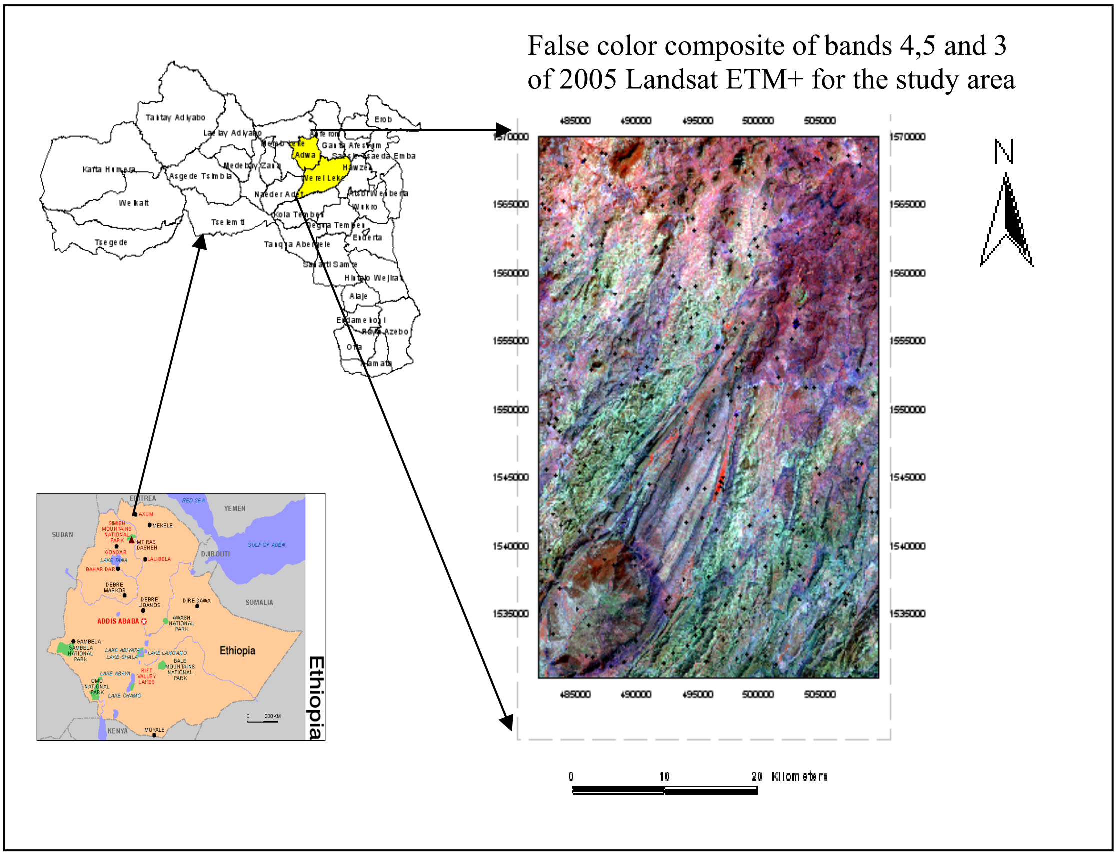


Figure 1. Location map of the study area, Tigray in northern Ethiopia.

7 Research motivation and problem definition

Environmental degradation (e.g. soil erosion and decrease in natural vegetation) and deterioration of agricultural productivity are increasing in Tigray, northern Ethiopia, mainly because of an increasing population and increasing demand for food, animal feed and woody biomass. To protect the environment from being eroded and to guarantee sustainable and adequate agricultural productivity, understanding of underlying processes such as changes in LULC and agro-biodiversity are necessary. However, there is no spatial and temporal information on LULC and agro-biodiversity in Tigray, northern Ethiopia. Moreover, there is limited understanding of the agro-biodiversity-productivity-sustainability relationship in agricultural landscapes, especially in developing countries like Ethiopia where 85% of the population directly depend on agriculture (Shiferaw and Holden, 1999; CSA, 2004).

LULC changes caused by human-induced and natural drivers pose serious problems in the study area. The existing land use system of Tigray exerts high pressure on the environment from the increasing human population density (Goe, 1999).

Destruction of natural habitat by over-grazing, land clearing and fuelwood cutting is the starting point of the process of natural vegetation degradation, resulting in breakdown of soil structure and loss of soil organic matter (Spooner et al., 2003). Lack of analysis of LULC change dynamics may have contributed to low awareness of the magnitude of the problem and its role in enhancing unsustainability and loss of agro-biodiversity. Rural development plans are not usually based on the production capability and suitability of the land. Thus, new rural agricultural technologies are usually implemented without understanding the past and present land use system which could have guided development activities according to the diversified land resources available (Nair, 1998).

Information on the relevance of agro-biodiversity for productivity at field scale, in combination with information on the rate of land use/land cover (LULC) change at the regional scale is highly relevant for land use policies, and can stimulate new directions for improving resource use in Tigray, Ethiopia (Hurni, 1993; Dejene, 2003; Shiferaw and Holden, 2000). Although spatial tools such as GIS and remote sensing provide good opportunities for describing changes in agro-biodiversity at the regional scale, inferred from land use/land cover assessment (Carpenter and Turner, 1998), time series of remote sensing data have not been analyzed, to our knowledge, for the Tigray region. In view of both the intrinsic and the functional aspects of agro-biodiversity, the lack of spatial information on the changes in natural habitat is a reason for concern.

In this thesis agro-biodiversity is considered to consist of tree/shrub diversity (number of tree- and shrub species) and crop diversity (number of landraces) in and around agricultural lands. These agro-biodiversity resources, which have co-existed with agriculture for a long time, are currently under threat from genetic erosion, for example, by replacement of a great variety of landraces by a few high yielding varieties. Loss of traditional knowledge of crop management practices, changes in cropping pattern, land use changes, overexploitation due to increasing human population pressure, and drought are major causes of loss of agro-biodiversity (Worede et al., 1991; Teshome et al., 1999).

Research on experimental stations or with computer models dealing with agricultural or land use systems can lead to better understanding of processes in detail (Grace et al., 1997). However, there is lack of integration of knowledge obtained at different spatial scales (e.g. from field level to regional scales). Agricultural technologies tested at field level are mostly recommended to regional level without taking into account the enormous diversity in the area such as variations in altitude, rainfall, soil and natural habitat. In order to understand systems at higher level, field scale research outputs should be up-scaled to landscape or regional scales using the opportunities of GIS and remote sensing techniques.

In addition to the unavailability of land use information at different scales, there is a lack of understanding of the relationships among agro-biodiversity, sustainability and agricultural productivity. Rural development policies in the country should not only be formulated to alleviate immediate problems, for example, increasing crop production to feed the ever increasing human population through the introduction of high input agricultural packages without considering locally available resources (Holden et al., 2005). LULC changes and loss of agro-biodiversity may have consequences for the reduction of natural ecosystems, depletion of soil fertility and an increase in soil erosion which in turn may decline agricultural productivity (Foley et al., 2005). Therefore, the present research addressed LULC, agro-biodiversity, sustainability and agricultural productivity, and their relationship at different spatial and temporal scales in the heterogeneous tropical highland region of Tigray, northern Ethiopia. Spatial and temporal approaches are adopted to understand these processes in relation to their drivers and provide recommendations for future sustainable land use management in the study region.

8 Objectives of the research

The overall goal of this thesis is to identify and analyze factors affecting LULC changes and agro-biodiversity in relation to agricultural productivity in Tigray, northern Ethiopia. The specific objectives are:

1. To detect (LULC) changes based on a time series of remote sensing data and identify drivers of the changes at a regional scale **(Chapter 2);**
2. To identify and analyze factors affecting agro-biodiversity and sustainability (with soil erosion as indicator), focusing on relationships between agro-biodiversity, physical environment, crop production characteristics and measures of wealth at farm and regional scales **(Chapter 3)**;
3. To study spatial and temporal variation in agro-biodiversity and soil degradation in relation to farm, productivity, wealth, social, and development drivers and topographic characteristics between 2000 and 2005 at farm and regional scale **(Chapter 4)**; and
4. To investigate the effects of *Acacia albida* based land use systems on crop productivity at field and regional scales **(Chapter 5)**.

9 Structure of the thesis

The chapters of the thesis are organized according to the above research objectives. In Chapter 2, time series of remotely sensed data (1964, 1994 and 2005) are used to assess LULC changes and the drivers of these changes at a regional scale. Regional scale agro-biodiversity and agricultural sustainability in relation to the physical environment, crop production characteristics and measures of wealth are identified and assessed in chapter 3 (Figure 2). Changes in spatial and temporal agro-biodiversity and sustainability distribution in agricultural landscapes in relation to infrastructure, physical, farm management and social characteristics between 2000 and 2005 are studied at farm and regional scales in chapter 4. In chapter 5, implications of land use management for the agro-biodiversity-productivity relationships at field and regional scales are investigated. In particular, barley yields are compared in different *Acacia lbida* tree-based land use systems in 2005. Finally the results obtained in chapters 2-5 are integrated in a discussion of the implications for land use planning and policymakers in Tigray (Chapter 6). The results of this research can assist developmental activities in providing data, information and recommendations for local and higher level decision makers.

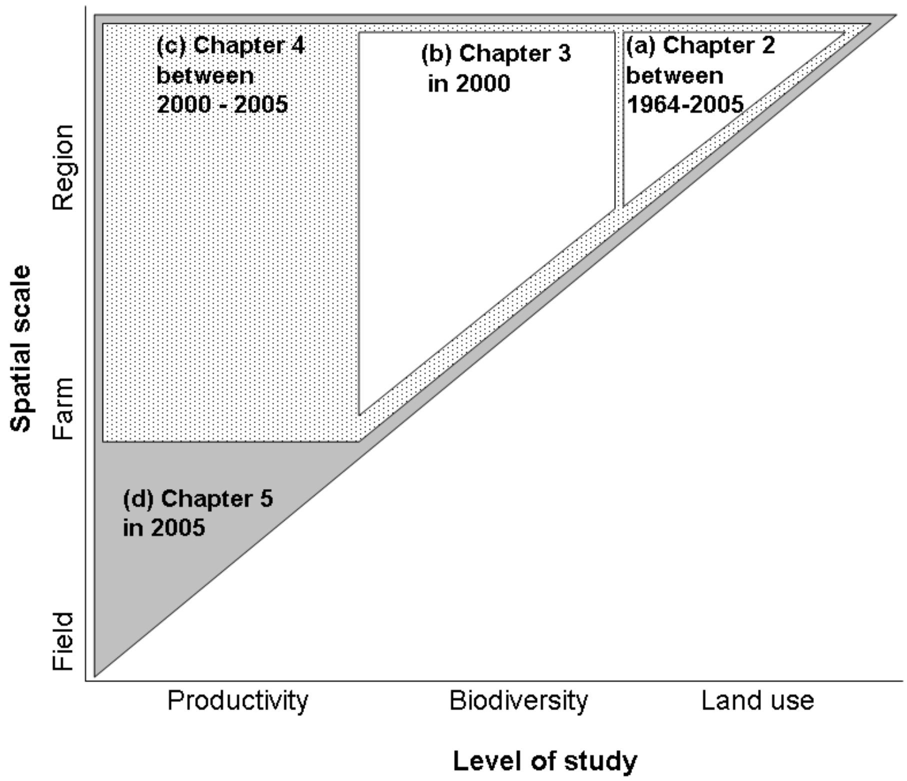


Figure 2. Productivity, agro-biodiversity and land use at different spatial scales in the highlands of Tigray.

References

Altieri, M.A., 1994. Biodiversity and Pest Management in Agroecosystems. Hayworth Press. New York.

Altieri, M.A., 1999. The ecological role of biodiversity in agroecosytems. Agric. Ecosyst. Environ. 74, 19 – 31.

Amalu U.C., 2002. Food security: sustainable food production in Sub-Saharan Africa. Outlook Agric. 31, 177 – 185.

Balvanera, P., Pfisterer, A. B., Buchmann, N., He, J.-S., Nakashizuka, T., Raffaelli D., Schmid, B., 2006. Quantifying the evidence for biodiversity effects on ecosystem functioning and services. Ecology Letters. 9, 1146–1156.

Belsky, A.J., Amundson, R.G., Duxburg, J.M., Riha, S.L., Mwonga, S.W., 1989. The effects of trees on their physical, chemical and biological environments in semiarid savanna in Kenya. J. Appl.Ecol. 26, 1005 – 1024.

Brandt, J., Townsend, P.A., 2006. Land use – land cover conversion, regeneration and degradation in the high elevation Bolivian Andes. Landscape Ecol. 21, 607 – 623.

Buresh, R.J., Tian, G.,1998. Soil improvement by trees in sub-Saharan Africa. Agrofor. Syst. 38. 51–76.

Caldwell, M.M., Richards, J.H., 1989. Hydraulic lift: water efflux from upper roots improves effectiveness of water uptake by roots. Oecologia. 75, 1 – 5.

Cannell, M.G.R., Van Noordwijk, M., Ong , C. K., 1996. The central agroforestry hypothesis: the trees must acquire resources that the crop would not otherwise acquire. Agrofor. Syst. 34, 27 – 31.

Carpenter, S.R., Turner, M.G., 1998. At last: a journal devoted to ecosystems. Ecosystems. 1, 1 – 5.

Casper, B.B., Jackson, R.B., 1997. Plant competition underground. Annu. Rev. Ecol. Syst. 28, 545–570.

Chapin III, F.S., Zavaleta, E. S., Eviner, V.T., Naylor, R.L., Vitousek, P.M., Reynolds, H.L., Hooper, D.U., Lavorel, S., Sala, O.E., Hobbie, S.E., Mack, M.C., Díaz, S., 2000. Consequences of changing biodiversity. Nature. 405, 234 – 242.

CSA, 2004. Statistical Abstracts. Ethiopian Central Statistical Authority (CSA), Addis Ababa.

Dawson, J.F., 1993. Hydraulic lift and water use by plants: implications for water balance, performance and plant-plant interactions. Oecologia. 95, 565 – 574.

Dejene, A., 2003. Integrated Natural Resources Management to Enhance Food Security: The Case for Community-Based Approaches in Ethiopia. Environment and Natural Resources Working Paper No. 16. FAO. Rome.

Deurloo, H.A., Haileselassie, T., 1994. Rehabilitation of Degraded and Degrading Areas of Tigray, Ethiopia, Survey on Farm Practices based on Local Knowledge, Wageningen Agricultural University, Wageningen.

Feoli, E., Vuerich, L.G., Woldu, Z., 2002. Processes of environmental degradation and opportunities for rehabilitation in Adwa, northern Ethiopia. Landscape Ecol. 17, 315–325.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily,G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global Consequences of Land Use. Science. 309, 570 – 574.

Francis, C.A., 1986. Multiple Cropping Systems. MacMillan, New York.

García-Barrios, L., Ong, C.K., 2004. Ecological interactions, management lessons and design tools in tropical agroforestry systems. Agrofor. Syst. 61, 221–236.

Giller, K., 2001. Nitrogen Fixation in Tropical Cropping Systems. CAB International, Wallingford.

Gliessman, S., 2001. Agroecosystem Sustainability: Developing Practical Strategies. CRC Press LLC, Boca Raton, Florida.

Grace, J., van Gardingen, P., Luan, J., 1997. Tackling large-scale problems by scaling-up. In: van Gardingen, P., Foody, G., Curran, P. (Eds.), Scaling up – from cell to landscape. Cambridge University Press, Cambridge, pp. 7 – 16.

Goe, M.R., 1999. Influence of slope and stone cover on tillage operations in the Ethiopian highlands. Soil Tillage Res. 49, 289 – 300.

Goldberg, D., 1990. Components of Resource Competition in Plant Communities.. In: Grace, J.B., Tilman, D. (Eds.), Perspectives on Plant Competition. Academic Press, New York. pp. 27 – 49.

Hartemink, A.E., Veldkamp, V, Bai, Z., 2008. Land Cover Change and Soil Fertility Decline in Tropical Regions. Turk J Agric For. 32, 195 – 213.

Hauggaard-Nielsen, H., Jensen, E., 2005. Facilitative root interactions in intercrops. Plant Soil. 274, 237–250.

Hiremath, A.J., Ewel, J.J., Cole, T.G., 2002. Nutrient Use Efficiency in Three Fast-Growing Tropical Trees. Forest Sci. 48, 662 – 672.

Holden, S., Shiferaw, B., Pender, J., 2005. Policy analysis for sustainable land management and food security in Ethiopia: A bioeconomic model with market imperfections. Report No. 140. International food policy research institute, Washington, DC.

Holmgren, M., Scheffer, M., Huston, M., 1997. The interplay of facilitation and competition in plant communities. Ecology. 78, 1966 – 1975.

Hölzel, N., Haub, C., Ingelfingert, M.P., Otte, A., Pilipenko, V.N., 2002. The return of the steppe – large-scale restoration of degraded land in southern Russia during the post-Soviet era. J. Nat. Conserv. 10, 75–85.

Hunter, A.F., Aarssen, L.W., 1988. Plants helping plants. Bio-Science. 38, 34 – 40.

Hurni, H., 1993. Land degradation, famine and land resources scenario in Ethiopia. In: Pimentel, D. (Ed), World Soil Erosion and Conservation, Cambridge University Press, Cambridge, pp. 27–62.

Jung, G., 1970. Variations saisonnières des caractéristiques microbiologiques d'un sol ferrugineux tropical peulessivé (Dior) soumis à l'influence d'Acacia albida (Del.). Oecol. Plant. 5, 113–116.

Kawanabe, H., 1996. Linkage between ecological complexity and biodiversity. In: Di Castri, F., Younes, T. (Eds.), Biodiversity, science and development: towards a new partnership. CAB International, Wallingford, pp. 149 – 152.

Kho, R.M., 2000. A general tree-environment-crop interaction equation for predictive understanding of agroforestry systems. Agric. Ecosyst. Environ. 80, 87 – 100.

Kidanu, S., Mamo, T., Stroosnijder, L., 2004. Eucalyptus–wheat interaction on Ethiopian Nitosols. Agr. Syst.. 80, 151–170.

Lambin, E.F., 1997. Modelling and monitoring land-cover change processes in tropical regions. Prog. Phys. Geogr. 21, 375 – 393.

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 Continental Scale. Remote Sens. Environ. 61, 181 – 200.

Lambin, E.F., Rounsevell, M.D.A., Geist, H.J., 2000. Are agricultural land-use models able to predict changes in land-use intensity? Agric. Ecosys. Environ. 82, 321 – 331.

Lambin, E.F., Geist, H.J., Lepers, E., 2003. Dynamics of land-use and land-cover change in tropical regions. Annu. Rev. Environ. Resour. 28, 205 – 41.

Liebman, M., Gallandt, E.R., 1997. Many little hammers: ecology management of crop-weed interactions. In: Jackson, L.E. (Ed.), Ecology in Agriculture. Academic press. New York, pp. 291 – 343.

Malézieux, E., Crozat, Y., Dupraz, C. Laurans, M. Makowski, D. Ozier-Lafontaine, H., Rapidel, B., de Tourdonnet, S., Valantin-Morison, M., 2008. Mixing plant species in cropping systems: concepts, tools and models. A review. Agron. Sustain. Dev. 28, 1 – 20.

MEA, 2003a. Ecosystems and Human Well-being: A Framework for Assessment. In: Millennium Ecosystem Assessment (MEA), Island press, Washington, DC.

MEA, 2005. Ecosystems and Human Well-being: Biodiversity Synthesis. In:

Millennium Ecosystem Assessment (MEA), World Resources Institute, Washington, DC.

Mertens, B., Lambin, E., 1999. Modelling land cover dynamics: Integration of fine-scale land cover data with landscape attributes. Int. J. Appl. Earth Observ. Geoinform. 1, 48 – 52.

Monteith, J.L., Ong, C.K., Corlett, J.E., 1991. Microclimatic interactions in agroforestry systems. Forest Ecol. Manag. 45, 31 – 44.

Nair, P.K.R., 1998. Directions in tropical agroforestry research: past, present, and future. Agrofor. Syst. 38, 223–245.

Radersma, S., Grierson, P.F., 2004. Phosphorus mobilization in agroforestry: organic anions, phosphatase activity and phosphorus fractions in the rhizosphere. Plant Soil. 259, 209 – 219.

Ramakrishnan, P.S., 1996. Ecological functions of biodiversity: The human dimension. In: Di Castri, F., Younes, T. (Eds.), Biodiversity, science and development: towards a new partnership. CAB International, Wallingford, pp. 114 – 129.

Rao, M.R., Nair, P.K.R. Ong, C.K., 1998. Biophysical interactions in tropical agroforestry systems. Agrofor. Syst. 38, 3 – 50.

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). Int. J. Appl. Earth Observ. Geoinform. 2, 181 – 189.

Ridenour, W.M., Callaway, R.M., 2001. The relative importance of allelopathy in interference: the effects of an invasive weed on a native bunchgrass. Oecologia. 126, 444 – 450.

Riebsame, W.E., Meyer, W.B., Turner II, B.L., 1994. Modeling land use and cover as part of global environmental change. Clim. Change. 28, 45 – 64.

Rigby, D., Cáceres, D., 2001. Organic Farming and the Sustainability of Agricultural Systems. Agr. Syst.. 68: 21 – 40.

Robin, S.R, Russel, L.K, Nyawira, M., Andualem, T., Sara, W., Cathleen, J.W., Woudyalew, M., 2000. Land-use and land-cover dynamics in response to changes in climatic, biological and socio-political forces: the case of South Western Ethiopia. Landscape Ecol. 15, 339 – 355.

Roose, E., Barthès, B., 2001. Organic matter management for soil conservation and productivity restoration in Africa: a contribution from Francophone research. Nutr. Cycl. Agroecosys. 61, 159–170.

Odhiambo, H.O., Ong, C.K., Deans, J.D., Wilson, J., Khan, A.A.H., Sprent, J.I., 2001. Roots, soil water and crop yield: tree crop interactions in a semi-arid agroforestry systems in Kenya. Plant Soil. 235, 221 – 233.

Ong, C.K., 1995. The ‘dark side’of intercropping: manipulation of soil resources. In: Sinoquent H., Cruz P. (Eds.), Ecophysiology of Tropical Intercropping. Institute National de la Recherche Agronomique, Paris, pp. 45 – 65.

Ong, C.K., Black, C.K., Marshall, F.M., Corlett, J.E., 1996. Principles of resource capture and utilization of light and water. In: Ong C.K., Hurley P. (Eds.), Tree-crop Interactions: A physiological Approach. CAB International, Wallingford, pp. 73 – 158.

Ong, C.K., Black, C.R., Wallace, J.S., Khan, A.A.H., Lott, J.E., Jackson, N.A., Howard, S.B. Smith, D.M., 2000. Productivity, microclimate and water use in *Grevillea robusta*-based agroforestry systems on hillslopes in semi-arid Kenya. Agric. Ecosyst. Environ. 80, 121–141.

Sanchez, P.A., 2002. Soil Fertility and Hunger in Africa. Science. 295, 2019 – 2020.

Sarraute, J.L.,Vonder, O.W., 1994. Rehabilitation of Degraded and Degrading Areas of Tigray, Ethiopia: landsurface, landcover and change detection classifications based on remote sensing. Wageningen Agricultural University, Wageningen.

Shiferaw, B., Holden, S.T., 1999. Farm-level benefits to investments for mitigating land degradation: empirical evidence from Ethiopia. Environ. Devel. Econ. 6, 335 – 358.

Shiferaw, B., Holden, S.T., 2000. Policy instruments for sustainable land management. Can. J. Soil Sci.75, 401 – 406.

Smith, D.M., Jackson, N.A., Roberts, J.M., Ong, C.K., 1999. Root distributions in a Grevillea robusta – maize agroforestry system in semi-arid Kenya. Plant soil. 211, 191 – 205.

Spooner, P.G., Lunt, I.D., Briggs, S.V., Freudenberger, D., 2003. Effects of soil disturbance from roadworks on roadside shrubs in a fragmented agricultural landscape. Biol. Conserv. 117, 393 – 406.

Teshome, A., Fahrig, L., Torrance, J. K., Lambert, J. D., Arnason, T.J., Baum, B.R., 1999. Maintenance of sorghum (*Sorghum bicolor*, Poaceae) landrace diversity by farmers’selection in Ethiopia. Econ. Bot. 53, 79 – 88.

Trinh, M.V., Dinh D.N., van Keulen, H. 2005. Using Landsat images for studying land use dynamics and soil degradation – case study in Tamduong District, Vinhphuc Province, Vietnam. Int. J. Geoinfo. 1, 157 – 164.

Vandenbelt, R.J., Williams, J.H., 1992. The effect of soil surface temperature on the gwoth of millet in relation to the effct of Faidherbia albida trees. Agricult. Forest Meterol. 60, 93 – 100.

Vandermeer, J., 1989. The Ecology of Intercropping. Cambridge University Press, Cambridge.

Vandermeer, J., Perfecto, I., 1995. Breakfast of Biodiversity: The Truth about Rainforest Destruction. Food First Books, Oakland.

Vavilov, N.I., 1951. The origin, variation, immunity, and breeding of cultivated plants. Selected Writings of N.I. Vavilov. Chronica Botanica, London.

Verinumbe, I., 1987. Crop production on soil under some forest plantations in the Sahel. Agrofor. Syst.. 5, 185 – 188.

World Commission on Environment and Development(WCED), 1987. Our Common Future. Oxford University Press, Oxford.

Worede, M., 1991. An Ethiopian perspective on conservation and utilization of plant genetic resources. In: Engels, J.M.M, Hawkes, J.G., Worede, M. (Eds.), Plant Genetic Resources of Ethiopia. Cambridge University Press, Cambridge, pp. 3 – 19.

Wood, D., Lenné, J.M., 1999. Why Agrobiodiversity? In: Wood, D., Lenné, J.M. (Eds.), Agrobiodiversity: Characterization, Utilization and Management. CABI Publishing, Wallington, pp. 1 – 13.

Yachi, S., Loreau, M., 1999. Biodiversity and ecosystem productivity in a fluctuating environment: The insurance hypothesis. Proc. Natl. Acad. Sci. USA. 96, 1463 – 1468.

Young, A., 1989. Agroforestry for soil conservation. CAB International, Wallingford.

Young, A., 1997. Agroforestry for Soil Management. CAB International, Wallingford.

Chapter 2

Detection of land use/land cover changes by remote sensing and associated drivers for the period 1964 – 2005 in the highlands of Tigray, Ethiopia

Kiros Meles Hadgu[a,b,c], L. Kooistra[b], W.A.H. Rossing[c], A.H.C. van Bruggen[c]

[a] Faculty of Natural Resources and Agriculture, Mekelle University, P.O. Box 231, Mekelle, Tigray, Ethiopia
[b] Centre for Geo-Information, Wageningen University and Research Centre, Droevendaalsesteeg 3, 6700 AA Wageningen, The Netherlands
[c] Biological Farming Systems Group, Wageningen University and Research Centre, Marijkeweg 22, 6709 PG Wageningen, The Netherlands

(Submitted to Agriculture, Ecosystems and Environment)

Abstract

Land use/land cover (LULC) dynamics and their associated drivers of change in the highlands of Tigray, northern Ethiopia were investigated for the period 1964-2005 using remotely sensed data and multiple logistic regression models. Over the past 41 years, agricultural land areas increased significantly (from 10% in 1964 to 40% in 2005) at the cost of the surface area for natural vegetation (woodland and shrub land). Especially a significant decline in woodland area was observed (from 28% in 1964 to 3% in 2005) with the largest changes in the period before 1994. The results from multiple logistic regression show that anthropogenic drivers were the primary drivers for LULC change. In the period between 1964 and 1994 woodland areas were primarily reduced in remote areas, likely due to war, drought and famine, whereas in recent decades until 2005 reductions in woodland and expansion and intensification of agriculture were associated with road construction, settlement expansions and population pressure.

Keywords: LULC change; LULC classification; LULC drivers of change; multiple logistic regression model; post-classification.

1 Introduction

Land use/land cover (LULC) changes are important land surface conversions which are receiving increasing attention in global environmental change studies (Foley et al., 2005). LULC are two related land surface characteristics where land cover (e.g., grassland, woodland, shrub land, etc) refers to a surface cover of the earth whereas land use (e.g., agriculture, intensively cultivated, moderately cultivated etc) is the way in which humans exploit the land cover (Riebsame et al., 1994). LULC changes are caused by natural and human drivers, such as construction of human settlements, government policies, climate change or other biophysical drivers (Riebsame et al., 1994; Lambin et al., 2000). While human-environmental relationships, hereafter called - drivers of change, can explain changes in LULC in time and space (Bürgi et al., 2005), such LULC changes can in turn have serious implications for biodiversity, soil, water and other natural resources (Riebsame et al., 1994; Foley et al., 2005). Increased demands for food production and associated agricultural intensification also cause loss of natural components from agricultural areas thereby influencing LULC (Lambin et al., 2000; Foley et al., 2005; Ningal et al., 2007).

Our understanding of where, when and why land cover changes take place in tropical regions is seriously hampered by incomplete availability of quantitative data (Lambin, 1997). Many studies, however, show opportunities to apply remote sensing combined with field information to map LULC and their related drivers (e.g., Lambin and Ehrlich, 1997; Mertens and Lambin, 1999; Rembold et al., 2000). LULC change detection induced through biophysical and anthropogenic factors is best observed by analysing multi-date remotely sensed data, including aerial photographs and satellite images (Singh, 1989; Rembold et al., 2000). Landsat satellite images (e.g., Landsat Thematic Mapper: TM and Enhanced Thematic Mapper Plus: ETM+), with their relatively high spatial resolution and regular revisit time, give an opportunity to study the dynamics of LULC (e.g., Trinh et al., 2005; Yemefack et al., 2006; Fan et al., 2007; Muñoz-Villers and López-Blanco, 2007). There are many techniques for analysing LULC changes using remote sensing data: image differencing, vegetation indices, principal component analysis, spectral mixture analysis and post classification analysis (Singh, 1989; Lu et al., 2004). These analysis techniques produce "change/no-change" maps without presenting the nature of the change (Ridd and Liu, 1998; Singh, 1989). Post classification methods depend on independently classified remotely sensed images acquired at different times to quantify and interpret the different types of LULC changes (Foody, 2002).

In the past few decades, serious declines in forest ecosystems (4 million hectares annually) have been documented for Africa (FAO, 2006). However, spatial assessment of LULC change in Africa is still limited both in coverage and spatial detail. Because of Africa's high variability in climatological conditions at a variety of spatial and temporal scales, ecosystems are inherently dynamic, and LULC change studies require long-term time-series assessments (Lambin and Ehrlich, 1997). LULC assessment and analysis has to be given due emphasis in order to prevent irreversible biodiversity loss and land degradation, and is an important step in sustainable land management planning (Brandt and Townsend, 2006).

One of the countries in Africa where natural ecosystems are increasingly replaced by agricultural systems is Ethiopia. Agriculture is the mainstay of the economy in Ethiopia where 85% of the population depends on farming and more than 85% of the total export income of the country comes from the agricultural sector (Khairo et al., 2005). However, sustainable agricultural development is hampered by land degradation problems mainly because of increasing human population pressure and inappropriate land use (Hurni, 1993; Sonneveld and Keyzer, 2003; Holden and Shiferaw, 2004). Studies in the country indicate that intensity of land use has changed over time because of demographic, policy and natural factors (e.g., Tekle and Hedlund, 2000; Zeleke and Hurni, 2001; Feoli et al., 2002). These studies, however, have shown limited understanding of the relationships between drivers of change (natural and human) and loss of natural ecosystems, agricultural intensification and associated environmental problems, such as erosion. No attempt has been made in Tigray, northern Ethiopia, to identify and understand the role of change drivers in specific types of LULC which could lead to recommendations for appropriate development strategies and sustainable land use planning.

Therefore, the objectives of this study were: (i) to characterize the dynamics of LULC changes in the Tigray region in north Ethiopia for the period 1964 – 2005 using multi-spectral remotely sensed data; and (ii) to identify and quantify the drivers associated with LULC changes.

2 Study area

The study site is located in central Tigray, northern Ethiopia (4° 82' – 5° 10' N and 15° 66' – 15° 28' E), and covers an area of 30 × 40 km at an elevation of 1300 – 2800 metres above sea level (m.a.s.l.) (Figure 1). The climate of the area is semi-arid, with two rainy seasons, the main season beginning in late June and lasting until September, and a minor rainy season between March and April. The average annual rainfall ranges from 740 mm at 1500 to 900 mm at 2000 m (Deurloo and Haileselassie, 1994). Wide variation in rainfall from year to year is characteristic of the area. Soils are predominantly Cambisols, Fluvisols, Xerosols, Vertisols and Luvisols (Sarraute and

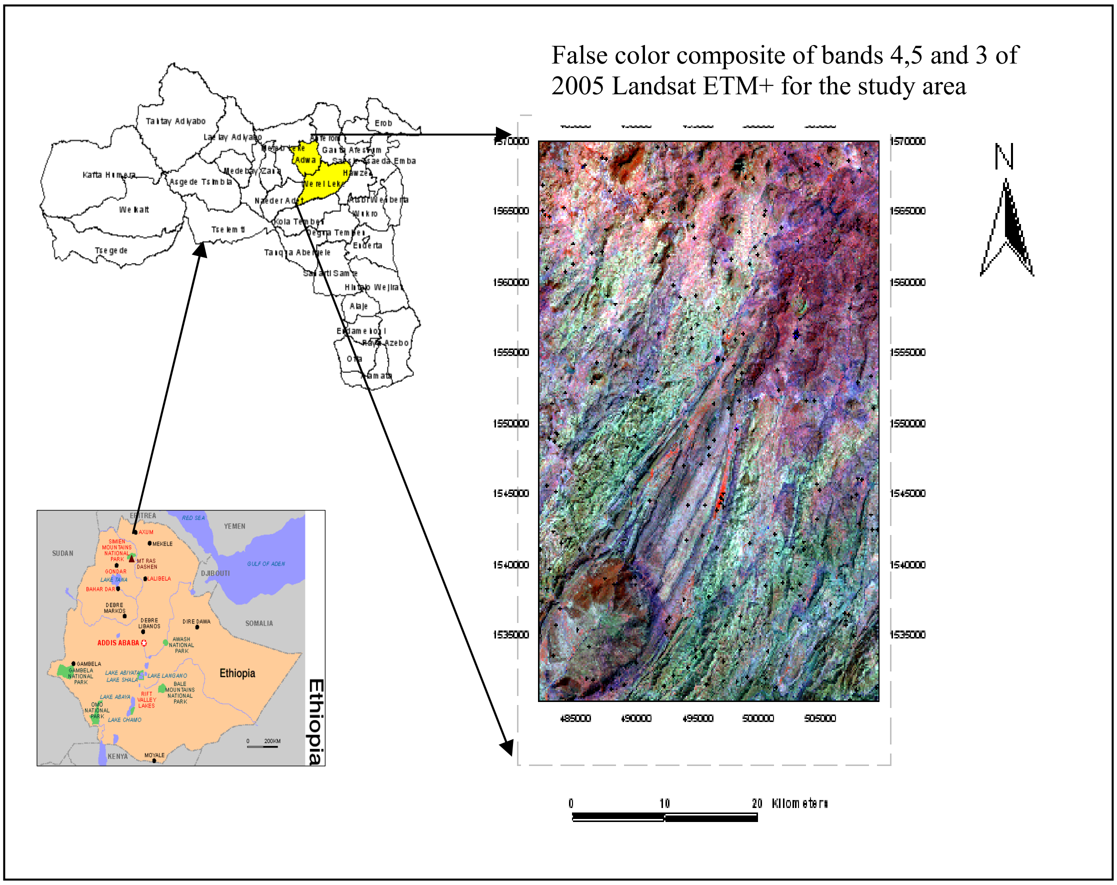


Figure 1. Location map of the study area represented by false colour composition of bands: 4,5,3 of Landsat ETM+ 2005 image.

Vonder, 1994). The study area is considered as one of the most densely populated areas in Ethiopia (Feoli et al., 2002). The typical agricultural practice in the study area is a mixed crop-livestock small holder farming system.

Like in other parts of Ethiopia, land use history in the study area can be divided broadly into three eras: (i) Pre-1974, (ii) 1974 – 1991 and (iii) Post-1991, which correspond to the periods of the Imperial government, the military-socialist regime and the current government, respectively (Abegaz, 2004). In the pre-1974 period, land was controlled by the state, the crown, the Orthodox Church, individuals and their families (Cohen and Weintraub, 1975; Ottaway, 1977; Abegaz, 2004). Land use was characterized by traditional extensive agriculture, mostly without the use of fertilizers and pesticides. During the military-socialist regime (1974 – 1991), land was nationalized and distributed to farmers (about 1 ha per farm family) for indefinite use, but remained in public ownership (Rahmato, 1985; Griffin, 1992). The use of new cultivars and synthetic fertilizers was limited to demonstration plots and agricultural areas close to extension centers. This period is also known for its civil wars in the study area, which also resulted in vegetation degradation (Abegaz, 2004). The current government still keeps all land (rural and urban) under public ownership but allows land leasing and hiring although it prohibits land sale or purchase (FDRE, 1995; Benin and Pender, 2001). In the meantime, the use of improved cultivars and fertilizers has been promoted in an agricultural extension package in most agricultural areas to increase crop production, but also farmers have started to return to their traditional farming practices.

3 Materials and methods

3.1 General approach and datasets

Aerial photographs (1964 and 1994), Landsat satellite images (1994 and 2005), topographic maps (1994), Shuttle Radar Topographic Mission (SRTM) and field survey data (Table 1) were used as input in our analysis. To characterize LULC change in the Tigray region and to derive the main drivers of change, we followed the approach as presented in Figure 2. First, LULC types were classified from aerial photographs of 1964 and Landsat images of 1994 and 2005, according to the LULC classification of the Tigray Bureau of Agriculture and Natural Resources (BoNAR, 2000) (Table 2). Second, four dominant LULC classes, viz. woodland, shrub land, scrubland and agricultural land, were analyzed based on their change (1) and no change (0) maps for the periods 1964 – 1994 and 1994 – 2005. Depending on availability for all study years (1964, 1994 and 2005), six potential factors associated

Table 1. List of spatial data used for LULC classification in Tigray, northern Ethiopia.

Data	Year + month	Path/row	Resolution/ Scale	Source
Landsat ETM+	2005,10	169/050	30 meter	USGS
Landsat TM	1994,10	169/050	30 meter	Centre for Geo-Information, Wageningen University
Aerial Photograph	1964 and 1994,11			Ethiopian Mapping Agency
Topographic map	1994			Ethiopian Mapping Agency
Shuttle Radar Topographic Mission (SRTM)	2000		90 meter	USGS

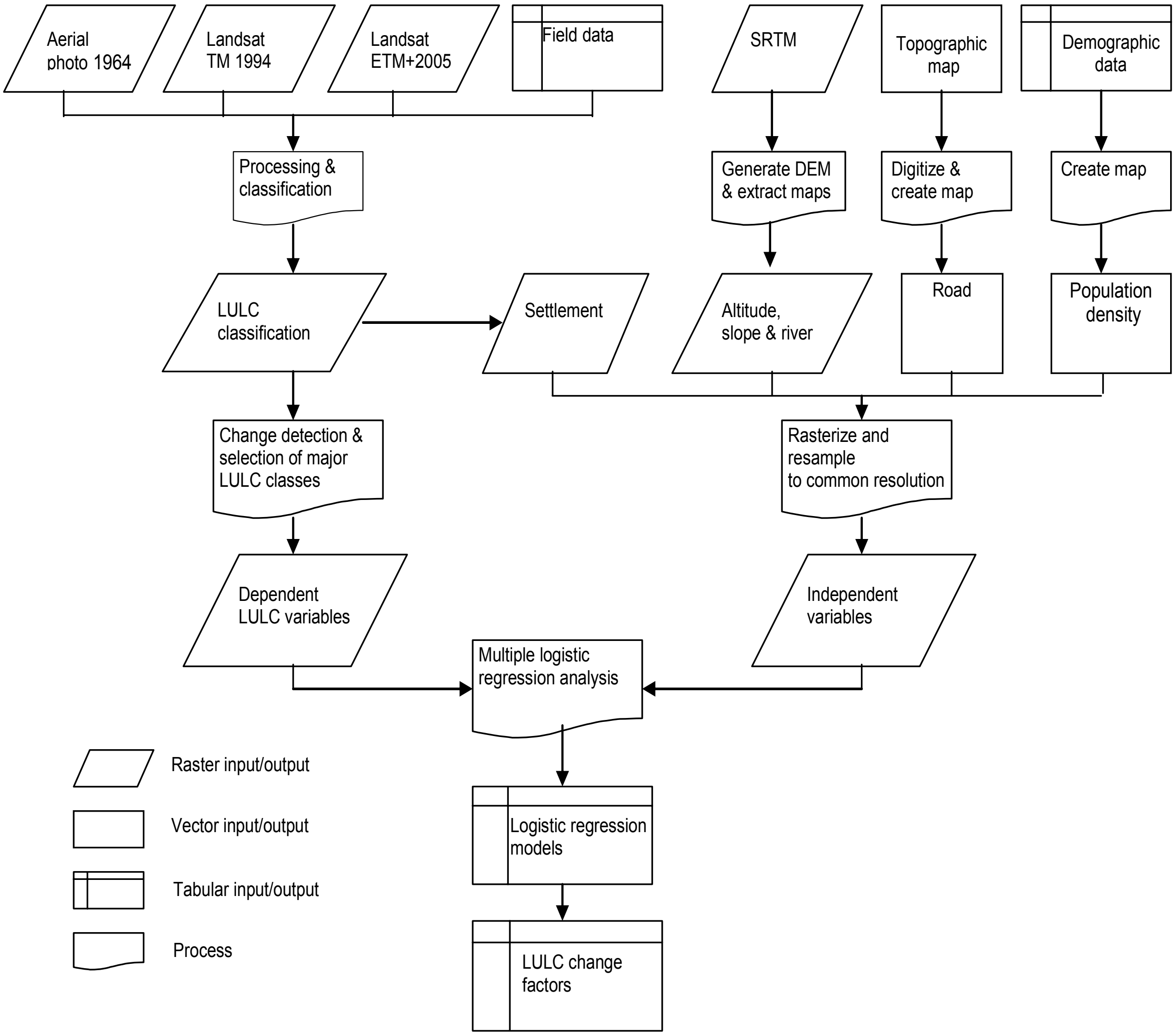


Figure 2. Schematic flow chart of general study approach for Tigray, northern Ethiopia.

with LULC change, viz. altitude, slope, distance to a major river, distance to a road, distance to a settlement and population density per square kilometer, were derived from Shuttle Radar Topographic Mission (SRTM) (USGS, Sioux Falls, SD), topographic maps (Ethiopian Mapping Agency, Addis Abeba) and census data (Ethiopian Central Statistical Agency, Addis Abeba). Finally, changes in LULC classes (dependent variables) and potential factors associated with LULC change (independent variables) were analyzed by multiple logistic regression models to derive major drivers of LULC change. ERDAS IMAGINE 9.1 (Leica Geosystems, Norcross, GA, USA) and ArcGIS 9.2 (ESRI, Redlands, CA, USA) were used for processing the satellite imagery and the aerial photographs. SAS/STAT (SAS inc., Cary, NC, USA) was used for the statistical analysis of the LULC change in relation to the drivers of LULC change.

Table 2. LULC classes for study area in Tigray, northern Ethiopia.

Class Name	Description
Woodland (Wd)	Land covered by trees, bushes, shrubs and herbs. Canopy cover is estimated to be 65% and the remaining (35%) is covered either by grasses, herbs or bare land.
Shrub land (Sh)	Land supporting stands of shrubs, usually not exceeding 3m in height, with a canopy cover of more than 30% while the remaining may be covered by grasses, herbs or bare.
Scrubland (Sc)	Land covered by strata of shrubs and grasses or herbs growing here and there.
Sparsely Cultivated land (SCu)	It is classified as sparsely cultivated (only 20 – 40%) of the entire mapping unit is under cultivation while the remaining area can be covered by trees, shrubs or herbs.
Moderately cultivated land (MCu)	It is estimated that of this mapping unit 40 – 70% of the land is under annual and perennial crop while the remaining area can be covered by covered by trees, shrubs or herbs.
Intensively Cultivated land (ICu)	It is estimated that of this mapping unit over 70% of the land is under annual and perennial crops while the remaining area can be covered by trees, shrubs or herbs.
Grassland (Gr)	Open grassland with some shrubs and occasional trees.
Water body (W)	Water in micro dams.
Settlement (Se)	Residential and industrial areas.

3.2 Field data collection

A reconnaissance field survey was carried out in 2005, using stereoscopically delineated classes on aerial photographs of 1964 and 1994 and unsupervised classifications on Landsat images of 1994 and 2005, to identify the major LULC types in the study area. Next, 272 randomly distributed training samples from 9 homogenous LULC types (Table 2) were collected in the field using hand held GPS in the same year. When the LULC class assigned to the 1964 and 1994 data did not correspond to the type observed in the field, elderly farmers (approximately 30 in total) were consulted about land use changes over the past decades. To assess the plausibility of the classification, ground truth data including location, altitude, observed land use and land cover were recorded in the field for each homogenous LULC training class.

Spectral profile and feature space layer analyses were applied to check class separability of the training samples (Gu et al., 1991; Yemefack et al., 2006). Random independent validation points (n=275) collected from the field were used for validating the 2005 LULC classification accuracy. The same random validation points (n=275) were also available to be checked on the 1994 aerial photographs to validate the 1994 LULC classification accuracy. The available aerial photographs and Landsat images were subjected to digital remote sensing processing and classification (Figure 2).

3.3 Remote sensing data and image processing

Twenty aerial photographs for 1964 and 1994 acquired from the Ethiopian Mapping Agency, Addis Abeba, were converted to digital format by scanning each photograph at 450 dpi. For each scanned aerial photograph four fiducial marks were entered from the analog aerial photographs. Each aerial photograph was geo-referenced with points from 1:50 000 topographic maps and known ground control points (crossing of roads and river junctions collected from the field with hand held GPS) which were distinct both on the aerial photographs and on the ground. Each geo-referenced photograph was ortho-rectified to minimize scale and topographic distortion (Casson et al., 2003) and resampled to 3 m resolution using the nearest neighbor method.

A geometrically corrected Landsat 7 Enhanced Thematic Mapper Plus (ETM+) image of the study area in 2005 was received from USGS, Sioux Falls, SD,USA (Table 1). The root mean standard error (R.M.S.E.) was minimized to less than 0.3 m through a first order polynomial transformation (Lawrence and Ripple, 1999) by using ground control points from river junctions and crossings of roads collected with the hand held GPS. A Landsat 5 Thematic Mapper (TM) image of the same area in 1994 (Table 1) was co-registered to the geometrically corrected Landsat 2005 image. The image-to-image registration method reduced the R.M.S.E. to less than 0.3 m. The Landsat image of 1994 was resampled to match the spatial extent and pixel size (30 m) of the Landsat image of 2005 using the nearest neighbor resampling method. In order to avoid topographic effects in the Landsat images of 1994 and 2005, we applied Lambertain topographic normalization procedures (Rembold et al., 2000; Currit, 2005).

3.4 LULC classification and accuracy assessment

LULC maps for the study area were based on aerial photographs from 1964 and Landsat images of 1994 and 2005 (Table 1). Selection of suitable remotely sensed data (aerial photographs and satellite images) was mainly based on availability of data for ground truthing. Digital Elevation Model (DEM), river, slope and altitude maps were generated from 90 m resolution SRTM.

In producing LULC maps for 2005, 185 spectrally homogenous training samples for Landsat ETM+ 2005 were collected from randomly distributed points from the field with a hand-held GPS. Image processing was based on Digital Values (DNs) as the classification of each image was done independently (Foody, 2002; Kiage et al., 2007). The maximum likelihood classifier (MLC) (Bauer et al., 1994) was used for the supervised classification of the image. The mixed spectral signature of settlements on the Landsat ETM+ 2005 made it difficult to separate the classes with the training samples collected from the field. Therefore, we defined settlement class from GPS points collected from field observations for each settlement boundary within the study area. Classification with the MLC method and the additional settlement data layer were merged. The same procedure was applied to the water body class which appeared in the Landsat ETM+ image of 2005, because spectral separability of water from other classes was difficult mainly due to water turbidity, shallow water depth and vegetation interference in and around the water bodies behind the micro-dams.

For the Landsat TM image of 1994, 185 field-verified homogeneous training samples were collected from 1994 aerial photographs of the same area. Class separability of the training sample classes was evaluated by their mean spectral profile and feature space layers (Gu et al., 1991; Yemefack et al., 2006). Settlement classes, digitized from aerial photographs and topographic maps of the same spatial and temporal scale were combined with classification results of MLC from the Landsat TM data of 1994. Similar image processing methods used for the Landsat TM+ 2005 image were followed for processing the Landsat TM 1994 image.

A LULC map of 1964 produced from manually digitized aerial photographs using stereoscopes and ortho-rectified aerial photographs was used as base image. The LULC classes used for the interpretation of the 1964 ortho-rectified aerial photographs are presented in Table 2. Similar polygons were given the same code and class names were merged to the same LULC class.

A post classification method was used for detection of LULC changes where orthorectified aerial photographs and satellite images were classified independently and then a comparison was made for the generated LULC maps of 1964 – 1994 and 1994 – 2005 (Foody, 2002).

Accuracy assessment, which is an analysis method for validating LULC results (Foody, 2002), was carried out using the random independent validation points (n=275) collected from the field to be compared with the Landsat image of 2005. For the Landsat 1994 image classification, the same random points were also checked for their LULC class on the 1994 aerial photographs. Accuracy was assessed by the Kappa statistic which is a measure to indicate if the confusion matrix is significantly different from a random result (Foody, 2002). Overall accuracy which is the ratio of total correct pixels and the total number of pixels was also calculated. Overall accuracy was also expressed by producer's accuracy (error of omission), based on the field reference data of 2005, and the user's accuracy (commission error), based on the total number of pixels classified in a specific class (Smits et al., 1999).

3.5 Determination of factors associated with LULC changes

3.5.1 Spatially explicit multiple logistic regression model

Multiple logistic regression models were used to estimate the probability of occurrence of a LULC class change as affected by a set of independent variables (altitude, slope, distance to river, distance to road, distance to settlement and population per square kilometer). This resulted in coefficients indicating the extent and direction to which each independent variable affected the probability of occurrence of a LULC class change (Serneels and Lambin, 2001).

The general formula of a multiple logistic regression model is:

$$\text{Logit}\ (p) = \log \left[\frac{p}{1-p}\right] = \alpha + \beta_1 X_1 + \beta_2 X_2 \ldots + \beta_n X_n \qquad (1)$$

where p is the probability of occurrence of a LULC type, α is the intercept, β_i is a regression coefficient, and X_i is and independent variable.

The probability values of occurrence of LULC type can also be quantitatively expressed in terms of factors of change in the following way:

$$p = \frac{\exp(\alpha + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n)}{1 + \exp(\alpha + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n)} \qquad (2)$$

The relative importance of the factors explaining the changes in LULC was evaluated with the Wald statistic ($\chi 2$) (Serneels and Lambin, 2001).

3.5.2 Independent variables

To understand and explain LULC changes, six independent variables were considered: elevation, slope, distance to major river, distance to main road, distance to settlement and population per square kilometer. Road networks and settlement covers were digitized from 1:50,000 topographic map of 1994 and updated from the satellite images and aerial photographs. Areas occupied by roads, towns and major rivers were calculated as 30 m wide buffers expanding from each arc in a raster environment. Slope, altitude and major rivers were generated from 90 m resolution SRTM as continuous data. Human population density per basic administrative unit ("Tabia") over time was obtained from census data of the Ethiopian Statistical Agency (CSA, 2004). The population density was calculated as persons per square kilometer.

All available data were converted to raster format and resampled to a common spatial resolution of 30 m which was determined by the 30 m resolution of the dependent LULC variables. Correlation analysis was carried out for all independent variables to check for collinearity between the independent variables and was found below the critical value of 0.80 (Menard, 1995).

Samples for multiple logistic regression were selected randomly, stratified by LULC class, on the 30 m spatial resolution LULC change maps. A total of 2000 sample points was selected for each dependent variable, namely 1000 changed (1) and 1000 unchanged (0) samples. The sample size was mainly determined by the maximum available number of changed (1) values (only 1000 observation points) of woodland during 1994 – 2005. Values of dependent and independent variables were recorded for each of the 2000 observation points.

3.5.3 Dependent variables

LULC change was calculated by overlaying of LULC maps for two of the three years (1964 – 1994 and 1994 – 2005). The dependent variables used for multiple logistic regression were: woodland, shrub land, scrubland and agricultural land for each period. Because of their small coverage, grassland, settlement and water body classes were not included as dependent variables.

4 Results

4.1 LULC in 1964, 1994 and 2005

Based on interpretation of pre-fieldwork aerial photograph delineation, reconnaissance ground surveys and interviews with farmers in the region in 2005, 6, 8 and 9 LULC classes were identified for 1964, 1994 and 2005, respectively (Table 2). Agricultural land was represented in one type (sparsely cultivated) in the 1964 classification and in 3 types (sparsely cultivated, moderately cultivated and intensively cultivated) in the 1994 and 2005 classifications. Because of micro-dam constructions after 1994, a water body class was identified only in 2005.

Shrub land was dominant in 1964 covering 50,749 ha (46% of the area) followed by woodland with a coverage of 30,833 ha (28% of the area) (Table 3 and Figure 3). However, agriculture (combination of the three agricultural classes: sparsely cultivated, moderately cultivated and intensively cultivated) was dominant in both 1994 and 2005 covering 37,470 ha (34%) and 44,492 (40%), respectively. The next dominant LULC types in 1994 and 2005 were shrub land with a coverage of 23,293 ha (21%) and 42,743 (39%), and scrubland with a coverage of 32,870 ha (30%) and 18,066 (16%), respectively. The settlement class covered 1723 ha in 2005, an increase of 1624 ha over the 99 ha in 1964. Water bodies, behind micro dams covered 15 ha in 2005. Grassland covered 238 861 and 151 ha of the total study area in 1964, 1994 and 2005, respectively (Table 3 and Figure 3).

Over the whole study period (1964 – 2005), land cover changed substantially. For instance, 32.4 and 33.1% of shrub land was converted into combined agricultural land (sparsely cultivated, moderately cultivated and intensively cultivated) in 1964 – 1994 and 1994 – 2005, respectively (Table 4). Moreover, 59.3 and 50.1% of grassland was converted into agricultural land in 1964 – 1994 and 1994 – 2005, respectively. The analysis also revealed that 25.7% of sparsely cultivated land in 1964 – 1994 and 37.3% in 1994 – 2005 were converted into moderately cultivated land. The conversion rate of sparsely cultivated into intensively cultivated increased from 5.1% in 1964 – 1994 to 10.6% in 1994 – 2005.

Table 3. LULC changes between 1964, 1994 and 2005 in Tigray, northern Ethiopia.

Land use/land cover classes	Land use/land cover (LULC) area (ha)			LULC area (ha) change between 1964 and 2005		
	1964	1994	2005	1964 – 1994	1994 – 2005	1964 – 2005
Wd[1]	30833.1	15746.0	3340.0	–15087.2	–12406.0	–27493.1
Sh	50748.8	23293.9	42743.8	–27454.9	+19449.9	–8005.0
Sc	17340.6	32869.9	18066.2	+15529.4	–14803.8	+725.6
SCu	11559.5	25228.2	9316.9	+13668.7	–15911.3	–2242.5
MCu		10984.5	28638.4	+10984.5	+17653.9	+28638.4
ICu		1257.2	6536.3	+1257.2	+5279.2	+6536.3
Gr	237.9	860.9	151.0	+623.1	–709.9	–86.8
W			15.2		+15.2	+15.2
Se	98.7	516.3	1722.5	+417.6	+1206.1	+1623.8

[1]Class acronyms are presented in Table 2

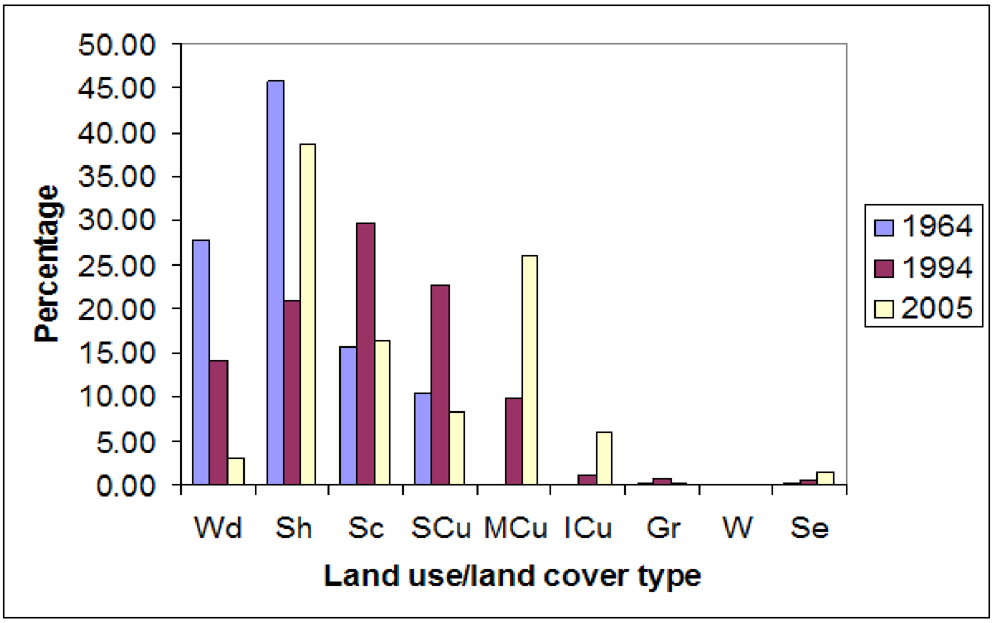


Figure 3. Percentages LULC over time (1964, 1994 and 2005) in Tigray, Ethiopia. Note: Class acronyms are presented in Table 2.

In 1964, woodlands were still located at high and intermediate altitudes (1600 – 2800 m.a.s.l.) besides low altitudes (1300 – 1400 m.a.s.l.), but were restricted to the highlands (2000 – 2800 m.a.s.l.) and extreme lowlands (1300 – 1400 m.a.s.l.) in 2005. Shrub- and scrublands were spread throughout the study area. Agricultural land was located at altitudes from 1500 – 2200 m.a.s.l. in 1964, and the slope ranged from 0 – 13%. By 1994, agricultural land had expanded to 1400 – 1500 and above 2200 m.a.s.l, with slopes up to 21%. In 2005, agriculture was also practiced at low altitudes (1300 m.a.s.l.) with slopes of 21%. Settlements expanded especially in this last period mostly along roads.

Overall accuracy, producer's accuracy, user's accuracy and Kappa coefficient were calculated for the classification of Landsat 1994 and Landsat 2005 images (Table 5). The overall accuracy and overall Kappa statistic for the Landsat 1994 image were 78% and 71%, respectively. For the Landsat 2005 image, overall accuracy and Kappa statistic were 74% and 67%, respectively. In the Landsat 1994 image classification, the producer's and user's accuracy was greater than 70% for the majority of LULC classes except for grassland (Gr) with a producer's accuracy of 58% and moderately cultivated land (MCu) with a user's accuracy of 52% (Table 5a). In the Landsat 2005 image classification, water body (W) was the poorest (40%) in producer's accuracy, and sparsely cultivated land (SCu) showed low producer's and user's accuracy (60%) whereas the majority of the LULC classes had greater than 70% producer's and user's accuracy (Table 5b).

Table 4. LULC conversion in 1964 – 1994 and 1994 – 2005 in Tigray, northern Ethiopia.

(a) Between 1964 and 1994

Category								
	1994							
1964	Wd %	Sh %	Sc %	Scu %	Mcu %	Icu %	Gr %	Se %
Wd[1]	25.4	25.6	24.6	18.1	5.2	0.0	1.1	0.01
Sh	13.4	23.3	30.0	23.0	8.6	0.8	0.7	0.36
Sc	5.3	14.8	46.9	20.0	11.3	1.4	0.2	0.21
Scu	1.7	9.1	17.4	38.8	25.7	5.1	0.5	1.72
Gr	0.6	2.4	0.0	44.9	12.5	1.9	37.7	0.00
Se	0.0	0.0	0.0	0.1	2.5	0.3	0.0	97.1

(b) Between 1994 and 2005

Category									
	2005								
1994	Wd %	Sh %	Sc %	Scu %	Mcu %	Icu%	Gr%	W%	Se%
Wd	13.4	49.9	22.8	7.4	6.0	0.3	0.1	0.0	0.1
Sh	2.4	49.9	14.3	10.7	20.9	1.5	0.0	0.0	0.3
Sc	1.4	43.0	24.4	3.1	22.8	4.7	0.0	0.0	0.6
Scu	0.7	27.4	6.8	14.3	37.3	10.6	0.2	0.0	2.7
Mcu	0.2	17.8	12.0	6.7	50.1	12.1	0.1	0.0	1.1
Icu	0.2	4.9	0.7	0.4	24.4	61.7	0.0	0.0	7.7
Gr	0.5	35.6	3.1	30.2	16.6	3.3	7.4	0.0	3.3
Se	0.0	0.5	0.0	0.6	0.6	0.0	0.0	0.0	98.3

[1] Class acronyms are presented in Table 2.

Table 5. Confusion matrix for the classification of Landsat 1994 and 2005 images of Tigray, northern Ethiopia.

(a) Confusion matrix for 1994

Classified data (LULC type)	Reference data									
	Wd	Sh	Sc	SCu	MCu	ICu	Gr	Row total	Producer's accuracy[1] (%)	User's accuracy[2] (%)
Wd[3]	26	1	2	1			2	32	70	81
Sh	4	45	4	4				57	70	79
Sc	4	11	58	3	4			80	84	73
Scu	3	4	2	48	3	1	3	64	72	75
Mcu		2	3	10	16			31	70	52
Icu						2		2	67	100
Gr		1		1			7	9	58	78
Total[4]	37	64	69	67	23	3	12			

(b) Confusion matrix for 2005

Classified data (LULC type)	Reference data										
	Wd	Sh	Sc	SCu	MCu	ICu	Gr	W	Raw total	Producer accuracy (%)	User's accuracy (%)
Wd	7	1							8	78	88
Sh		77	5	5	4			3	94	75	82
Scr	1	11	42		2	1			57	81	74
Scu	1	2		9				3	15	60	60
Mcu		11	5	1	55	3			75	90	73
Icu						10			10	71	100
Gr							9		9	100	100
W								4	4	40	100
Total	9	102	52	15	61	14	9	10			

[1] Producer's accuracy = Number correct/ Reference total * 100.

[2] User's accuracy = Number correct/ Classified total * 100.

[3] Class acronyms are presented in Table 2.

[4] Three points without classification are not presented in the Table.

4.2 Drivers of LULC change

To interpret the factors associated with LULC change identified by multiple logistic regression, the changes in Figure 3 and their geographic locations in Figure 4 were consulted together with the results from logistic regression in Table 6. Multiple logistic regression for changes in woodland, shrub land and scrubland locations indicated that distance to a road was the most important factor explaining the reductions in wood- and shrub land and the increase in scrubland (Figure 3; Table 6a) between 1964 and 1994 ($\chi2= 63$, $P < 0.0001$; $\chi2= 13$, $P=0.0003$; $\chi2= 24$, $P < 0.0001$, respectively). The farther the location was from a road so much the greater was the probability of changes (reductions) in wood and shrub land and the associated increase in scrub land (Table 4 and Figure 3). Besides distance to a road, several topographic factors such as slope, elevation and distance to a river also influenced changes in the different natural habitat areas, but these relationships were less consistent (Table 6a). In addition, human population density or distance to a settlement significantly influenced the reduction in woodland and shrub land locations ($\chi2= 27$, $P < 0.0001$; $\chi2= 6$, $P=0.015$, respectively). The higher the population density (especially around Adwa town in the North West of the study area) the less was the change in woodland locations, and the closer to settlements the smaller the change in shrub land locations. On the other hand, the increase in locations occupied by agricultural land between 1964 and 1994 was primarily associated with an increase in population density ($\chi2=29$, $P < 0.0001$) and relatively flat terrains ($\chi2=12$, $P=0.0006$) (Figure 4 and Table 6a).

Between 1994 and 2005, distance to a road became a less important factor affecting changes in natural habitat (Table 6b). Only the change in shrub land area was still significantly affected by distance to a road ($\chi2=21$; $P<0.0001$), but the relationship was reverse to that between 1964 and 1994. Thus, the farther a location was from a road the less was the change in shrub land area, indicating that the change (primarily increase, Figure 3) in shrub land area was associated with the decrease in woodland area relatively close to roads and settlements in the Northeastern part of the study area (Figure 4). Indeed, woodland locations changed most close to settlements and at high elevations and steep slopes (Table 6b), indicating that this was in the Northeastern part of the study area, as woodland did not change into shrub land close to Adwa (Figure 4). Woodland did also change into shrub land in the Southwestern corner of the study area (Figure 4), especially on steep slopes. In this second period of the study, the increase in shrub land was also associated with a decrease in scrubland (Table 4). This change was negatively related to elevation (Table 6b): the lower the elevation and population density the greater was the change (reduction) in scrubland. This combination was mainly found in the Southeastern part of the study area (Figure 4).

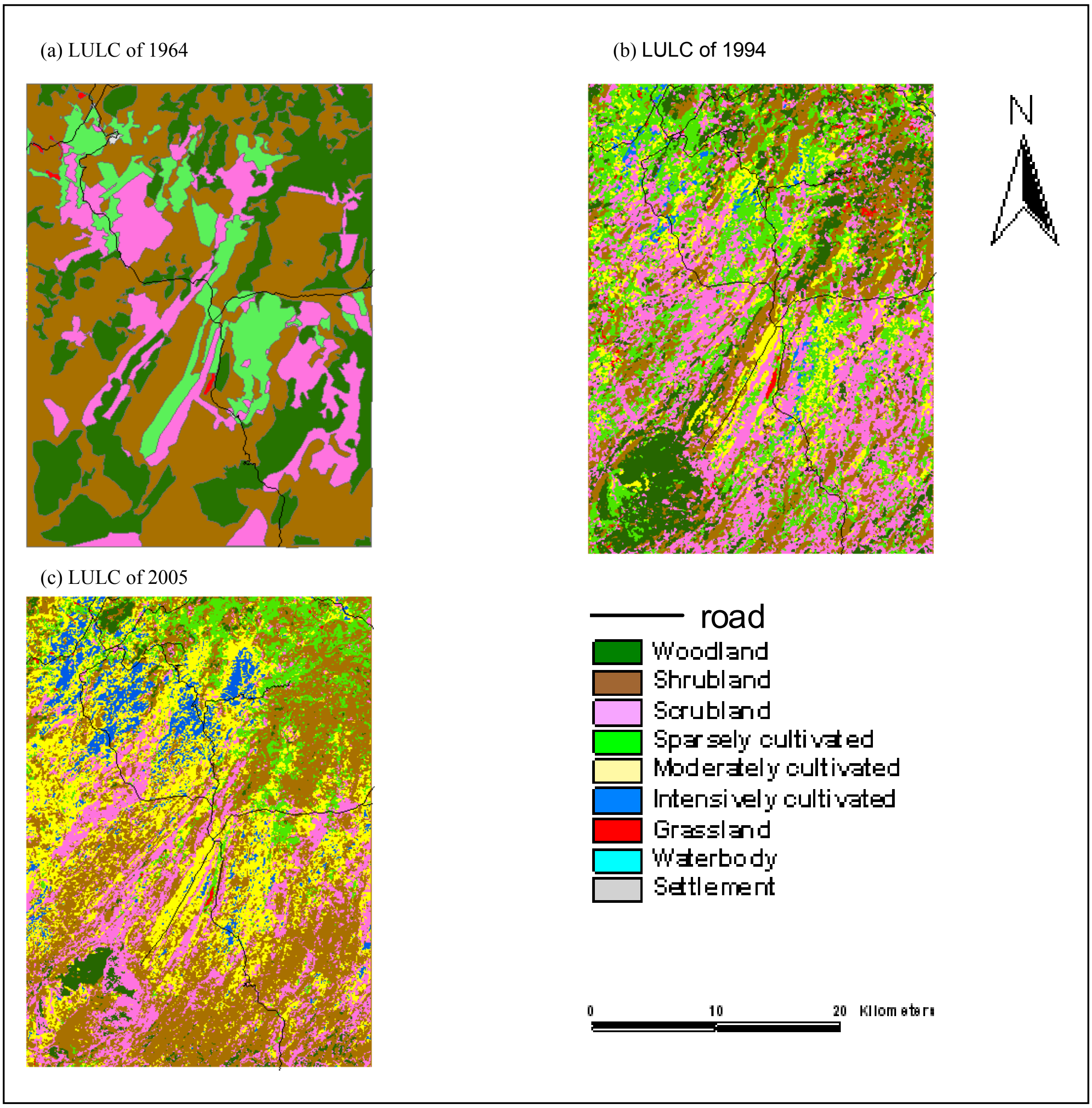


Figure 4. LULC maps of 1964, 1994 and 2005 combined with road maps of the study area in Tigray, northern Ethiopia.

Similar to the first period, a higher population density was again the main factor associated with the increase in agricultural area ($\chi2=6$; P=0.01), particularly the medium and intensively cultivated areas (Figure 3). Population density was also associated with the decrease in scrubland and increase in shrub land, but not with a change in woodland (Table 6b). This combination occurred primarily in the Northeastern part of the study area with relatively high population densities.

Despite the overall decrease in woodland area, woodlands increased in a small location North of Adwa (Figure 4). This was associated with a reforestation program of degraded natural habitats in the second study period. Reforestation programs were also initiated along roads in other parts of Tigray, but the effects of these efforts were not yet noticeable on the classification maps.

Table 6. Significant independent variables selected in multiple logistic regression of LULC changes (a) 1964 – 1994; (b) 1994 – 2005, n = 2000 in Tigray, northern Ethiopia.

(a) 1964 – 1994 (Period 1)

Dependent variable: change in	Independent variable	Parameter estimate	Standard Error	Wald $\chi 2$	P > $\chi 2$
Woodland area	Road	0.000140	0.000018	63.0060	<0.0001
	Population	–0.022500	0.004330	26.9482	<0.0001
	Slope	0.027000	0.009180	8.62840	0.0033
	River	0.000170	0.000060	0.27150	0.0040
Shrubland area	Road	0.000061	0.000017	12.9334	0.0003
	River	–0.000200	0.000058	12.0570	0.0005
	Slope	–0.023500	0.009170	6.5527	0.0105
	Settlement	–0.000040	0.000017	5.8686	0.0154
Scrubland area	Road	0.000085	0.000017	24.3030	<0.0001
	Elevation	0.001050	0.000200	27.4822	<0.0001
Agricultural area	Population	0.021500	0.00399	29.1837	<0.0001
	Slope	–0.037000	0.0107	11.9040	0.0006
	River	–0.000120	0.000058	4.5719	0.0325

(b) 1994 – 2005 (Period 2)

Dependent variable: change in	Independent variable	Parameter Estimate	Standard Error	Wald $\chi 2$	P > $\chi 2$
Woodland area	Slope	0.045900	0.008820	27.0738	<0.0001
	Settlement	–0.000100	0.000023	18.9117	<0.0001
	Elevation	0.000580	0.000189	9.4760	0.0021
Shrubland area	Road	–0.000120	0.000026	21.1896	<0.0001
	Elevation	–0.000440	0.000202	4.8481	0.0277
	Population	0.000463	0.000226	4.1815	0.0409
Scrubland area	Elevation	–0.000910	0.000210	18.8794	<0.0001
	Population	–0.000400	0.000181	4.9192	0.0266
Agricultural area	Population	0.000400	0.000161	6.3195	0.0119
	Road	–0.000054	0.000026	4.2426	0.0394

5 Discussion

5.1 LULC and associated drivers in Tigray, Ethiopia

This study provides an approach to improve the understanding of LULC changes and their drivers in both their spatial and temporal context for heterogeneous landscapes of the tropical highlands. Based on a study period of 41 years (1964 – 2005), our results reveal unique spatially explicit information on LULC changes indicating a sharp reduction of natural habitats and an increase in agricultural land in the highlands of Tigray, northern Ethiopia (Figure 3). In the same study period, an increased change in extent and location of agricultural land was observed mainly because of increasing human population (CSA, 2004). These results are consistent with other studies in Ethiopia, which also indicated a decrease in natural habitat and expansion of agricultural land (Rembold et al., 2000; Tekle and Hedlund, 2000; Zeleke and Hurni, 2001; Feoli et al. 2002). The remote sensing based LULC classification provides good accuracy for such a heterogeneous landscape as the highland of Tigray (Table 5). Besides, the study explains these major LULC changes in relation to their drivers of change.

Despite the strength of our study approach in deriving LULC changes and associated driving factors, there are some limitations to this study. Remotely sensed data were not available for the 1970's and 1980's, when severe droughts occurred in Ethiopia. Because of the unavailability of spatially explicit data (e.g., soil map, livestock population and policies) at the same spatial scale in 1964 as in 1994 or 2005, it was difficult to evaluate differences in LULC changes between the two time periods.

Taking these limitations into account, our analysis showed nevertheless that between 1964 and 1994 the probability of changes (reductions) in natural habitats (woodland and shrub land) was higher at locations farther from a road (Table 6a). The changes in natural habitat, mainly an increase in shrub land at the expense of woodland close to roads was less between 1994 and 2005 than between 1964 and 1994 (Table 6b). In both study periods, an increase in locations occupied by agricultural land was associated with higher population density (Table 6a and b). The sharp reduction in natural habitats and increase in agricultural lands can be attributed to changes in land use policies during the first study period. In 1975, a nation wide change in land distribution took place resulting in a change of ownership from relatively few landlords to many individual farmers (Abegaz, 2004). This policy contributed considerably to cutting of trees and shrubs from both natural habitats and agricultural lands. The greater destruction of natural habitats in remote areas compared to areas close to roads in 1964 – 1994 can be attributed to the 1974 and 1984 droughts and the civil war which lasted for almost two decades (1974 – 1991) (Dawit, 1989; Keller, 1992; Amacher et al., 2004). Lack of food probably contributed to the cutting of trees and shrubs from natural habitats far away from roads, likely for selling the wood or producing charcoal to generate income to buy food.

In the second period (1994 – 2005), proximity to settlements, high altitude and steep slopes were associated with the change in extent and location of woodland (Table 6b). At high altitude locations with steep slopes, conversion of woodland to other LULC classes was greatest in close proximity to settlements. This was contrary to the natural habitat destruction in more remote areas in the first study period. Consistent with this trend of wood removal close to settlements in the second period, shrub land increased in this period in close proximity to roads. In this same period, there was a higher average road network compared to the 1964 – 1994 study period (Figure 4). Population pressure was still the main driver to changes (increases) in agricultural land as well as agricultural intensification, especially in the Southeastern part of the study area. This change was associated with human population pressure, not only in settlements but also in rural areas (CSA, 2004), coupled with a market oriented agricultural policy (IMF, 2004).

5.2 Comparison with other LULC studies in Africa

Unlike our research, there are no studies in Ethiopia that explain LULC changes in relation to their driving forces in a spatially explicit way. Nevertheless, there are few studies in Ethiopia that documented LULC changes in time and space, primarily an increase in agricultural land at the expense of natural vegetation in Southwestern Ethiopia (Reid et al., 2000), the rift valley (Rembold et al., 2000), northern Ethiopia (Tekle and Hedlund, 2000), and central highlands (Amsalu et al., 2007). Thus, the results of our study are in agreement with these previous studies. Also, similar to our observations North of Adwa, an increase in woodland area was documented using remote sensing thanks to reforestation efforts in Blue Nile basin (Bewket, 2002; and Bewket and Sterk, 2005).

Spatial and temporal LULC changes without linking the changes to spatially explicit driving forces are also common in other African LULC studies, e.g., in Zambia (Petit et al., 2001), Kenya (Kiage et al., 2007), South Africa (Giannecchini et al., 2007), and Kenya (Baldyga et al., 2008). These studies demonstrate a reduction in natural habitat and an increase in agricultural areas which are similar to our results. In a limited number of studies LULC changes were related to driving forces. Using Landsat MSS and TM, Serneels and Lambin (2001) found significant relationships between LULC changes and distances to roads, villages or water, population density, suitability of soil for agriculture, and elevation in Kenya between 1985 and 1995. In Cameroon, accessibility to roads and towns contributed to deforestation derived from Landsat MSS and SPOT XS between 1973 to 1996 (Mertens and Lambin, 2000). Braimoh and Vlek (2005) also found that population density, distance to market, distance to road and soil quality were drivers of LULC changes, derived from Landsat TM images, between 1984 and 1999 in Ghana. In agreement with our results for the second period (1994 – 2005), the previous studies showed that natural habitats were reduced (Mertens and Lambin, 2000; Braimoh and Vlek, 2005) and agriculture expanded (Braimoh and Vlek, 2005) closer to roads and settlements. This was opposite to our results for the first study period (1964 – 1994), when wood and shrub lands diminished in remote areas. Serneels and Lambin (2001) also found that rangeland (scrubland in this study) decreased farther away from roads and settlements in Kenya, but this was due to establishment of irrigated commercial farms in those areas. In Tigray, irrigated commercial farms do not exist, and the reduction in natural habitats between 1964 and 1994 was likely due to war, drought and famine.

5.3 Comparison with LULC changes in other continents

The results of this study were compared with similar studies in tropical highlands of the Andes and the Himalaya. There are only a limited number of studies in those regions, which explain LULC changes in relation to their drivers in spatially explicit multiple regression models. Most studies in tropical Andes regions on changes in forest cover in relation to their drivers have been carried out in Chile (Dubroeucq and Livenaise, 2004; Echeverra et al., 2008), Colombia (Mendoza and Etter, 2002; Armenteras et al., 2006; Etter et al., 2006a, 2006b, 2006c) and Ecuador (Pan et al., 2004). Only few studies are available related to LULC changes and their drivers in the Himalaya, mainly in India (Rao and Pant, 2001; Wakeel et al., 2005), Nepal (Gautam, et al., 2003) and Tibet (Wang et al., 2008).

Similar to our results population growth, expansion of road networks and topographic factors explained land use patterns and dynamics, as determined from Landsat TM images, in the tropical Andean region of Ecuador between 1990 and 1999 (Pan et al., 2004). In a 1950 – 1999 study in the tropical highlands of Chile, deforestation was related to human interventions, based on interpretation of aerial photographs and historical databases (Dubroeucq and Livenaise, 2004). Another study in Chile, based on Landsat MSS, TM and ETM+ images, indicated that socio-economic activities, such as forest cutting for fuel wood, forest clearance for pasture and farming contributed to deforestation between 1976 – 1999 (Echeverra et al., 2008). Etter et al. (2006a, 2006b and 2006c) proposed that changes in policies and institutions, accessibility to major roads, towns and major rivers, as derived from aerial photographs, Landsat (TM and ETM+) and MODIS images contributed to deforestation in Colombia. In 1985 – 2001, deforestation, as indicated by Landsat MSS, TM and ETM+, was associated with population density in Colombia (Armenteras et al., 2006). An aerial photograph-based study by Mendoza and Etter (2002) showed that deforestation was mainly caused by the historical macro-economic policies between 1940 and 1996 in Colombia.

In contrast to the approach used for the Andes and now also for Ethiopia, none of the LULC change studies in tropical Himalaya regions applied spatially explicit regression models to explain the observed LULC changes. Nevertheless, Wang et al. (2008) proposed that socio-economic developments and climatic changes were the main drivers of land use change classified from Landsat TM images in the Tibetan plateau between 1990 and 2000 without indicating which socio-economic or climatic factors contributed to the observed land use changes. Studies in the tropical Himalayas revealed only temporal LULC changes, particularly forest area reduction and agricultural area expansion in India, between 1963 and 1996 using Landsat TM images (Rao and Pant., 2001) and between 1967 and 1997 using Landsat TM images and Indian Remote Sensing Satellite – LISS – III data (Wakeel et al., 2005). Gautam et al. (2003) analyzed Landsat (MSS and TM) and Indian Remote Sensing Satellite images (IRS-1C, LISS-III) between 1976 and 2000 to demonstrate forest improvement and agricultural area expansion in Nepal, but also without linking the changes to their potential drivers.

5.4 Implications for land use planning and sustainability

The approach as presented in this study provides LULC information based on a spatially explicit model that may be useful for local and national land use planners and decision makers. For example, in recent decades, expansion of settlement areas has been associated with an increase in consumption of fuel wood and cutting of trees for construction, adversely affecting natural habitats particularly at high altitudes and steep terrains in Tigray. This has severe implications for loss of biodiversity and sustainability due to enhanced risks of soil erosion (Hadgu et al., 2008). In addition, as the amount of available wood is reduced, farmers more and more resort to the use of cow dung for cooking resulting in a decline in soil fertility and crop productivity (EPA, 1997; Abegaz et al., 2007; Hadgu et al., 2008). Therefore, reforestation and rehabilitation of natural habitats, particularly on steep slopes at extreme (low and high) altitudes becomes imperative to be able to maintain the resource base for sustenance of life in Tigray. For example, land use planners and decision makers may reserve the

Southwestern part of the study area (Figure 4), which still has remnants of primary forests, as a natural park. Local farmers may become actively involved in managing a natural park and restoring some of the degraded scrubland after raising their ecological awareness through farmers' field schools (Rola et al., 2002).

Degradation of natural habitats went hand-in-hand with expansion and intensification of agricultural lands because of changes in the land tenure system, population pressure and development policies during the study period. Especially in the last decades of the study period, sparsely cultivated agricultural areas (agro-forestry systems) were converted into intensively cultivated areas. It is predicted that human population in Tigray will be doubled by 2020 (CSA, 2004) as compared to the current population. This implies population pressure will remain the main driver for expansion and intensification of agricultural lands at the expense of natural habitats in Tigray, if no conservation measures are taken. An appropriate land use policy would need to be implemented that integrates natural habitat conservation and sustainable agricultural development to provide for the needs of the increasing human population. For example, encouragement of agroforestry, contour cropping, intercropping and mixed crop-livestock systems is recommended. A recent report by IAASTD (2008) also proposed sustainable ways of increasing agricultural productivity by diversification of the agroecosystems of small scale farms where the potential for improved agricultural productivity by synthetic inputs is low. An earlier report by IAC (2004) had proposed to use best science and technology, including synthetic inputs, to increase agricultural productivity in Africa. However, the more recent suggestion (IAASTD, 2008) may be more appropriate for resource-poor rural populations who are dependent on locally available resources as they lack the means to purchase synthetic inputs (Hadgu et al., 2008).

6 Conclusions

This study reveals major LULC changes over a period of 41 years (1964 – 2005) in Tigray, northern Ethiopia, in particular natural vegetation depletion and agricultural land expansion and intensification. Spatially explicit multiple logistic regression modelling of LULC was important to understand the processes of LULC change in relation to their associated drivers. Our analysis showed that the reduction in extent and location of natural habitats (woodland and shrub land) was higher as locations were farther from a road in the first study period (1964 – 1994). These were unique results compared to those of similar studies in Africa likely because of war, drought and famine in our study area. In the second period (1994 – 2005), however, shrub land and woodland were reduced closer to roads and settlements, respectively, particularly at high altitudes and on steep terrains. In both study periods, population density was an important driver for expansion and intensification of agricultural land. Our study provides a spatially explicit approach using time-series remote sensing that can help to understand LULC changes in relation to their drivers in heterogeneous landscapes of tropical highlands.

7 Acknowledgement

Financial support was provided by an IITA-Lukas Bader Fellowship and a NUFFIC fellowship to the first author. We thank IITA for providing IITA- Lukas Brader Fellowship. We also thank Mr B. Oyewole, for logistic support, and Dr Morag Ferguson and Dr Michael Pillay, for being IITA supervisors.

References

Abegaz, B., 2004. Escaping Ethiopia's poverty trap: the case for a second agrarian reform. J. Mod. Afr. Stud. 42, 313 – 342.

Abegaz, A., Van Keulen, H., Haile, M., Oosting, S.J., 2007. Nutrient dynamics on smallholder farms in Teghane, Northern Highlands of Ethiopia. In: Botiono, A., Job, K., Joseph, K., Boaz, W. (Eds.), Advances in integrated soil fertility management in Sub-Saharan Africa: Challenges and Opportunities. Springer, Dordrecht.

Amacher, G.S., Ersado, L., Hyde, W.F., Osorio, A., 2004. Tree planting in Tigray, Ethiopia: the importance of human disease and water microdams. Agroforest. Syst. 60, 211 – 225.

Amsalu, A., Stroosnijder, L., de Graaff, J., 2007. Long-term dynamics in land resource use and the driving forces in the Beressa watershed, highlands of Ethiopia. J. Environ. Manage. 83, 448 – 459.

Armenteras, D., Rudas, G., Rodriquez, N., Sua, S., Romero, M., 2006. Patterns and causes of deforestation in the Colombian Amazon. Ecol. Indic. 6, 353 – 368.

Baldyga, T. J., Miller, S.N., Driese, K. L., Gichaba, C.M., 2008. Assessing land cover change in Kenya's Mau Forest region using remotely sensed data. Afr. J. Ecol. 46, 46 – 54.

Bauer, M.E., Burk, T.E., Ek, A.R., Coppin, P.R., Lime, S.D., Walters, D.k., Befort, W., Heinzen, D.F., 1994. Satellite inventory of Minnesota forests. Photogramm. Eng. Rem. Sens. 60, 287 – 298.

Benin, S., Pender, J., 2001. Impacts of land redistribution on land management and productivity in the Ethiopian highlands. Land Degrad. Dev. 12, 555 – 568.

Bewket, W., 2002. Land Cover Dynamics Since the 1950s in Chemoga Watershed, Blue Nile Basin, Ethiopia. Mt.Res.Dev. 22, 263 – 269.

Bewket, W., Sterk, G., 2005. Dynamics in land cover and its effect on stream flow in the Chemoga watershed, Blue Nile basin, Ethiopia. Hydrol. Process. 19, 445 – 458.

BoNAR, 2000. Climate, vegetation and land use/land cover of Tigray, Tigray Bureau of Agriculture and Natural Resources (BoNAR). Mekelle.

Brandt, J., Townsend, P.A., 2006. Land use – land cover conversion, regeneration and degradation in the high elevation Bolivian Andes. Landscape Ecol. 21, 607 – 623.

Braimoh, A.K., Vlek, P.L.G., 2005. Land – Cover Change Trajectories in Northern Ghana. Environ. Manage. 36, 356 – 373.

Bürgi, M., Hersperger, A.M., Schneeberger, N., 2005. Driving forces of landscape change – current and new directions. Landscape Ecol. 19, 857 – 868.

Casson, B., Delacourt, C., Baratoux, D., Allemand. P., 2003. Seventeen years of the “La Clapière” landslide evolution analysed from ortho-rectified aerial photographs. Eng. Geol. 68, 123 – 139.

Cohen, J., Weintraub, D., 1975. Land and Peasants in Imperial Ethiopia: the social background to a revolution. Van Gorcum and Co., Assen, The Netherlands.

CSA, 2004. Statistical Abstracts. Ethiopian Central Statistical Authority (CSA), Addis Ababa.

Currit, N., 2005. Development of a remotely sensed, historical land – cover change database for rural Chihuahua, Mexico. Int. J. Appl. Earth Observ. Geoinform. 7, 232 – 247.

Dawit, W., 1989. Red Tears: War, Famine and Revolution in Ethiopia. The Red Sea Press, Trenton, New Jersey.

Deurloo, H.A., Haileselassie, T., 1994. Rehabilitation of Degraded and Degrading Areas of Tigray, Ethiopia, Survey on Farm Practices based on Local Knowledge. Wageningen Agricultural University, Wageningen.

Dubroeucq, D., Livenais, P., 2004. Land cover and land use changes in relation to social evolution – a case study from Northern Chile. J. Arid Environ. 56, 193 – 211.

Echeverria, C., Coomes, D.A., Hall, M., Newton, A.C., 2008. Spatially explicit models to analyze forest loss and fragmentation between 1976 and 2020 in Southern Chile. Ecol. Model. 212, 439 – 449.

EPA, 1997. Environmental Policy of the Federal Democratic Republic of Ethiopia. Environmental Protection Authority (EPA). Addis Ababa.

Etter, A., McAlpine, C., Phinn, S., Pullar, D., Possingham, H., 2006a. Unplanned land clearing of Colombian rainforests: Spreading like disease? Landscape Urban Plan. 77, 240 – 254.

Etter, A., McAlpine, C., Puller, D., Possingham, H., 2006b. Modelling the conversion of Colombian lowland ecosystems since 1940: Drivers, patterns and rates. J. Environ. Manage. 79, 74 – 87.

Etter, A., McAlpine, C., Wilson, K., Phinn, S., Possingham, H., 2006c. Regional patterns of agricultural land use and deforestation in Colombia. Agric. Ecosyst. Environ. 114, 369 – 386.

Fan, F., Weng, Q., Wang, Y., 2007. Land use and land cover change in Guangzhou, China, from 1998 to 2003, based on Landsat TM /ETM+ imagery. Sensor. 7, 1323 – 1342.

FDRE, 1995. The Constitution of the Federal Democratic Republic of Ethiopia (FDRE), In Federal Nagarit Gazeta, First Year Number. 1, 97 – 99. Addis Ababa.

Feoli, E., Vuerich, L.G., Woldu, Z., 2002. Processes of environmental degradation and opportunities for rehabilitation in Adwa, northern Ethiopia. Landscape Ecol. 17, 315–325.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily,G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global Consequences of Land Use. Science. 309, 570 – 574.

FAO, 2006. Global forest resources assessment 2005. Food and Agricultural Organization (FAO). FAO, Rome.

Foody, G.M., 2002. Status of land cover classification accuracy assessment. Remote Sens. Environ. 80, 185–201.

Gautam, A.P., Webb, E.L., Shivakoti, G.P., Zoebisch, M.A., 2003. Land use dynamics and landscape change pattern in a mountain watershed in Nepal. Agric. Ecosyst. Environ. 99, 83 – 96.

Giannecchini, M. ,Twine, W., Vogel,. C., 2007. Land – cover change and human-environment interactions in a rural cultural landscape in South Africa. Geogr. J. 173, 26–42.

Griffin, K. 1992. The Economy of Ethiopia. St. Martin’s Press, New York.

Gu, Z.Q., Duncan, C.N., Grant, P.M., Cowan, C.F.N., Renshaw, E., Mugglestone, M.A., 1991. Textural and spectral features as an aid to cloud classification. Int. J. Remote Sens. 12, 953 – 968.

Hadgu, K.M., Epema, G.F., van Bruggen, A.H.C., 2008. Biodiversity and sustainability in agricultural landscapes in Tigray, northern Ethiopia. Submitted

to Landscape Urban Plan.
Holden, S., Shiferaw, B., 2004. Land degradation, drought and food security in a less-favoured area in the Ethiopian highlands: a bio – economic model with market imperfections. Agric. Econ. 30, 31 – 49.
Hurni, H., 1993. Land degradation, famine and land resources scenario in Ethiopia. In: D. Pimentel (Ed), World Soil Erosion and Conservation, Cambridge University Press, Cambridge, pp. 27–62.
Keller, E.J., 1992. Drought, War, and the Politics of Famine in Ethiopia and Eritrea. J. Mod. Afri. Stud. 30, 609 – 624.
Khairo, S.A., Battese, G.E., Mullen, J.D., 2005. Agriculture, food insecurity and agricultural policy in Ethiopia. Outlook Agric. 34, 77 – 82.
Kiage, L.M., Liu, K. – B., Walker, N.D., Lam, N., Huh, O.K., 2007. Recent land-cover/use change associated with land degradation in the Lake Baringo catchment, Kenya, East Africa: Evidence from Landsat TM and ETM+. Int. J. Remote Sens. 28, 4285 – 4309.
IAASTD, 2008. Executive Summary of the Synthesis Report of the International Assessment of Agricultural Knowledge, Science and Technology for Development. International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD), Johannesburg.
IAC, 2004. Realizing the promise and potential of African agriculture. Inter Academy Council (IAC), Amsterdam.
IMF, 2004. International Monetary Fund. The Federal Democratic Republic of Ethiopia: Poverty Reduction Strategy Paper. Annual Progress Report. In: Country Report No. 04/37. (IMF) International Monetary Fund, Washington D.C.
Lambin, E.F., 1997. Modelling and monitoring land – cover change processes in tropical regions. Prog. Phys. Geogr. 21, 375 – 393.
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 Continental Scale. Remote Sens. Environ. 61, 181 – 200.
Lambin, E.F., Rounsevell, M.D.A., Geist, H.J., 2000. Are agricultural land-use models able to predict changes in land – use intensity? Agric. Ecosyst. Environ. 82, 321 – 331.
Lawrence, R. L., Ripple, W. J., 1999. Calculating Change Curves for Multitemporal Satellite Imagery: Mount St. Helens 1980–1995. Remote Sens. Environ. 67, 309 – 319.
Lu, D., Mausel, P., Brondízio, E., Moran, E., 2004. Change detection techniques. Int.

J. Remote Sens. 25, 2365 – 2401.
Menard, S., 1995. Applied logistic regression analysis. Quantitative Application in the Social Sciences. No. 106. Saga publications, London.
Mendoza, S.J.E., Etter, R.A., 2002. Multitemporal analysis (1940 – 1996) of land cover changes in the Southwestern Bogota high plain (Colombia). Landscape Urban Plann. 59, 147 – 158.
Mertens, B., Lambin, E., 1999. Modelling land cover dynamics: Integration of fine-scale land cover data with landscape attributes. Int. J. Appl. Earth Observ. Geoinform. 1, 48 – 52.
Mertens, B., Lambin, F E. 2000. Land-Cover-Change Trajectories in Southern Cameroon. Ann. Assoc.Am. Geogr. 90, 467 – 494.
Muñoz-Villers, L. E., López-Blanco, J., 2007. Land use/cover changes using Landsat TM/ETM images in a tropical and biodiverse mountainous area of central-eastern Mexico. Int. J. Remote Sens. 29, 71 – 93.
Ningal, T., Hartemink, A.E., Bregt, A.K., 2007. Land use change and population growth in the Morobe Province of Papua New Guinea between 1975 and 2000. J. Environ. Manage. 87, 117 – 124.
Ottaway, M., 1977. Land Reform in Ethiopia 1974 – 1977. Peasants in Africa. Afr. Stud. Rev. 20, 79 – 90.
Pan, W.K.Y., Walsh, S.J., Bilsborrow, R.E., Frizzelle, B.G., Erlien, C.M., Baquero, F., 2004. Farm – level models of spatial patterns of land use and land cover dynamics in the Ecuadorian Amazon. Agric. Ecosyst. Environ. 101, 117 – 134.
Petit, C., Scudder, T. Lambin, E.F., 2001. Quantifying processes of land-cover change by remote sensing: resettlement and rapid land – cover changes in south-eastern Zambia. Int. J. Remote Sens. 22, 3435 — 3456.
Rahmato, D., 1985. Agrarian Reform in Ethiopia. Red Sea Press, Trenton, New Jersey.
Rao, K.S., Pant, R., 2001. Land use dynamics and landscape change pattern in a typical micro watershed in the mid elevation zone of central Himalaya, India. Agric. Ecosyst. Environ. 86, 113 – 123.
Reid, R.S., Kruska, R.L., Muthui, N., Taye, A., Wotton, S., Wilson, C.J., Mulatu, W., 2000. Land-use and land-cover dynamics in response to changes in climate, biological and socio – political forces: the case of Southwestern Ethiopia. Landscape Ecol. 15, 339 – 355.
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). Int. J. Appl. Earth Observ. Geoinform. 2, 181 – 189.
Ridd, M.K., Liu, J., 1998. A comparison of four algorithms for change detection in an

urban environment. Remote Sens. Environ. 63, 95 – 100.

Riebsame, W.E., Meyer, W.B., Turner II, B.L., 1994. Modeling land use and cover as part of global environmental change. Clim. Change. 28, 45 – 64.

Rola, A.C., Jamias, S. B., Quizon, J. B., 2002. Do Farmer Field School graduates retain and share what they learn? An investigation in Iloilo, Philippines. J. Int. Agric. Ext. Educ. 9, 65 – 76.

Sarraute, J.L.,Vonder, O.W., 1994. Rehabilitation of Degraded and Degrading Areas of Tigray, Ethiopia: landsurface, landcover and change detection classifications based on remote sensing. Wageningen Agricultural University, Wageningen.

Serneels, S., Lambin, E.F., 2001. Proximate causes of land-use change in Narok District, Kenya: a spatial statistics model. Agric. Ecosyst. Environ. 85, 65 – 81.

Singh, A., 1989. Review article – Digital change detection techniques using remotely-sensed data. Int. J. Remote Sens. 10, 989 – 1003.

Smits, P. C., Dellepiane, S. G., Schowengerdt, R.A., 1999. Quality assessment of image classification algorithms for land-cover mapping: a review and a proposal for a cost-based approach. Int. J. Remote Sens. 20, 1461 – 1486.

Sonneveld, B.G.J.S, Keyzer, M.A., 2003. Land under pressure: soil conservation concerns and opportunities for Ethiopia. Land Degrad. Dev. 14, 5 – 23.

Tekle, K., Hedlund, L., 2000. Land cover changes between 1958 and 1986 in Kalu District, southern Wello, Ethiopia. Mt. Res. Dev. 20, 42 – 51.

Trinh, M.V., Dinh D.N., van Keulen, H. 2005. Using Landsat images for studying land use dynamics and soil degradation – case study in Tamduong District, Vinhphuc Province, Vietnam. Int. J. Geoinfo. 1, 157 – 164.

Wakeel, A., Rao, K.S., Maikhuri, R.K., Saxena, K.G., 2005. Forest management and land use/ cover changes in a typical micro watershed in the mid elevation zone of Central Himalaya, India. Forest Ecol. Manage. 213, 229 – 242.

Wang, X., Zheng, D., Shen, Y., 2008. Land use change and its driving forces on the Tibetan Plateau during 1990 – 2000. Catena. 72, 56 – 66.

Yemefack, M., Bijker, W., De Jong, S.M., 2006. Investigating relationships between Landsat - 7 ETM+ data and spatial segregation of LULC types under shifting agriculture in southern Cameroon. Int. J. Appl. Earth Observ. Geoinform. 8, 96 – 112.

Zeleke, G., Hurni, H., 2001. Implications of land use and land cover dynamics for mountain resource degradation in the northwestern Ethiopian Highlands. Mt. Res. Dev. 21, 184 – 191.

Chapter 3

Biodiversity and sustainability in agricultural landscapes in Tigray, northern Ethiopia

Kiros Meles Hadgu[a,b,c], Gerrit F. Epema[b] and Ariena H.C. van Bruggen[c]

[a] Faculty of Natural Resources and Dryland Agriculture, Mekelle University, P.O. Box 231, Mekelle, Tigray, Ethiopia
[b] Centre for Geo-information, Wageningen University and Research Centre, Droevendaalsesteeg 3, 6708 PB Wageningen, The Netherlands
[c] Biological Farming Systems Group, Wageningen University and Research Centre, Marijkeweg 22, 6709 PG Wageningen, The Netherlands

(Submitted to Landscape and Urban Planning)

Abstract

Biodiversity has received increasing attention in recent years as a way of promoting sustainable agriculture throughout the world. In this paper we quantitatively examine relationships between diversity of tree and shrub species (further called: plant diversity) and crops in relation to farm altitude, soil fertility class, soil erosion, crop production characteristics, farmers' wealth parameters, and proximity to roads and urban areas in Tigray, northern Ethiopia. The objective of this study was to identify spatial and non-spatial factors affecting biodiversity and sustainability in agricultural landscapes. Soil erosion was considered as the main indicator of unsustainability. We interviewed 188 farmers and observed their fields for plant and crop diversity. GIS buffering and proximity analyses of urban areas and roads were carried out. Plant diversity increased significantly with altitude, soil quality class and number of crop selection criteria, while plant diversity declined as farmers' access to credit and inorganic fertiliser use increased. Plant and crop diversity were positively correlated with number of weed species and number of insect pests per farm but negatively with soil erosion class. Soil erosion was positively associated with inorganic fertilizer use and negatively with plant diversity and numbers of animals per household, as indigenous plants and landraces were purposefully maintained to feed the animals. Proximity of farms to urban areas and roads negatively affected biodiversity (plant and crop diversity) in agricultural landscapes. Our results suggest that indigenous farming practices are associated with higher biodiversity and sustainability in agricultural landscapes in Tigray, northern Ethiopia.

Keywords: Erosion; fertilizer; GIS; landraces; survey; trees.

1 Introduction

Biological diversity is important for sustenance, health and well being of humans. Ramakrishnan (1996) also indicates that enormous diversity of life is of crucial value, probably giving greater resilience to ecosystems and organisms. Kawanabe (1996) reported that biodiversity encompasses the broad differences between ecosystem types, and the diversity of habitats, species and ecological processes occurring within each ecosystem type. Durán and Rodríguez (2008) indicate in a scientific review that diversity of vegetation and associated organisms contributes to the formation and maintenance of soil structure and the retention of moisture and nutrient levels, and promotes the recycling of nutrients. Moreover, Hölzel et al. (2002) reveal loss of biological diversity through clearing of vegetation has contributed to the salinization of soils, leaching of nutrients, loss of minerals and accelerated erosion of topsoil, reducing the land's productivity.

Wood and Lenné (1999) defined agrobiodiversity as the most important part of biodiversity for human survival and involves different levels of biodiversity (ecosystem, habitat, species and genetic level). Qualset et al. (1995) also described agrobiodiversity as a genetic variation within different agricultural sectors . Biodiversity in agricultural landscapes, as used in this study, refers to crop diversity and plant diversity (trees/shrubs) in agricultural landscapes as affected by biological and socio-economic processes including decisions of individual farmers, local administrators and national policy makers (Jackson et al., 2007).

As Greenland (1994) and Hartemink (1998) indicate, sustainability may be defined as the ability to last, endure or continue indefinitely. The idea of sustainability has economic, social, as well as environmental or ecological dimensions, all of which synergistically interrelate. Sustainable agriculture, which relies on recycling and balanced in- and out-puts of soil nutrients, crop rotations, crop mixtures and biological methods to control pests and diseases, can maintain agroecological stability and food security (Rasul and Thapa, 2004). Intensive agriculture can lead to soil erosion, which can be considered as both a result and an indicator of environmental deterioration and of unsustainability.

Francis (1986) reported maintaining diversity of crops both in time and space is a traditional strategy to promote diversity in income sources, production stability, minimization of risk, reduced insect pest and disease incidence, efficient use of labor, increased production with limited resources and maximization of returns under low levels of technology. Crop diversity can result in higher total yields per hectare than monocropping, even when yields of individual components are reduced. Altieri (1995) also reported mixtures of crops result in more efficient use of light, water and nutrients because of their different nutrient requirements, height and canopy structure. In addition, Altieri (1994 and 1999) demonstrate that diverse genotypes of a single crop can provide the opportunity to more effectively exploit different microhabitats in spatially heterogeneous agricultural fields, resulting in more efficient use of resources and higher productivity for a longer period of time. Diversified crops and genotypes can also provide insurance against crop failure, especially in areas subject to land degradation and drought, such as Tigray, the study area. Thus, when one of the crops or genotypes of a crop is damaged early in the growing season, the other crops or genotypes may compensate for the loss.

According to Vavilov (1951) Ethiopia is one of the eight world's centres of origin and diversity of agricultural products. The enormous variety and complexity of habitats, diversified agroclimatic environments and the diverse farming systems and cultural practices have provided an array of micro-habitats which in turn have created large differences in the amount and distribution of genetic variation in general and the diversity of crop species in particular (Robin et al., 2000). The country exhibits extraordinary genetic diversity in many crop plants, such as coffee (*Coffea arabica*), tef (*Eragrostis tef*), enset (*Musa ensete*), sesame (*Sesamum indicum*), anchote (*Coccinia abyssinica*) and 'noya' (*Vernonia galamensis*). It is the main centre of genetic diversity for noug (*Guizotia abyssinica*) and rapeseed (*Brassica carinata*). It has also very high genetic diversity in four of the world's widely grown food crops: wheat (*Triticum* spp.), barley (*Hordeum vulgaris*), sorghum (*Sorghum bicolor*) and beans (*Phaseolus vulgaris*), and in a number of other crop plants of global or local importance.

However, these crop genetic resources are currently under attack from genetic erosion, for example, by replacement of a great variety of land races by few high yielding varieties. Furthermore, several studies (e.g., Frankel, 1974; Chambers, 1983; Hawkes, 1983; Oldfield and Alcorn, 1987; Worede et al., 1991; Altieri, 1995; Teshome et al., 1999; Hadgu et al., 2008; unpublished) reported loss of traditional knowledge of cropping patterns and management practices, changes in cropping patterns, human induced habitat changes (by changes in land use, in agricultural and other resource management), natural calamities, overexploitation due to increasing human population pressure, and drought are considered major reasons for loss of agrobiodiversity in the area. Another potential reason for loss of biodiversity is land degradation that has been going on for many years in northern Ethiopia mainly due to population pressure, which led to cultivation of steep slopes (Hadgu et al., 2008; unpublished) and over-grazing (Asefa et al., 2003). Dragan et al. (2003) and Gebremedhin and Swinton (2003) also reveal that rapid population increase and a reduction in the available area for cultivation in the region led farmers to adopt more intensive, higher-input farming practices.

Many studies have been carried out in Tigray on crop productivity but few of these concerned the decrease in biodiversity in the agricultural landscape in relation to changing farming practices. No research has been carried out in the area to track status and spatial distribution of biodiversity. GIS and remote sensing techniques have the potential to identify biodiversity distribution in space, and have been applied to explore spatial relationships between land use, biodiversity, the biophysical environment and human settlements at the landscape level (Lindhult et al., 1988). Some studies (e.g., Hawbaker et al., 2004; Morschel et al., 2004) reported GIS analysis can provide information to planners and policy makers on how urban areas and roads influence ecological processes and contribute to landscape degradation by providing accessibility. However, the relationships between biodiversity and expansion of urban areas and roads have not been explored for the study area so far.

In this paper we identify and analyse factors affecting biodiversity in agricultural landscapes in Tigray, Ethiopia, and relate biodiversity to sustainability. Furthermore, the spatial distribution of biodiversity in the agricultural landscape is related to urban areas and road proximity as well as to elevation. Biodiversity, in this study, includes number of land races per farm in the survey year, number of land races per farm in the last 6 years, number of tree and shrub species (here considered plant diversity), and local to exotic trees/shrubs ratio. Soil erosion is considered as measure of unsustainability as it is the most visible form of land degradation in the area. The specific aims of the study are to see if there are relationships between diversity of crops (in terms of land races), plant diversity, physical environment (soil erosion classes, altitude, number of soil classes per farm and proximity to urban areas and roads), crop production characteristics (number of crop selection criteria, number of crops planted, weed species and insect pests per farm), and measurers of wealth (livestock holding per household, access to credit and use of inorganic fertiliser).

2 Materials and Methods

2.1 Study area

The study covers an area of 30 × 40 km, and is located in Tigray, northern Ethiopia (4° 82' – 5° 10' N and 15° 66' – 15° 28' E) at an elevation of 1300 – 2800 metres above sea level (m.a.s.l.) (Figure 1). The climate of the area is semi-arid, with two rainy seasons, the main beginning in late June and lasting until September, and the minor rainy season between March and April. The average annual rainfall ranges from 740 mm at 1500 m.a.s.l. to 900 mm at 2000 m.a.s.l. Wide variation in rainfall from

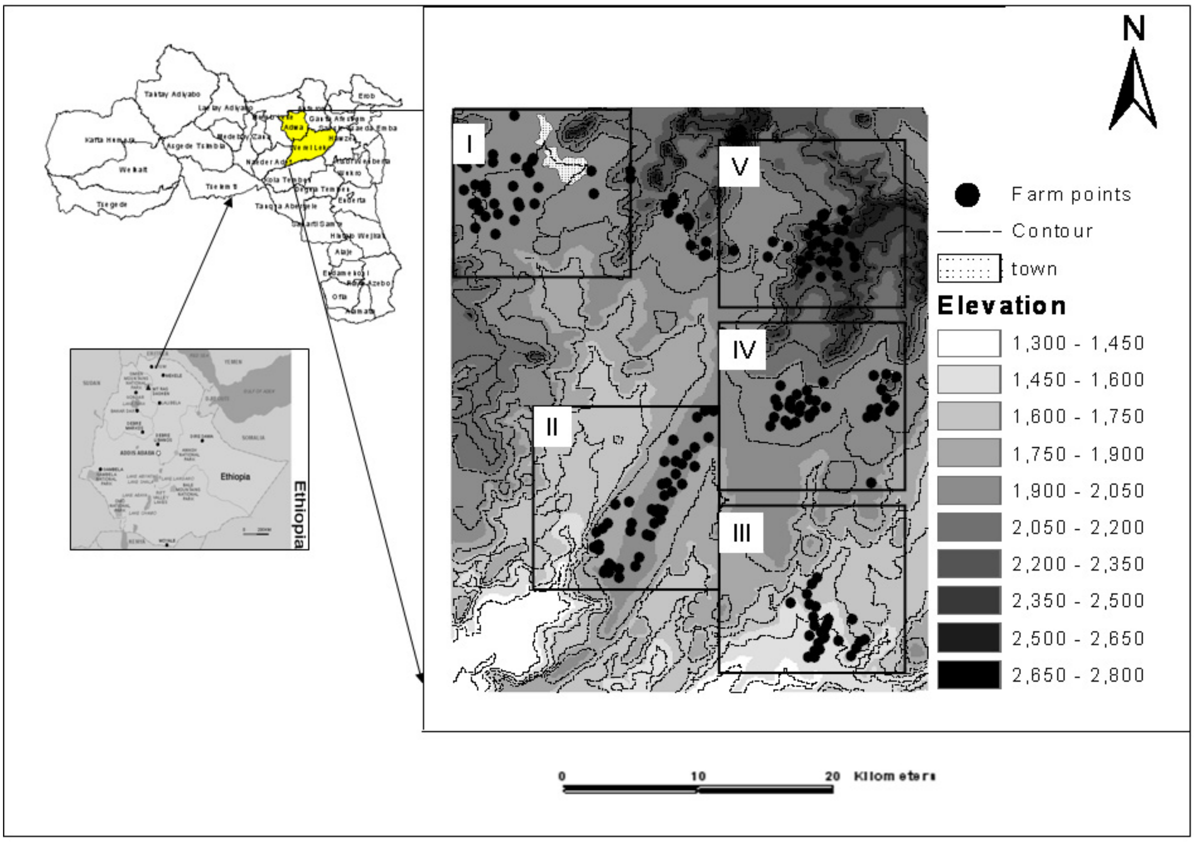


Figure 1. Map of the location of the study regions in Tigray, northern Ethiopia.

year to year is characteristic of the area. Soils are predominantly Cambisols, Fluvisols, Xerosols, Vertisols and Luvisols. Nine land use/land cover types (woodland, shrub land, scrubland, grassland sparsely cultivated, moderately cultivated, intensively cultivated, water body and settlement) were described for the area (Hadgu et al., 2008; unpublished.). The study area is one of the most populated areas in Ethiopia (Feoli et al., 2002).

Five regions with similar cultural and social characteristics, but differing in altitude, slope, agricultural management and natural vegetation were selected for this study (Figure 1 and 2c). The regions differed in altitude from lowland (1300 – 1600 m.a.s.l.) to intermediate altitudes (1600 – 1900 m.a.s.l.) and highland (>1900 m.a.s.l.). Selection of the five regions was based on the intensity of land use, natural vegetation and altitude with the aid of a Digital Elevation Model (DEM), aerial photographs and topographic maps of the study area:

Region 1: Area with pure agriculture: intensively cultivated (with no or few trees/shrubs) located close to the town of Adwa located at 1900 – 2200 m.a.s.l.

Region 2: Agriculture dominated area: intensively (with no or few trees/shrubs) or moderately cultivated (with moderate numbers of trees/shrubs), located at 1600 – 1900 m.a.s.l. Natural vegetation and agriculture in this region co-exist but the latter is dominant.

Region 3: Agriculture interwoven with nature: sparsely cultivated agricultural land (with more trees/shrubs) and natural vegetation in almost equal proportions, located at 1300 – 1600 m.a.s.l.

Region 4: Natural vegetation dominated area: both natural vegetation and agriculture present but natural vegetation dominating in the area, located at 1900 – 2200 m.a.s.l.

Region 5: Natural habitats: almost completely covered by natural vegetation with limited agricultural activities (sparsely cutivated), located above 2200 m.a.s.l.

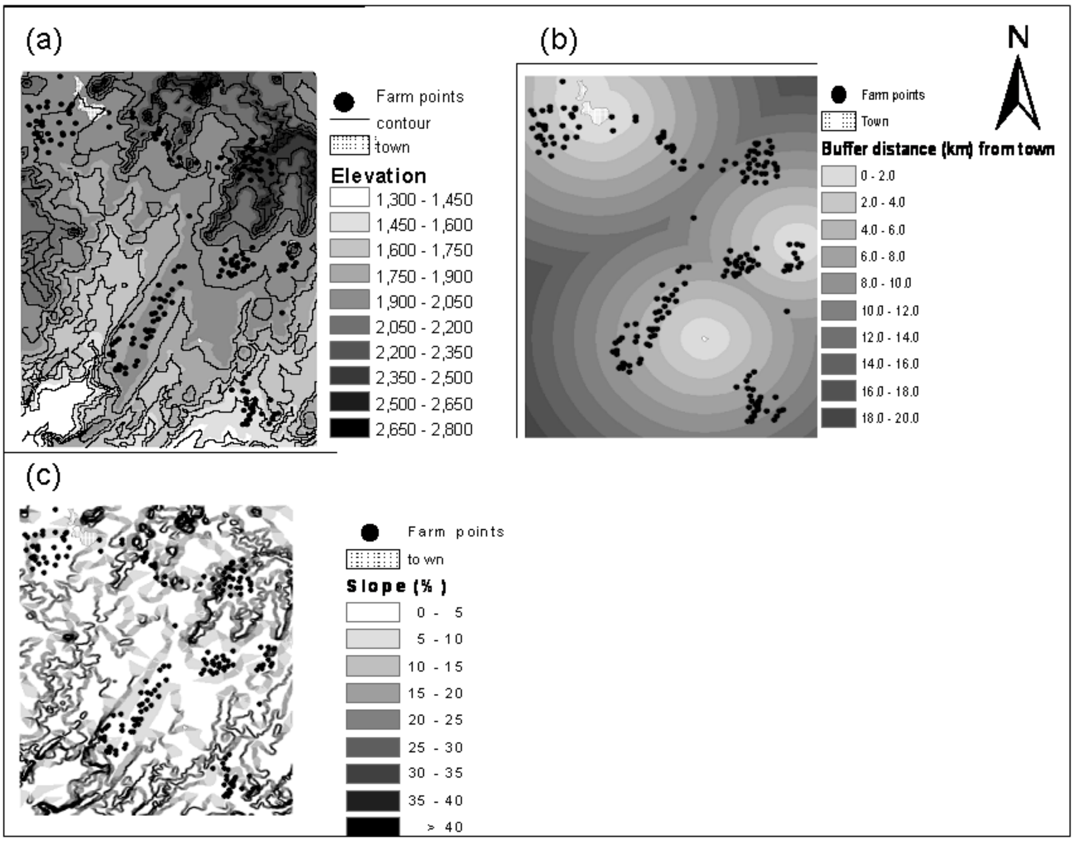


Figure 2. Overlay of farm point map over (a) elevation, (b) buffered urban area and (c) slope maps of the study area in Tigray, northern Ethiopia.

The typical agricultural practice in the study area is a mixed crop-livestock production. Subsistence farming with a limited involvement in the market economy is common for all the farmers in the study area. The common crops growing in the study area are: tef (*Eragrostis tef*), barley (*Hordeum vulgaris*), sorghum (*Sorghum bicolor*), wheat (*Triticum* spp.), finger millet (*Eleusine coracana*), maize (*Zea mays*), noug (*Guizotia abyssinica*), linseed (*Linum utilissimum*), rapeseed (*Brassica carinata*), lentil (*Lens culinaris*), safflower (*Carthamus tinctorius*), beans (*Phaseolus vulgaris*), faba bean (*Vicia faba*), field pea (*Pisum sativum*), chickpea (*Cicer arietinum*), castor bean (*Ricinus communis*), cowpea (*Vigna unguiculata*), grass pea (*Lathyrus sativus*), and pigeon pea (*Cajanus cajan*). Cattle, sheep, goats, pack animals, chickens and beehives are the animals kept by most farmers in the area.

The typical agricultural practice in the study area is a mixed crop-livestock production. Subsistence farming with a limited involvement in the market economy is common for all the farmers in the study area. The common crops growing in the study area are: tef (*Eragrostis tef*), barley (*Hordeum vulgaris*), sorghum (*Sorghum bicolor*), wheat (*Triticum* spp.), finger millet (*Eleusine coracana*), maize (*Zea mays*), noug (*Guizotia abyssinica*), linseed (*Linum utilissimum*), rapeseed (*Brassica carinata*), lentil (*Lens culinaris*), safflower (*Carthamus tinctorius*), beans (*Phaseolus vulgaris*), faba bean (*Vicia faba*), field pea (*Pisum sativum*), chickpea (*Cicer arietinum*), castor bean (*Ricinus communis*), cowpea (*Vigna unguiculata*), grass pea (*Lathyrus sativus*), and pigeon pea (*Cajanus cajan*). Cattle, sheep, goats, pack animals, chickens and beehives are the animals kept by most farmers in the area.

2.2 Data collection

A combination of non-spatial and spatial data were collected by means of a field survey, including personal observations and a questionnaire, and GPS-GIS techniques to study biodiversity and sustainability in agricultural landscapes in Tigray, northern Ethiopia.

2.2.1 Non-spatial data collection

A field survey was carried out in the 5 study regions after general observations were made in the area prior to the start of the fieldwork. Standardized questionnaires were prepared and tested with six randomly selected farmers from the study area for clarity before performing the actual survey. In addition to the responses of interviewed farmers, discussions with key informants and district and regional agriculture officials were held. Various government documents were reviewed to get information on agricultural policies of Ethiopia, their implementation and evaluation. In summary, the steps followed during the field work were: identification of the study regions using aerial photographs, elevation and topographic maps, contacting zonal (= provincial) administration, discussion with *Woreda* (= district) administration and Bureau of Agriculture and Natural Resources (BoANR) experts, communicating with *Tabia* (= village) administration and extension agents, pre-interview observations, individual sampled farmer interviews, and group discussions.

The sample fields for observation, field measurements and interviewing were chosen randomly from the *Tabias* included in the selected study regions (Figure 1). Stratified random sampling was followed, with the 5 study regions mentioned above as strata, to obtain a representative sample. About 5% (157 farmers) of the households were selected by a systematic random sampling technique taking every 10th registered farmer from a list of households in each selected village (*Tabia*). In addition to the 5% of the households from the selected *Tabias*, 31 key informants who were growing diversified crops and other plants, as compared to other farmers in the same area, were also included in the study so that in total 188 farmers were interviewed. A series of group interviews was carried out to explore historical data: land use, agricultural practices and biodiversity in the study regions. Interviews were held at the farmer's fields where tree and shrub species were counted and crop diversity was discussed.

Farmers' fields were crossed two to three times to identify, quantify and record crops and associated plant diversity (tree/shrub species) in and around the sample fields. Visual assessment of the area in terms of genetic diversity or uniformity was made in farmers' plots. Remnants of trees and shrubs were recorded and quantified to assess how diversified the local flora had been in the past. Plant specimens of tree and shrub species in and around farmers' plots were collected and identified according to flora of Ethiopia and Eritrea (Edwards et al., 2000). Farmers were asked why they decided to grow or maintain them. Plant diversity was calculated as the number of different species of trees and shrubs found in and around each field. In addition, the ratio of local to exotic trees and shrubs was calculated at the farm level.

Crop diversity was defined as the number of distinct crop landraces, as named by farmers, identified per farm (about 1 ha) in the survey year and in the last six years. A landrace according to Teshome et al. (1999) is a plant population with a limited range of genetic variation, which is adapted to local agroclimatic conditions and which has been generated, selected, named and maintained by traditional farmers. In addition to the observations and interviews with the sample farmers, visits to local markets were also made to see the range of local landraces and introduced cultivars.

The physical environment included farm altitude and number of farm soil fertility classes from the farmers' perspective (high, medium and low fertility of soils).

Soil fertility classification from farmers' perspective was based on yield, soil water holding capacity, colour, texture and depth, stoniness, and steepness. Past yield was the most important criterion of the soil fertility classification while the others were of secondary importance. Soil erosion as observed by the first author and the farmers was taken as sustainability measure. Five classes of soil erosion were distinguished: no, low, moderate, high and extremely high erosion, corresponding with no erosion at all, sheet erosion, rill erosion, sheet and rill erosion together, and gully erosion. Sheet erosion is caused by the even flow of water over sloped lands, which removes lighter soil particles, organic matter and soluble nutrients. Rill erosion is easily identified as a series of small channels up to 30 cm deep. Gullies are up to 30 m deep and interfere with normal tillage practices.

Crop production characteristics included were the number of crop selection criteria, the number of crops in the survey year and in the last 6 years, number of weed species and insect pests in the survey year and in the last 6 years at the farm level. Crop selection criteria used by a farmer to choose the landraces included yield, insect resistance, weed resistance, market value, early maturity, drought resistance, threshability, beverage quality and straw quality.

Similar areas of land had been allocated to all farmers who participated in the study (about 1 ha per farmer). Identification of poor, average and rich farmers, based on other criteria than land ownership or monetary income, was of paramount importance during the field survey. Wealth parameters were considered to be inorganic fertiliser use (kg per farm) and the number of credit sources (*Dedebit* - a local micro finance institute, local money lenders and relatives), since farm income could not be calculated (as most farmers produce primarily for home consumption). Credit was considered as wealth parameter because farmers take credit to buy inorganic fertiliser and repay their loan usually in a year; in case of crop failure resource poor farmers have nothing to repay their loans but the rich farmers can repay. Livestock holding (number of animals per farmer) was also included as wealth parameter, since animals provide status in the community and are used as dowry to the bridegroom's family.

2.2.2 Spatial data collection and processing

Spatial data included were an elevation map and GIS overlay maps of studied farm locations over a buffer map of urban areas and roads. The Digital Elevation Model (DEM) derived from Shuttle Radar Topographic Mission (SRTM) (USGS, Sioux Falls, SD) was used to generate elevation, slope and contour maps of the study area (Figure 2 a and c).

Spatial data of urban areas and roads were derived from aerial photographs and topographic maps (Ethiopian Mapping Agency, Addis Abeba). Twenty aerial photographs of the study area acquired from the Ethiopian Mapping Agency, Addis Abeba, were converted to digital format by scanning each photograph at 450 dots per inch (dpi), using ERDAS IMAGINE 9.1 (Leica Geosystems, Norcross, GA, USA) and ArcGIS 9.2 (ESRI, Redlands, CA, USA). For each scanned aerial photograph four fiducial marks were entered from the analog aerial photographs. Each aerial photograph was geo-referenced with points from 1:50,000 topographic maps and known ground control points (crossing of roads and river junctions) collected from the field with a hand-held Global Positioning System (GPS) (GARMIN International Inc., Kansas). Each geo-referenced photograph was ortho-rectified to minimize scale and topographic distortion (Casson et al., 2003) and resampled to 3 m resolution using the nearest neighbor method. Urban area and road features were delineated from the ortho-rectified aerial photographs using the on-screen digitization technique. The location of each surveyed farm was recorded with the hand-held GPS. All urban area, road and farm point features were projected into Universal Transverse Mercator (UTM) system, zone 37, Adindan. Distance to urban areas and roads were calculated by the buffering method in ArcGIS 9.2 (ESRI, Redlands, CA, USA). Proximities of farms to buffered urban areas and roads were calculated by overlaying the farm point map over the buffered urban areas and roads. Finally, the farm point map was also overlaid over the elevation map of the study areas.

2.3 Statistical analysis

The data resulting from the surveys and interviews were analysed with the general statistical program SAS (SAS, 1999) and the multivariate analysis program CANOCO 4.5 (ter Braak and Smilauer, 2002). The data were transformed to log normal distribution, and an alpha value of 0.05 was used to test for significance in all statistical tests.

Multiple-regression analysis was used to reveal relationships between crop and plant (tree/shrub) diversity and all other measurements. The individual predictor variables were then included in a stepwise multiple regression analysis (SAS, 1999) to generate the best model (with the highest R^2) for predicting crop land race diversity and plant diversity. Type III sums of squares were used in the significance tests so that the effect of each variable was examined after accounting for each of the effects of all the other variables in the model. The same procedure was used for the multiple regression analysis with soil erosion as dependent variable, and other measures (altitude, number of soil fertility classes, number of tree/shrub species, local to exotic tree/shrub ratio, number of land race crops in the survey year and number of crop land race in the last 6 years) as independent variables.

The Chi-square test was performed to see the effect of number of credit sources on crop landrace diversity. Chi-square tests were also used to explore the association of altitude with soil erosion classes, soil fertility classes and inorganic fertilizer use per farm. Pearson correlation coefficients were calculated to reveal correlations among all diversity, sustainability, crop management, environmental and farm variables.

In order to quantify and visualize the relationship between biodiversity (number of tree/shrub species, local to exotic tree/shrub ratio, number of crop land races in the survey year and in the last 6 years), sustainability (soil erosion class) and various other variables: physical environment (farm altitude, number of farm soil classes, soil erosion class, distance to a major road and distance to the nearest town), measures of wealth (livestock holding, access to credit and use of inorganic fertiliser) and crop characteristics (number of crop selection criteria, numbers of crops planted in the survey year and in the last 6 years, weed species and insect pests), redundancy analysis (RDA) was applied using the program CANOCO 4.5 (ter Braak and Smilauer, 2002). Region numbers were included as classification variable. A Monte Carlo permutation test was performed to determine the relative importance of each variable in explaining the variation in diversity and sustainability.

3 Results

3.1 Physical environment and fertilizer use in relation to altitude

Soil erosion was most severe at intermediate altitudes, with deep gullies (up to 30 m deep) on 37% of the farms. Deep gullies were rare in lowland areas, but rill erosion (a series of small channels up to 30 cm deep) did occur at all altitudes. In the high land areas, soil conservation efforts were underway including terrace formation and tree/shrub planting. As a result, deep gullies were less frequent in the highlands than at intermediate altitudes. However, soil erosion at farms of different altitude zones showed no significant relationship to altitude ($\chi^2 = 14.4$, DF = 8, $P > 0.05$).

The interviewed farmers distinguished three major soil classes based on soil fertility: high, medium and low. Low soil fertility classes were observed at 40.2%, 40.3% and 50% of the farms inthe high, intermediate and low altitudes, respectively. Farms with high natural soil fertility were slightly more frequent at intermediate altitudes (regions 1, 2 and 4) and in highland areas (region 5) than in the lowland area (region 3). However, the number of farms with the three soil fertility classes were not significantly different for different altitude zones ($\chi^2 = 0.82$, DF = 4, $P > 0.05$).

The rate of inorganic fertiliser use in the study area ranged from 0 to 150 kg ha^{-1}

Table 1. Fertiliser use in different altitude zones in Tigray, northern Ethiopia.

Fertiliser rate (kg ha^{-1})	Altitude zone					
	Highland		Intermediate		Lowland	
	No. of farms	% of farms	No. of farms	% of farms	No. of farms	% of farms
150	4	4.1	4	6.0	0	0.0
100	12	12.3	14	20.9	0	0.0
50	21	21.6	19	28.3	7	29.2
25	2	2.1	0	0	0	0.0
0	58	59.8	30	44.8	17	70.8

(Table 1). Fertiliser use was not significantly different in the three altitude zones (χ^2 = 12.9, DF = 8, $P > 0.05$). On average, 33 kg fertiliser was used per ha, consisting of urea and DAP (=Di-Ammonium Phosphate) in the following ratios: 50/50 or 75/25. DAP was used at the time of sowing and urea on the day of emergence. Relatively high rates of fertiliser (100 – 150 kg of inorganic fertiliser per ha) was used at intermediate and high altitudes (about 27% and 16% of the farms, respectively), while in the lowlands none of the farms applied these high rates. The majority of the farms, 59% of the farms in the highlands, 49% at intermediate altitudes, and 71% in the lowlands, were not applying inorganic fertiliser.

3.2 Crop diversity and crop production characteristics

Gramineous crops are the major crops grown by farmers in the study area (Table 2). Tef (*Eragrostis tef*) is the dominant crop in the highlands and at intermediate altitudes, while sorghum (*Sorghum bicolor*) is the most common crop in the lowlands. Legumes and oil crops are mostly considered as minor crops, but lentils (*Lens culinaris*) and noug (*Guizotia abyssinica*) are gaining importance at high and intermediate altitudes, respectively.

The total number of crops averaged 4.3 per farm in the survey year, and 7.3 in the last six years. The most extensive crop rotation was practiced at intermediate altitudes, with 13 crops grown in the last 6 years and 6 crops in the survey year, while at low altitude it was 8 crops in the last 6 years and 4 crops in the survey year. At high altitudes 5 crops were grown in the survey year and 11 crops in the last six years.

The total number of land races of various crops was on average 6.7 in the

Table 2. Crops in three altitude zones in Tigray, Northern Ethiopia.

Crop Scientific name	Common name	Category	Crops in different altitude zones: Highland Dominant (No. farms)	Highland Minor (No. farms)	Intermediate Dominant (No. farms)	Intermediate Minor (No. farms)	Lowland Dominant (No. farms)	Lowland Minor (No. farms)
Eragrostis tef	Tef	gramineous	24	7	17	11	3	4
Hordeum vulgaris	Barley	gramineous	15	7	3	8	0	0
Triticum spp.	Wheat	gramineous	11	5	2	5	0	0
Sorghum bicolar	Sorghum	gramineous	2	4	3	4	12	2
Zea mays	Maize	gramineous	6	7	7	2	2	3
Eleusine coracana	Millet	gramineous	2	3	5	11	4	4
Lathyrus sativus	Grass pea	leguminous	0	2	0	1	0	1
Cicer arietinum	Chickpea	leguminous	5	8	6	3	0	3
Vicia faba	Horse bean	leguminous	7	9	7	3	0	0
Pisum sativum	Pea	leguminous	3	11	2	6	0	1
Vigna unguiculata	Cowpea	leguminous	1	3	2	3	0	0
Linum usitatissimum	Linseed	oil crop	9	5	4	2	1	0
Lens culinaris	Lentils	oil crop	13	7	5	3	0	1
Brassica carinata	Mustard	oil crop	0	4	0	7	0	2
Ricinus cummunis	Cator bean	oil crop	0	5	2	3	0	0
Guizotia abyssinica	Noug	oil crop	0	10	2	13	2	3

survey year and 18.5 in the last six years. For most gramineous crops the number of land races exceeded the number of introduced cultivars except for maize. All leguminous and oil crops were local land races. Especially farmers with few credit sources planted a greater variety of crops ($\chi^2 = 18.55$, DF = 6, P=0.01).

Farmers were growing different crops in order to fulfil their various needs. In the lowlands, crops with high drought resistance were given first choice. However, straw quality was an important crop selection criterion for highland farmers to be used as animal feed. At intermediate and high altitudes, especially close to the town of Adwa located in North-western corner of the study area (Figure 1), high market value was the most important selection criterion (Figure 3). Different crops were grown for different soil fertility classes: exhausted land was planted with grass pea (*Latyrus sativus*) or noug (*Guizotia abyssynica*) while fertile land was planted with tef (*Eragrostis tef*). Intercropping of different crops (noug and tef, rapeseed and tef; or maize and sunflower) is sometimes practiced. Farmers who practiced intercropping did this because of yield stability and higher overall yield.

Farmers indicated that striga (*Striga hermontica*) was the most severe weed for almost all crops growing in the area, regardless of altitude (Table 3). In some farms, this parasitic weed was so severe that farmers abandoned susceptible crops (various gramineous crops). Other weeds were only occasionally severe. Insects, such as stem borer, army worm and corn ear worm were mentioned as major crop pests that occurred regularly. Stem borers and corn ear worm were especially damaging to maize and army worms to tef and other gramineous crops. Grasshoppers could be very damaging but occurred only in some years.

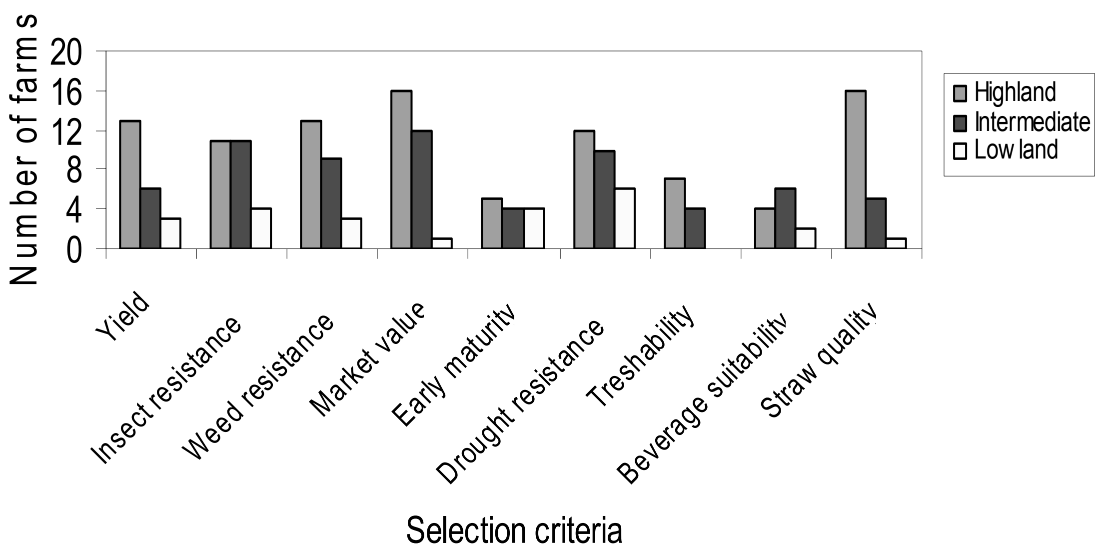


Figure 3. Number of farms using various crop selection criteria as first choice at different altitude zones in Tigray, northern Ethiopia.

Table 3. Weed species and their severity in different altitude zones in Tigray, northern Ethiopia.

Scientific name (Stroud and Parker, 1989)	Common name (Local name)	Altitude zone					
		Highland		Intermediate		Lowland	
		Severe (No. farms)	Occasional (No. farms)	Severe (No. farms)	Occasional (No. farms)	Severe (No. farms)	Occasional (No. farms)
Striga hermontica	Metselem	41	3	23	7	16	3
Achyranthes aspera	Mechelo	0	1	0	0	0	0
Carduus nyassanus	Dander	1	2	1	2	0	1
Delphinium dasycaulon	Tselim Debesom	0	1	0	1	0	0
Verbascum humifusa	Ti'rnka'a	1	2	0	0	0	0
Trifolium schimperi	Mesi	4	4	2	6	0	1
Galium aparinoides	Tsegwegot	0	2	0	0	0	0
Malva parviflora	Inkifteha	1	3	0	0	0	0
Solanum incanum	Engule	3	2	5	3	1	0
Becium filamentosum	Tebeb	1	3	2	4	0	0
Bidens sp.	Gelgle Meskel	3	5	4	5	1	1
Rumex nervosus	Hahot	1	3	0	2	0	0

3.3 Wealth characteristics

The amount of inorganic fertiliser applied, one of the main indicators of wealth, varied significantly as mentioned above (Table 1). Most farmers were too poor to be able to buy fertilisers. Most farmers borrowed some money, among others to pay for fertiliser, be it from relatives, local money lenders, or a local micro-credit organization (*Dedebit*). Highland farmers had most access to credit, especially from the local micro-credit organization, and lowland farmers least. This last group borrowed mostly from family members.

The types of animals kept by farmers were cattle, sheep, goats, pack animals (donkeys, mules, horses and camels), chickens and honeybees. Average numbers of cattle in the high, intermediate and low altitude areas were 3.1, 4.2, and 4.2 per household, respectively. The average number of sheep was highest in the highlands (7.1 per household) and lowest in the lowlands (0.3 per household), while the average number of goats was highest in the lowlands (7.8 per household) and lowest in the highlands (1.2 per household). Pack animals, chickens and beehives were slightly more numerous in the high altitude areas than in the intermediate and lowland areas.

3.4 Plant diversity (tree and shrub species)

A large number of tree and shrub species were observed in farmers' fields, on average 7.6 species per farm. These species belong to 12 families, the family Mimosoideae being dominant (Table 4).

Table 4. Tree and shrub species in different families encountered in areas surrounding farm lands at different altitude zones in Tigray, northern Ethiopia.

Family name	Total	Number of Species at each altitude zone		
		Highland	Intermediate	Lowland
Mimosoideae	9	4	6	6
Capparidaceae	2	2	2	0
Papilionoideae	4	4	3	2
Melianthaceae	3	2	2	0
Myrtaceae	1	1	1	1
Olacaceae	1	1	1	1
Rhamnaceae	2	1	2	0
Rutaceae	1	1	1	1
Sapindaceae	3	2	3	2
Apocynaceae	2	1	2	1
Pittosporaceae	3	2	3	0
Euphorbiaceae	1	1	1	0

The integration of trees and shrubs into farming systems is highly efficient, and the trees and shrubs have multiple functions, such as providing fodder, nutrients, and aiding soil conservation and water retention.

There were substantial differences in tree and shrub species diversity in and around farm lands at different altitudes. The number of tree and shrub species was highest at high altitudes (27 species), moderate at intermediate altitudes (22 species) and lowest in the lowlands (14 species). On average, the ratio of local to introduced tree and shrub species was 2.4, with a standard deviation of 1.2. The highest ratio was observed at 1600 – 2100 m above sea level.

Farms with many types of tree and shrub species generally had diversified crops. Crop diversity (both number of land races in the survey year and in the last 6 years) was highly correlated with total number of tree and shrub species (r=0.68 and r=0.58, respectively; $P < 0.001$).

3.5 Factors related to biodiversity in the agricultural landscape

Multiple regression analysis showed that the total number of tree and shrub species per farm and the ratio of native to exotic species were mainly associated with soil erosion class: the worse the erosion the smaller was the tree and shrub diversity (Table 5). The total number of tree and shrub species was also associated with the number of crops planted in the last six years (Table 5). The numbers of land races in the survey year and in the last 6 years were primarily positively associated with the numbers of selection criteria for planting a crop and the numbers of weed and insect species in the survey year and over the past 6 years (Table 5). In addition, the number of landraces in the survey year was negatively affected by the number of soil fertility classes and the extent of erosion (Table 5).

Plant diversity (number of tree/shrub species) and crop diversity decreased as the buffer distance from roads decreased to less than 1.5 km (Figure 4 and 5). Higher biodiversity was observed as the distance from roads increased, mostly in the north-eastern part of the study area. Road type was also an important factor affecting spatial biodiversity distribution. Biodiversity was more reduced around all weather roads compared to dry weather roads (Figure 4a and b). Biodiversity was also negatively affected by the proximity of farms to urban areas (Figure 2b and 5a and b). On the other hand, biodiversity was favored by high elevation, particularly in the north-eastern part of the study area (Figure 5c and d).

Redundancy analysis (Figure 6) showed that biodiversity (number of tree/shrub species, local to exotic tree/shrub ratio, crop varieties in the survey year and in the last 6 years), the sustainability indicator (soil erosion class) and other explanatory variables

Table 5. Variables selected in a multiple regression analysis for diversity parameters in Tigray, northern Ethiopia. The order of variable listed does not necessarily coincide with the order in the regression equations.

Independent Variables Source[1]	Dependent variables (Diversity)							
	VAR_YR[2]		VAR_6YR[3]		TOTTSPP[4]		T_RATIO[5]	
	Coeffi-cient	Pr >F	Coeffi-cient	Pr >F	Coeffi cient	Pr >F	Coeffi-cient	Pr >F
Alti	–0.01	0.444	0.01	0.05	0.01	0.01	0.01	0.17
Soilclas	–0.41	0.005	0.08	0.71	0.20	0.39	0.16	0.17
Erosclas	–0.24	0.002	0.19	0.12	–1.25	0.001	–0.38	0.001
T_cp_yr	0.39	0.001	0.33	0.66	0.22	0.22	0.16	0.07
T_c_6yr	0.26	0.001	0.08	0.38	0.39	0.001	0.07	0.13
Selcr	0.59	0.001	–0.56	0.001	0.02	0.88	0.01	0.97
Fer_kg	–0.01	0.68	0.01	0.05	–0.01	0.11	0.01	0.42
Weed_yr	0.67	0.001	2.91	0.001	0.11	0.66	0.03	0.83
Weed_6yr	0.31	0.01	1.36	0.001	0.03	0.87	0.01	0.89
Inse_yr	0.80	0.001	2.09	0.001	0.19	0.39	0.22	0.05
Inse-6yr	0.21	0.01	0.68	0.001	0.04	0.75	0.03	0.57

[1] Alti = altitude; Soilclas = number of farm soil fertility classes; Erosclas = Soil erosion class; Tottspp = Total tree/shrub species per farm; Var_yr = Number of landraces per farm in the survey year; Var_6yr = Number of landraces per farm in the last 6 years; T_ratio= local to exotic tree/shrub ratio; T_cp_yr= total number of crop types per farm in the survey year; T_cp_6yr= total number of crop types per farm in the last 6 years; Selcr= number of farmers' crop selection criteria; Fer_kg= inorganic fertiliser use per ha (kg); Weed_yr = number of weed species per farm in the survey year; Weed_6yr = number of weed species per farm in the last 6 years; Inse_yr = Insect pests per farm in the survey year; Inse_6yr = Insect pests per farm in the last 6 years.

[2] R^2= 0.888

[3] R^2= 0.834

[4] R^2= 0.758

[5] R^2= 0.577

resulted in a clear separation of regions. Especially the lowland region (region 3) was distinct from the other regions, as the natural vegetation is sparse and agricultural activities are minimal in region 3. Sample farms in region 5, the area with the highest altitude, were separated from the regions at intermediate altitudes, as they were located farther from towns and had higher biodiversity (Figure 6). Farms in region 1, close to the town of Adwa (Figure 1), were also somewhat separated from farms in other regions, and distinguished themselves by relatively high fertilizer use. The first axis accounted for 72.6% of the total variance while the second axis represented the remaining 9.3% of the total variance. The Monte Carlo test indicated that biodiversity was significantly related to each of the explanatory variables included ($P < 0.001$), but was particularly affected by distance to towns and roads (positive associations) and fertilizer use and erosion (negative associations). The number of landraces, number of tree/shrub species, local to exotic tree/shrub ratio were positively associated with farming practices such as the number of crops in the survey year and in the last 6 years, and number of crop selection criteria, but also with weed species and insect pest incidence (Figure 6). Fertiliser use (kg ha^{-1}) was a major factor negatively affecting individual measures of diversity (Figure 6). There were also significant negative correlations between fertiliser use and the various measures of diversity, for example the total number of tree and shrub species ($r = -0.37$; $P < 0.001$) or the number of crops in the last 6 years ($r = -0.28$; $P < 0.01$).

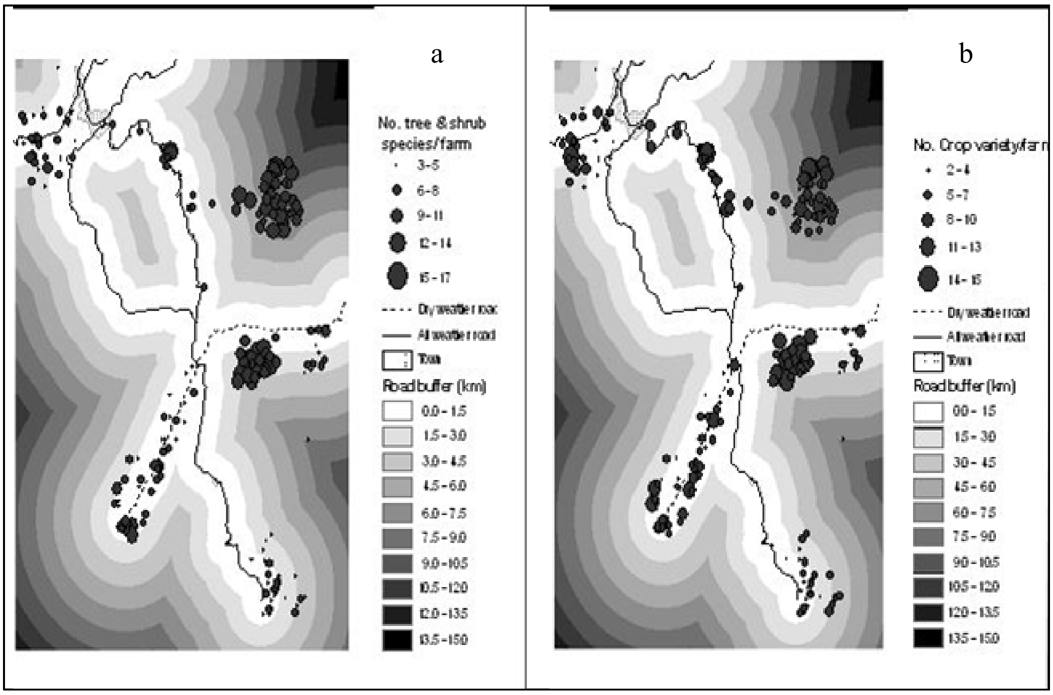


Figure 4. Spatial distribution of (a) tree/shrub species and (b) crop variety in relation to proximity to a road in Tigray, Ethiopia.

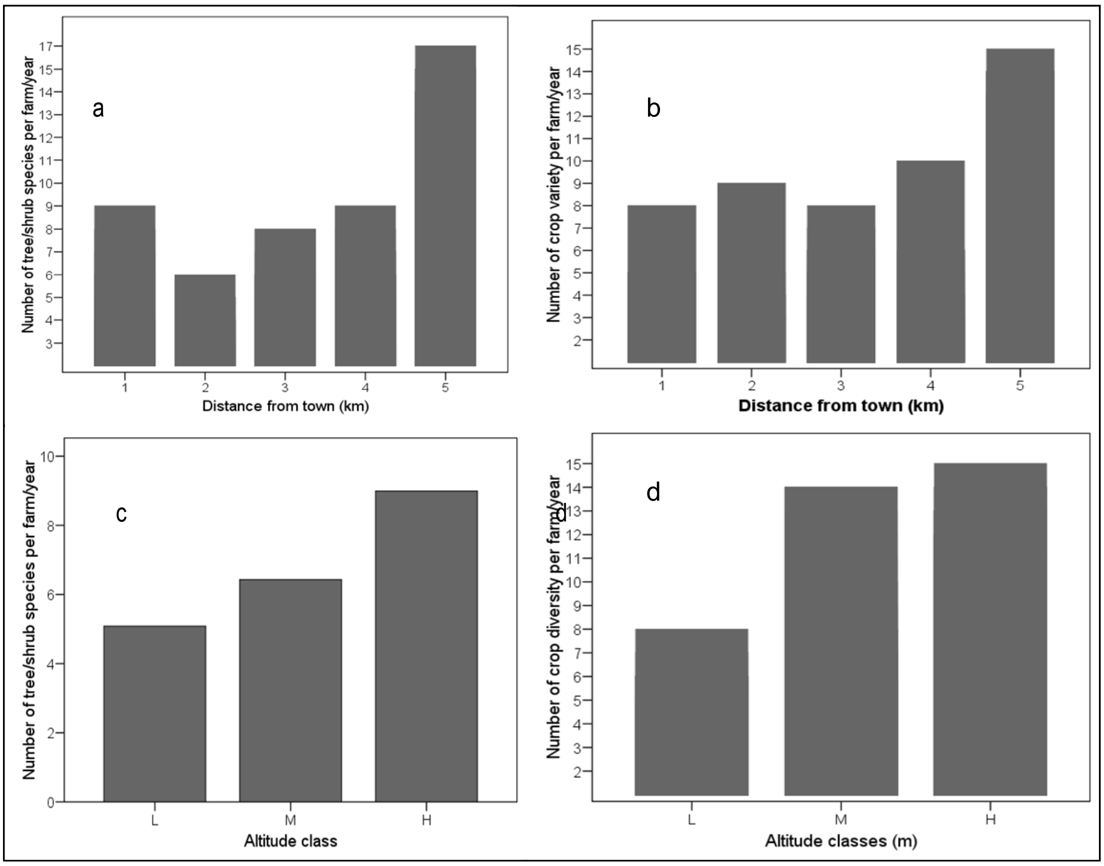
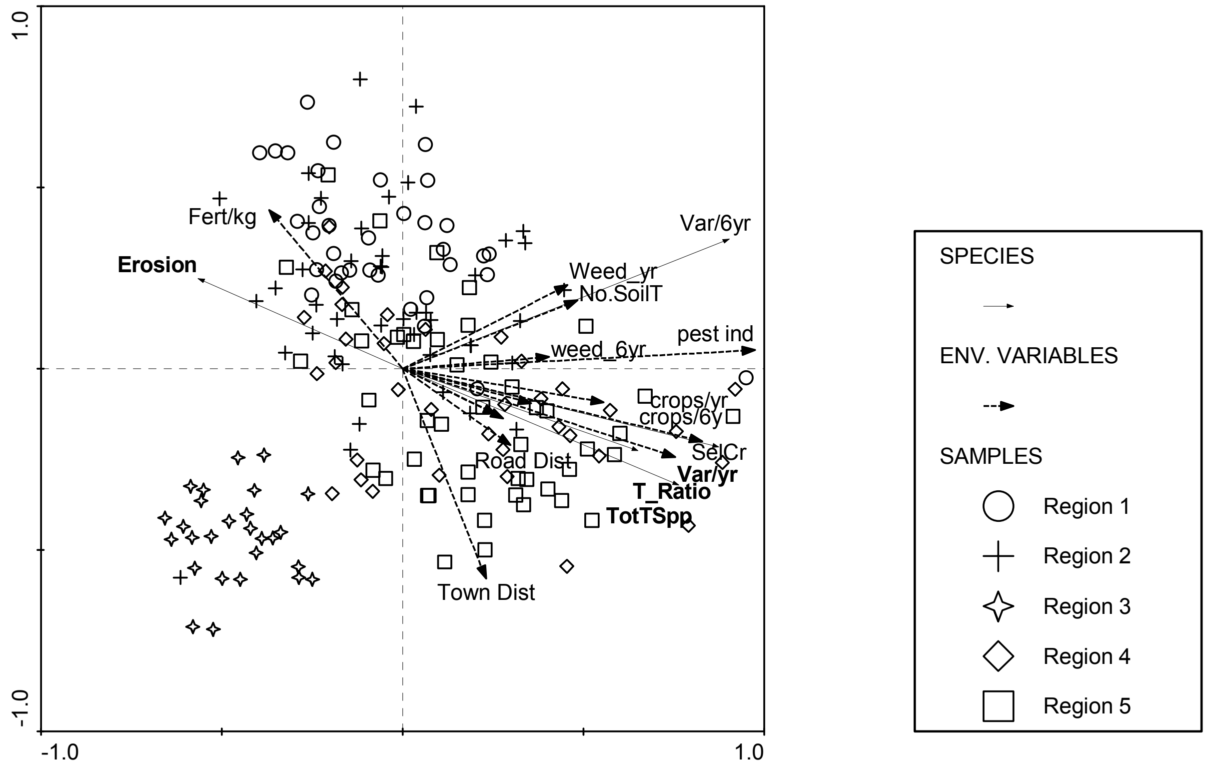


Figure 5. Biodiversity (tree/shrub species and crop diversity per farm) in relation to buffered distance to an urban area, and elevation in Tigray, northern Ethiopia.

Note: Distance categories, in kilometers (km), are buffered from towns: 1 = 0 – 1 km, 2 = 1 – 2 km, 3 = 2 – 3 km, 4 = 3 – 4 km, 5 = 5 km and above. Altitude classes are: L = high altitude (1300 – 1600 m.a.s.l), M = Medium altitude (1600 – 1900 m.a.s.l) and H = High altitude (above 1900 m.a.s.l).

3.6 Relationships with sustainability

Redundancy analysis and Pearson correlation analysis showed that farm soil erosion, considered as measure of unsustainability, had negative correlations with all measures of biodiversity ($P < 0.001$) (Figure 6), for example with the number of tree and shrub species (r=–0.74; $P < 0.001$). There were also negative correlations between soil erosion and number of landraces per year (r=–0.44; P=<0.001), number of crop selection criteria (r=–0.42; $P < 0.001$), numbers of crops planted in the last six years (r=–0.46; $P < 0.001$), and numbers of farm animals (r=–0.21; $P < 0.01$). This indicates



that erosion was less as farms were more traditional. On the other hand, there was a

Figure 6. A CANOCO redundancy analysis (RDA) plot showing the relationship between diversity and sustainability measures on the one hand, and environmental and management characteristics on the other. The variables contributing to the distinction among regions are displayed as arrows radiating from the centre of the diagram with the length of the arrows representing each variable's contribution to explaining the variation in the sample scores on each axis. Regions stand for study sites shown in figure 1 (P < 0.001; Axis1 Eigenvalue=0.726; Axis2 Eigenvalue=0.093).

positive correlation between soil erosion and fertiliser use (r=0.34; P < 0.001) indicating that erosion increased as crop production practices included the use of more inorganic fertiliser. Soil erosion was negatively correlated with the number of soil fertility classes (P < 0.001), indicating that natural variation in soil fertility, as observed by the farmers, was associated with less erosion. Similar relationships can be gleaned from the redundancy analysis (Figure 6).

4 Discussion and conclusion

In this paper, we documented that there is still considerable biodiversity (with on average 32 tree and shrub species per farm, 16 different crops and 19 landrace crops per farm in the last 6 years) in Tigray, northern Ethiopia. Crop, tree and shrub species diversities were greatest at high altitudes. Although environmental conditions allowed diverse plant growth, diversity in certain farms was much lower than its potential. This corresponds well with results found by Teshome et al. (1999) in north Shewa and South Wello in Ethiopia. The more soil fertility classes found per farmers' field the more diversified were the planted crops. From this relationship, we deduced that diversified crops were growing in a range of soils in order to exploit different soil niches (Altieri, 1994 and 1999).

We also documented that fertiliser use, on average, is still low in Tigray, but on the rise. Crop diversity and inorganic fertiliser use were negatively correlated. The use of inorganic fertiliser was probably one of the reasons for decline of crop diversity in the area. However, Lohar and Rana (1998) indicated that adoption of high input agricultural technologies is not necessarily the main reason for genetic erosion. Not only did the use of inorganic fertiliser have a negative correlation with diversity of crops in farmers' fields, but also factors such as drought, improved seeds imported as food grain by relief agencies and other agricultural policies (Worede, 1991 and 1997). The recurrent droughts in the country forced farmers to eat or sell their landrace seed reserves and therefore replaced landrace seeds by seeds provided by relief agencies, improved seeds provided through extension, and seeds found in the market. Recently Jackson et al. (2007) argued that population growth and rapid spread of international agricultural markets also contribute to the decline of biodiversity at agricultural landscapes and promote expansion of intensive agriculture into semi-natural ecosystems. Various biodiversity measures (plant diversity and associated crops) were also negatively related to the number of credit sources. Farmers with more credit sources were growing less diversified crops because of their preference to grow few high yielding varieties and high market value crops with applications of inorganic fertilisers.

There was a mixed relationship between wealth measures (fertiliser use, credit sources and livestock holding by farmers) and plant diversity. Although fertiliser use and access to credit sources were negatively correlated with biodiversity, the number of animals was positively correlated with biodiversity. Farmers grow diversified crops to satisfy their livestock needs, including straw-providing crops and forage crops of various plant species. This is in contrast with the opinion of Holling et al. (1995) who discussed that dependence of livestock on resource rich patches led to local extinction of many species and contributed to the total extinction of some plant species. In our study area, 'high input' crop production practices contribute more to loss of biodiversity than animal husbandry practices.

The relationship between crop production practices and biodiversity is also clear from our findings that landrace diversity in the farmers' fields increased as the number of farmers' selection criteria increased. The more selection criteria a farmer employs, the more landrace crops he or she must plant to meet all these criteria. Teshome et al. (1999) also indicated a similar relationship between farmers' selection criteria and crop diversity in other parts of Ethiopia. Farmers also grow a range of crops to avoid risks. In case of crop failure, a variety of crops increases the security of obtaining a satisfactory harvest. Farmers are consciously applying a range of selection criteria and choosing a range of land races to meet these criteria (Clawson, 1985; Altieri, 1995; Di Falco et al., 2007; Tsegaye and Berg, 2007). Farmers use both time and space strategically to maintain the genetic variety of the crop plants they grow (Altieri, 1995; Teshome et al., 1999). Interestingly, more crops are planted as more local tree and shrub species are left in the crop fields typical of agroforestry management. The presence of various trees and shrubs in the fields provides microhabitats differing in nutrients, moisture and other resources, which allow different crop varieties to grow simultaneously (Altieri, 1999).

A relationship between number of weed species and insect pests, and plant (tree/shrub) diversity at farm level was also observed. It is not known whether higher numbers of weed species and insect pests increased plant diversity, or higher diversity of plants increased number of weed species and insect pests in the farmers' fields, or whether the relationship was coincidental. Spahillari et al. (1999) indicated that weeds are indicators of biodiversity and the origin of land races of crops that they accompany.

Soil erosion, considered as a measure of unsustainability, was more severe at decreasing plant diversity and increasing fertiliser use in farmers' fields. The presence of less plant diversity exposes farms to soil erosion and thereby low formation and maintenance of soil structure. Reduced retention of moisture and nutrients could be the consequences of high intensity of soil erosion (Powers et al., 1998; Noordwijk and Swift, 1999; Bayu, et al., 2006).

Finally, spatial analysis showed that biodiversity (plant and crop diversity) was negatively influenced by the proximity to urban areas and roads, as new agricultural technologies can easily be practiced and adopted in farms easily accessible from roads and urban areas. Moreover, tree cutting and fire wood collections in close proximity to urban areas and roads may contribute to a reduction in biodiversity in agricultural landscapes. A land use land cover (LULC) study in the same area also indicates that intensive agriculture, associated with less biodiversity, has expanded mainly along roads and in close proximity to urban areas in recent decades (Hadgu et al., 2008; unpublished).

Sustainable agriculture depends on the existing biodiversity in agricultural landscapes associated with indigenous farming practices. Positive relations of biodiversity in agricultural landscapes with livestock holding and farmers' crop selection criteria, and negative relations with access to credit, fertiliser use and proximity to urban areas and roads suggest that biodiversity (crop and associated plant diversity) is reduced as farmers change from traditional farming systems to intensive modern farming systems. Agricultural technology packages including inorganic fertiliser and high yielding crop varieties are of paramount importance to increase the agricultural productivity to feed the ever-increasing population in the country. However, they are usually associated with a removal of landrace crops and native plants (tree/shrub) and thereby contribute to biodiversity loss. Therefore, agricultural development and biodiversity conservation should be balanced, and any agricultural development in the area should be integrated with conservation efforts. Furthermore, efforts should be made to improve the yield level of land races. Conservation of landraces is important, but landrace conservation alone cannot secure proper maintenance of biodiversity. It is also important to conserve biodiversity by considering the role of farmers' crop selection criteria in generating and maintaining crop diversity. Cultural and social values of conserving biodiversity should be given attention in order to maintain the present cultivated crops and their associated plant (tree/shrub) species.

5 Acknowledgement

We are indebted to the farmers of Tigray for sharing their farming practices and their knowledge of field crops, trees and shrubs with us. We are grateful to the LIAC – Larestein International Agricultural College, the Biological Farming Systems Group of Wageningen UR, the International Institute of Tropical Agriculture (IITA Lucas Brader Fellowship) and the Student Chaplaincy of Wageningen UR, The Netherlands, for sponsoring this study. The study was carried out in one of the research areas of the Sustainable Use of Natural Resources in Rural Systems of Eastern African Drylands (SUNRISE) project. We thank the SUNRISE project (EC contract ERBIC18 CT97 0139) for giving useful materials and help.

References

Altieri, M.A., 1994. The ecological role of biodiversity in agriculture. In: Altieri, M.A. (Ed.), Biodiversity and pest management in agroecosystems. Hayworth Press, New York, pp. 3 – 9.

Altieri, M.A., 1995. Traditional agriculture. In: Altieri, M.A. (Ed.), Agroecology: the science of sustainable agriculture. Westview Press, Boulder, pp.107 – 144.

Altieri, M.A., 1999. The ecological role of biodiversity in agroecosytems. Agric. Ecosyst. Environ. 74, 19 – 31.

Asefa, D. T., Oba, G., Weladji, R.B., Colman, J.E., 2003. An assessment of restoration of biodiversity in degraded high mountain lands in northern Ethiopia. Land Degrad. Develop. 14, 25 – 38.

Bayu, W., Rethman, N. F. G., Hammes, P. S., Alemu, G., 2006. Application of farmyard manure improved the chemical and physical properties of the soil in a semi-arid area in Ethiopia. Biol. Agric.Hortic. 24, 293 – 300.

Casson, B., Delacourt, C., Baratoux, D., Allemand. P., 2003. Seventeen years of the "La Clapière" landslide evolution analysed from ortho-rectified aerial photographs. Eng. Geol. 68, 123 – 139.

Chambers, R., 1983. Rural Development: Putting the Last First. Longman Inc., Longman, London.

Clawson, D. L., 1985. Harvest security and intraspecific diversity in traditional agriculture. Econ. Bot. 39, 56 – 67.

Di Falco, S., Chavas, J.P., Smale, M., 2007. Farmer management of production risk on degraded lands: the role of wheat variety diversity in the Tigray region, Ethiopia. Agric. Econ. 36, 147 – 156.

Dragan, M., Feoli, E., Fernetti, M., Zerihun, W., 2003. Application of a spatial decision support system (SDSS) to reduce soil erosion in northern Ethiopia. Environ. Model. Softw. 18, 861 – 868.

Durán, V., Rodríguez, C., 2008. Soil-erosion and runoff prevention by plant covers. A review. Agron. Sustain. Dev. 28, 65 – 86.

Edwards, S., Tadesse, M., Demissew, S., Hedberg, I., 2000. Flora of Ethiopia and Eritrea. Addis Ababa University, Addis Ababa.

Francis, C.A., 1986. Distribution and importance of multiple cropping. In: Francis, C.A. (Ed.), Multiple Cropping Systems. MacMillan, New York, pp. 1 – 19.

Frankel, O.H., 1974. Genetic conservation: Our evolutionary responsibility. Genet. 78, 53 – 65.

Gebremedhin, B., Swinton, S.M., 2003. Investment of soil conservation in northern Ethiopia: the role of land tenure security and public programs. Agric. Econ. 29, 69 – 84.

Greenland, D.J., 1994. Soil science and sustainable land management. In: Seyers, J.K., Rimmer, D.L. (Eds.), Soil Science and Sustainable Land Management in the Tropics. CAB International, Wallingford, pp. 1 – 15.

Hartemink, A.E., 1998. Soil chemical and physical properties as indicators of sustainable land management under sugar cane in Papua New Guinea. Geoderma. 85, 283 – 306.

Hawbaker, T.J., Radeloff, V.C., Hammer, R.B., Clayton, M.K., 2004. Road density and landscape pattern in relation to housing density, land ownership, land cover, and soils. Landscape Ecol. 20, 609 – 625.

Hawkes, J.G., 1983. The diversity of crop plants. Harvard University Press, Cambridge.

Holling, C.S, Schindler, D.W., Brain, W.W., Roughgarden, J., 1995. Biodiversity in the functioning of ecosystems: an ecological synthesis. In: Perrings, C., Mäler , K.-G., Folke, C., Holling, C.S., Jansson, B.-O. (Eds.), Biodiversity loss: economic and ecological issues. Cambridge University Press, Cambridge, pp. 44 – 83.

Hölzel, N., Haub, C., Ingelfingert, M.P., Otte, A., Pilipenko, V.N., 2002. The return of the steppe – large-scale restoration of degraded land in southern Russia during the post-Soviet era. J. Nat. Conserv. 10, 75 – 85.

Jackson, L.E., Pascual, U., Hodgkin, T., 2007. Utilizing and conserving agrobiodiversity in agricultural landscapes. Agric. Ecosys. Environ. 121, 196 – 210.

Kawanabe, H., 1996. Linkage between ecological complexity and biodiversity. In: Di Castri, F., Younes, T. (Eds.), Biodiversity, science and development: towards a new partnership. CAB International, Wallingford, pp. 149 – 152.

Lindhult, M.S., Fabos, J., Brown, P., Price, N., 1988. Using geographic information systems to assess conflicts between agriculture and development. Landscape Urban Plan. 16, 333 – 343.

Lohar, D.P., Rana, R.B., 1998. The dichotomy of crop diversity management issues in subsistence and commercial hill farming systems in Nepal. In: Partap, T., Sthapit, B. (Eds.), Managing Agrobiodiversity: Farmer's changing perspectives and institutional responses in the Hindu Kush-Himalayan region, International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, pp. 93 – 101.

Mander, Ü., Mikk, M., Külvik, M., 1999. Ecological and low intensity agriculture as contributors to landscape and biological diversity. Landscape Urban Plan. 46, 169 – 177.

Morschel, J., Fox, D.M., Bruno, J.-F., 2004. Limiting sediment deposition on roadways: topographic controls on vulnerable roads and cost analysis of planting grass buffer strips. Environ. Sci. Policy. 7, 39 – 45.

Oldfield, M.L., Alcorn, J.B., 1987. Conservation of traditional agroecosystems. Bioscience. 37, 199 – 208.

Powers, R.F., Tiarks, A.E., Boyle, J.R., 1998. Assessing soil quality: practicable standards for sustainable forest productivity in the United States. In: Admas, M.B., Ramakrishna, K., Davidson, E.A. (Eds.), The Contribution of Soil Science to the Development and Implementation of Criteria and Indicators of Sustainable Forest Management . Soil Sci. Soc. A. Spec. Pub., Madison, pp. 55 – 80.

Qualset, C.O., McGuire, P.E., Warburton, M.L., 1995. Agrobiodiversity key to agricultural productivity. Genetic Resource Conservation Program. California Agric. 49, 45 – 49.

Ramakrishnan, P.S., 1996. Ecological functions of biodiversity: The human dimension. In: Di Castri, F., Younes, T. (Eds.), Biodiversity, science and development: towards a new partnership. CAB International, Wallingford, pp. 114 – 129.

Rasul, G., Thapa, G.B., 2004. Sustainability of ecological and conventional agricultural systems in Bangladesh: An assessment based on environmental, economic and social perspectives. Agric. Syst. 79, 327 – 351.

Robin, S.R, Russel, L.K, Nyawira, M., Andualem, T., Sara, W., Cathleen, J.W., Woudyalew, M., 2000. Land-use and land-cover dynamics in response to changes in climatic, biological and socio-political forces: the case of South Western Ethiopia. Landscape Ecol. 15, 339 – 355.

SAS Institute, 1999. SAS/STAT User's manual. Volume I. SAS Institute Inc., Cary.

Spahillari, M., Hammer, K., Gladis, T., Diederichsen, A., 1999. Weeds as part of agrobiodiversity. Outlook Agric. 28, 227 – 232.

Stroud, A., Parker, C., 1989. A weed identification guide for Ethiopia. Food and Agriculture Organization of the United Nations (FAO), Rome.

Ter Braak, C.J.F., Smilauer, P., 2002. CANOCO Reference manual and CanoDraw for Windows User's guide: Software for Canonical Community Ordination (version 4.5). Microcomputer Power, New York.

Teshome, A., Fahrig, L., Torrance, J. K., Lambert, J. D., Arnason, T.J., Baum, B.R., 1999. Maintenance of sorghum (*Sorghum bicolor*, Poaceae) landrace diversity by farmers' selection in Ethiopia. Econ. Bot. 53, 79 – 88.

Tsegaye, B., Berg, T., 2007. Utilization of durum wheat landraces in East Shewa, central Ethiopia: Are home uses an incentive for on-farm conservation? Agric.Hum. Values. 24, 219 – 230.

Wood, D., Lenné, J.M., 1999. Why Agrobiodiversity? In: Wood, D., Lenné, J.M. (Eds.), Agrobiodiversity: Characterization, Utilization and Management. CABI publishing, Wallington, pp. 1 – 13.

Worede, M., 1991. An Ethiopian perspective on conservation and utilization of plant genetic resources. In: Engels, J.M.M, Hawkes, J.G., Worede, M. (Eds.), Plant Genetic Resources of Ethiopia. Cambridge University Press, Cambridge, pp. 3 – 19.

Worede, M., 1997. Ethiopian in situ conservation. In: Maxted, N., Ford-lloyd, B.V., Hawkes, J.G. (Eds.), Plant Genetic Conservation: the in situ approach. Chapman and Hall, London, pp. 290 – 301.

Vavilov, N.I. 1951. The origin, variation, immunity, and breeding of cultivated plants. Selected Writings of N.I. Vavilov. Chronica Botanica, London.

Chapter 4

Spatial variation in biodiversity, soil degradation and productivity in agricultural landscapes in the highlands of Tigray, northern Ethiopia

K.M. Hadgu[a,b,c], W.A.H. Rossing[b], L. Kooistra[c] and A.H.C. van Bruggen[b]

[a] Faculty of Natural Resources and Agriculture , Mekelle University, P.O. Box 231, Mekelle, Tigray, Ethiopia.
[b] Biological Farming Systems, Department of Plant Sciences, Wageningen University, Marijkeweg 22, 6709 PG Wageningen, The Netherlands
[c] Laboratory for Geo-information and Remote Sensing, Department of Environmental Sciences, Wageningen University, Droevendaalsesteeg 3, 6708 PB Wageningen, The Netherlands

(Submitted to Food Security)

Abstract

There is a growing concern about food security and sustainability of agricultural production in developing countries. However, there are limited attempts to quantify agro-biodiversity losses and relate these losses to soil degradation and crop productivity, particularly in Tigray, Ethiopia. In this study, spatial variation in agro-biodiversity and soil degradation was assessed in 2000 and 2005 at 151 farms in relation to farm, productivity, wealth, social, developmental and topographic characteristics in Tigray, northern Ethiopia. A significant decrease in agro-biodiversity was documented between 2000 and 2005, mainly associated with inorganic fertilizer use, number of credit sources and proximity to towns and major roads. Agro-biodiversity was higher at farms with higher soil fertility (available P and total N) and higher productivity (total caloric crop yield). Low soil organic matter, few crop selection criteria, and steep slopes contributed to soil erosion, and severe soil erosion was associated with a large number of insect pests. Sparsely and intensively cultivated land use types, as determined from satellite images, were associated with high and low agro-biodiversity classes as determined during on-farm surveys in 2005. This study gives insight in the status of and recent changes in agro-biodiversity and soil degradation at different spatial scales, which can help to improve food security through the maintenance of agro-biodiversity resources.

Keywords: Biodiversity; GIS; productivity; soil degradation; spatial-scale.

1 Introduction

Population growth, environmental change, increasing food demands and globalization of agricultural markets are adversely affecting agro-biodiversity and ecosystem functions (MEA, 2005; Mooney et al., 2005). Land use change is exerting the largest impact on agro-biodiversity loss (Chapin III et al., 2000). There is especially concern about the loss of agro-biodiversity as a result of changes in land use affecting the sustainability of agricultural production and food security in the tropics (Thrupp, 2000). Here we focus on sustainable use and conservation of biodiversity in agricultural landscapes in Ethiopia.

Biodiversity in agricultural landscapes provides ecosystem services which can contribute to the improvement of agricultural productivity (McNeely and Scherr, 2003; MEA, 2005). These ecosystem services include: yield improvement by intercropping (Vandermeer et al., 2002) and mixed cropping (Zhu et al., 2000), and soil fertility enrichment (e.g. soil Nitrogen) by permanent plants in agricultural landscapes (Drinkwater et al., 1998). In addition, biodiversity provides insurance to agricultural production by increasing resilience and minimizing risk of crop failure (Swift et al., 2004; Tscharntke et al., 2005). However, expansion and intensification of agricultural land threaten biodiversity (Tilman et al., 2001; Tscharntke et al., 2005). The loss of biodiversity in agricultural landscapes is exacerbated by the loss of traditional farming practices in the tropics (Thrupp, 2000). These changes are usually accompanied by agricultural land use intensification including removal of trees and shrubs, use of inorganic fertilizer, a shift to few high yielding crop varieties, and the use of pesticides (MEA, 2005; Mooney et al., 2005).

In Ethiopia where agriculture is based on smallholder farming systems, increased food demand, mainly due to increasing population density, is playing a key role in the conversion of natural habitats to agricultural land (Hadgu et al., 2008b). The consequence of expanding land use for agriculture is increased vulnerability of rural landscapes from which poor farmers directly derive ecosystem services (WRI, 2005). However, there have been few attempts to explore agro-biodiversity losses and explain these losses from topographic, farm, and farmer characteristics. Local decision makers have not paid much attention to biodiversity conservation either, possibly due to a lack of awareness of the magnitude of the problem and the pressure to give more attention to immediate crises: increasing food demand in response to population increase and globalization of agricultural markets.

A recent analysis of spatially explicit land use/land cover changes showed that road networks and settlement expansions were the major drivers for large reductions in natural habitats, mainly at locations with steep slopes in the highlands of Tigray, northern Ethiopia, between 1964 and 2005 (Hadgu et al., 2008b). In the same study period, an increase in agricultural land was observed mainly because of increasing human population. Furthermore, increased access to credit and higher inorganic fertiliser use, especially at farms located close to urban areas and major roads was associated with the decrease in agro-biodiversity, which in turn was positively associated with soil erosion in Tigray, in 2000 (Hadgu et al., 2008a). A higher number of soil types per farm, higher farm altitude, larger number of planted crop types per farm, number of crop selection criteria per farm and number of livestock units per farm were associated with increased agro-biodiversity and decreased soil erosion (Hadgu et al., 2008a). Moreover, field measurements in part of the same study area in 2005 showed that crop productivity and soil moisture contents were higher at field locations close to *A. albida* tree trunks compared to locations outside the tree canopy for different *A. albida*-based land use systems (Hadgu et al., 2008c). This indicates that the presence of trees contributes to crop productivity at the prevailing production levels, and challenges policies promoting the reliance on external inputs.

In this study, we compared the spatial variation in agro-biodiversity and soil degradation in agricultural landscapes in Tigray in 2000 and 2005. Our operational definition of agro-biodiversity is the sum of the number of tree- or shrub species per farm (tree/shrub diversity) and the number of land races per farm (crop diversity). Soil degradation is estimated as visible soil erosion (Hadgu et al., 2008a). Based on our previous studies in this region (Hadgu et al., 2008a, 2008b, 2008c), we hypothesize that agro-biodiversity and crop productivity have declined in recent years, while soil erosion has increased. To test these hypotheses, on-farm surveys were conducted in 2005, and the data were as much as possible compared with similar data collected in 2000 (Hadgu et al., 2008a). The specific aims of the study were to assess changes in spatial agro-biodiversity and soil degradation in relation to farm characteristics, wealth characteristics, social characteristics, development indicators and topographic characteristics. The ultimate aim of this study was to enhance our understanding of the drivers of agricultural intensification and associated loss of agro-biodiversity, to relate agro-biodiversity to agricultural productivity, and to provide recommendations for local policy makers on approaches to integrate biodiversity conservation and the promotion of sustainable agriculture.

2 Materials and methods

2.1 Study area

The study was carried out in the highlands of Tigray in northern Ethiopia (Figure 1). The study area (4° 82’ – 5° 10’ N and 15° 66’ – 15° 28’ E) is located South-East of the

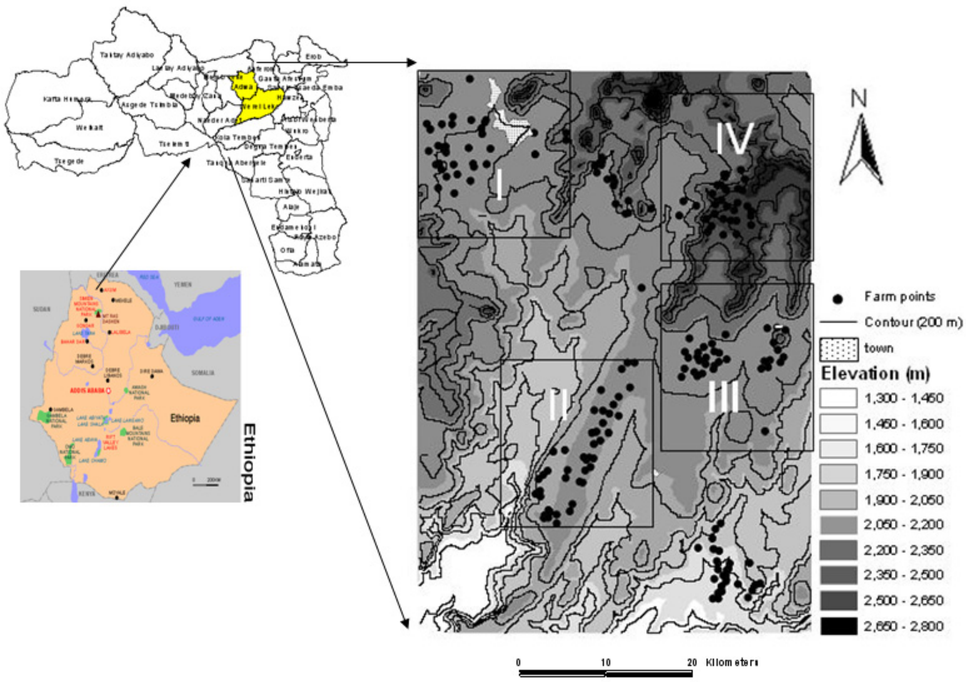


Figure 1. Elevation map of the study area in Tigray, northern Ethiopia, indicating the location of selected farms in regions I – IV.

town of Adwa and covers an area of about 30 by 40 km at an elevation of 1300 – 2800 meters above sea level (m.a.s.l.). The climate of the area is semi-arid, with two rainy seasons, the main season starting in late June and lasting until September, and a minor season between March and April. The average annual rainfall ranges from 740 mm at 1500 m.a.s.l. to 900 mm at 2000 m.a.s.l. (Deurloo and Haileselassie, 1994). Wide variation in rainfall from year to year is characteristic for the study area. Soils are categorized as Cambisols, Fluvisols, Xerosols, Vertisols and Luvisols (Sarraute and Vonder, 1994). The study area is considered as one of the most densely populated areas in Ethiopia (Feoli et al., 2002). Land use within the area consists of four dominant classes: woodland, shrub land, scrubland and agricultural land (Hadgu et al., 2008b). The typical agricultural practice in the study area is a mixed crop-livestock small holder farming system. Within this farming system different degrees of agricultural intensification can be identified ranging from sparsely cultivated (Scu) to intensively cultivated (Icu) areas (Table 1) (Hadgu et al., 2008b).

Out of five regions surveyed in 2000 (Hadgu et al., 2008a), four regions (I – IV; Figure 1) were revisited in 2005, using latitude and longitude data collected with a hand held Global Positioning System (GPS) (GARMIN International Inc., Kansas) in

Table 1. Agricultural land use types for the study area in Tigray, northern Ethiopia.

Land use type	Description
Sparsely cultivated land (SCu)	Between 20 and 40% of the mapping unit is under cultivation while the remaining area is covered by trees, shrubs, grasses or herbs.
Moderately cultivated land (MCu)	Between 40 and 70% of the mapping unit is under annual and perennial crop while the remaining area is covered by trees, shrubs, grasses or herbs.
Intensively cultivated land (ICu)	Over 70% of the land is under annual and perennial crops while the remaining area is covered by trees, shrubs, grasses or herbs.

2000. The area that was left out in 2005 concerned a lowland region with a relatively different farm management. Elevation in the four regions ranges from intermediate altitude (1600 – 1900 m.a.s.l.) to high altitude (>1900 m.a.s.l.). Selection of the four regions was based on a land use map derived from remote sensing data (Hadgu et al., 2008b) and an elevation map of the study area created from a Digital Elevation Model (DEM) which in turn was generated from the Shuttle Radar Topographic Mission (SRTM) (USGS, Sioux Falls, SD). This resulted in regions with the following characteristics:

Region I: Area with pure agriculture: intensively cultivated (with few or no trees or shrubs) located close to the town of Adwa at 1900 – 2200 m.a.s.l.

Region II: Agriculture-dominated area: intensively (with no or few trees/shrubs) or moderately cultivated (with moderate numbers of trees/shrubs), located at 1600 – 1900 m.a.s.l. Natural vegetation and agriculture in this region co-exist but the latter is dominant.

Region III: Natural vegetation dominated area: both natural vegetation and agriculture (moderately cultivated) are present but natural vegetation is dominating in the area, located at 1900 – 2200 m.a.s.l.

Region IV: Natural habitats: almost completely covered by natural vegetation with limited agricultural activities (sparsely cultivated), located above 2200 m.a.s.l.

2.2 Dataset and study approach

Data were collected by a combination of field measurements, farm surveys and GIS analyses to explore the changes in spatial variation in agro-biodiversity and soil degradation between 2000 and 2005 in agricultural landscapes in Tigray, northern Ethiopia.

2.2.1 Field measurement and survey datasets

In the four regions (Figure 1), 151 farms were revisited in 2005 by locating their exact geographic coordinates using the GOTO function of the hand held GPS. Farmers were interviewed based on a questionnaire and their fields were crossed two to three times to identify trees and shrubs and to record the number of tree/shrub species in and around agricultural fields. In case plants could not be identified on the spot, samples of trees and shrubs were collected and the species were identified according to the flora of Ethiopia and Eritrea (Edwards et al., 2000). Besides, farmers were asked about the number of planted crops, cultivars and landraces.

Agro-biodiversity was considered to have two components: tree/shrub diversity, which was quantified as the number of different species of trees and shrubs found in and around each field, and crop diversity, which was measured as the number of distinct crop landraces. Each landrace has a limited range of genetic variation, is adapted to local agroclimatic conditions and has been generated, selected, named and maintained by traditional farmers over many generations (Hadgu et al., 2008a).

Farm characteristics included soil quality (a subjective score by the farmer in 2000, and measured organic matter (OM) content (%), total N (%) and available P (mg kg^{-1}) in 2005), number of crops planted per year (number $farm^{-1}$), animal manure use (kg ha^{-1}), weed species encountered in the farm (counted together with farmers) (number $farm^{-1}$) and insect pests as stated by the farmers (number $farm^{-1}$). In addition, farmers were asked which of the following criteria they used to select land races or cultivars (crop selection criteria – number $farm^{-1}$): yield, insect resistance, weed resistance, market value, early maturity, drought resistance, thresh-ability, beverage quality and straw quality.

Caloric yield was not measured in 2000. In 2005, it was estimated as the yield of all crops harvested per farm multiplied by their caloric content (Mcal $farm^{-1}$) in 2005. Yields of the various crops per unit area were not available, as many crops were planted as mixtures. Yield of each crop type per farm was estimated by counting the number of standard sacks (1 quintal) with harvestable product per farm. Total grain weights were estimated from the total volume (number of sacks per farm) and were multiplied by the default caloric content of each crop (Borlaug, 1996; FAO, 2003). The caloric values for all crops were added and expressed as Megacalorie per farm (Mcal $farm^{-1}$). The major crop types in the study area were: tef (*Eragrostis tef*) (1.11 kcal g^{-1}), barley (*Hordeum vulgaris*) (3.90 kcal g^{-1}), wheat (*Triticum* spp.) (3.85 kcal g^{-1}), maize (*Zea mays*) (3.97 kcal g^{-1}), sorghum (*Sorghum bicolor*) (3.97 kcal g^{-1}), finger millet (*Eleusine coracana*) (3.94 kcal g^{-1}), faba bean (*Vicia faba*) (4.07 kcal g^{-1}) and chickpea (*Cicer arietinum*) (4.07 kcal g^{-1}) (Borlaug, 1996; FAO, 2003).

The wealth of each farm household was assessed by inorganic fertiliser use (kg ha^{-1}) and number of credit sources, including *Dedebit* - a local micro finance institution, local money lenders and/or relatives. Monetary income could not be included, because most farmers produce primarily for home consumption. The number of credit sources (number $farm^{-1}$) was considered a wealth characteristic because most farmers depend on credit to buy inorganic fertiliser and return their loan in a year. Resource poor farmers usually face difficulty in repaying their credit in case of crop failure, whereas rich farmers with more credit sources have possibilities to repay their loans even in the case of crop failure. Livestock holding (number of animals $farm^{-1}$) was considered as wealth characteristic because animals provide status in the community and are used as dowry for the bridegroom's family. Employment opportunities were estimated by asking about the number of family members with fulltime or part-time employment outside the farm (number $farm^{-1}$) and the level of education of the family (at least primary school - number $farm^{-1}$).

Farm distance from the nearest town (km) and major road (km) were considered as development drivers. These distances were determined as described under 2.2.4. Finally, farm elevation (m) and slope (%) were included as topographic characteristics.

2.2.2 Laboratory analysis

From the 0 – 15 cm plough layer, 4 soil samples (1 kg $sample^{-1}$) from different field locations were collected at each of the 151 farms, pooled per farm and stored in sealed and labeled plastic bags. The collected soil samples were sieved through a 2 mm mesh, air dried and analyzed according to the methods described in MoNRDEP (1990). Total nitrogen content (%) was determined using the Kjeldahl method. The Walkley and Black method was used to determine the organic matter content (%) and available phosphorus was determined by the Olsen method (mg kg^{-1}).

2.2.3 Soil erosion calculation

In 2000, soil erosion was estimated by visual classification (Hadgu et al., 2008a). In 2005, soil erosion was estimated for the 151 farm plots using the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) which was modified to suit Ethiopian conditions by Hurni (1985). The USLE equation is an empirical expression which estimates mean annual soil loss in tons per hectare per year based on rainfall amount and intensity, soil erodibility, slope length, slope steepness, crop management and erosion control practice. Based on calculated soil erosion results for 2005 and visual observations for 2000, soil erosion severity was categorized into four classes: low (<10 ton ha^{-1}), moderate (10 – 20 ton ha^{-1}), high (20 – 30 ton ha^{-1}) and extremely high (>40 ton ha^{-1}).

2.2.4 GIS analysis

An elevation map and buffer maps of towns and roads were overlaid with farm location maps of 2000 and 2005. To produce elevation, slope and contour maps of the study area, the Digital Elevation Model (DEM) from Shuttle Radar Topographic Mission (SRTM) (USGS, Sioux Falls, SD) was used. Spatial data of towns and roads were derived from aerial photographs and topographic maps (Ethiopian Mapping Agency, Addis Abeba) that were converted to digital format as described previously (Hadgu et al., 2008b). Each aerial photograph was geo-referenced with points from 1:50,000 topographic maps and known ground control points (crossing of roads and river junctions) collected from the field with a hand-held GPS. Each geo-referenced photograph was ortho-rectified as described before (Hadgu et al., 2008b). Town and road features were delineated from the ortho-rectified aerial photographs using the on-screen digitization technique. The location of each surveyed farm was recorded with a hand-held GPS. All town, road and farm point features were projected onto the Universal Transverse Mercator (UTM) system, zone 37, Adindan. Distances to the nearest town and major road were calculated by the buffering spatial analysis method in ArcGIS 9.2 (ESRI, Redlands, CA, USA). Proximity of farms to buffered towns and roads was calculated by overlaying the farm point map with the buffered town and road maps. Finally, the farm point map was also overlaid with the elevation map of the study areas.

Land use types for 2005 (Table 1) derived from the Landsat Enhanced Thematic Mapper Plus (ETM+) satellite image were overlaid and intersected with the location map of biodiversity classes using ArcGIS 9.2 (Hadgu et al., 2008b).

2.3 Statistical analysis

The data collected from field measurements, farm surveys and GIS analyses were analysed using SAS (SAS, 1999). All the datasets including farm and wealth characteristics, crop productivity, topography, development drivers, social characteristics, agro-biodiversity, and soil erosion were analyzed for each year (2000 and 2005) separately and by comparing the two years. An analysis of the data of 2000 has been reported elsewhere (Hadgu et al., 2008a). Here we focus on 2005 and the comparison between 2000 and 2005. The data of 2005 were subjected to chi-square tests to evaluate whether social characteristics (farmer's education and employment opportunities) were associated with agro-biodiversity and soil erosion in 2005.

After transforming all data to lognormal values, discriminant analyses were carried out to relate various environmental variables to agro-biodiversity and soil erosion. Agro-biodiversity and soil erosion were first categorized into classes. Based on the number of species or landraces per farm, agro-biodiversity was classified as low (< 7), medium (7 – 12) or high (>12), 33% of the data fitting in each class. Similarly, soil erosion severity was grouped into four classes: low (<10 ton ha^{-1}), moderate (10 – 20 ton ha^{-1}), high (20 – 40 ton ha^{-1}) and very high (>40 ton ha^{-1}) soil erosion. Discriminant analysis was then carried out to determine if farms with different agro-biodiversity levels (3 classes) could be distinguished on the basis of farm, wealth, productivity, development and topographic characteristics. In addition to these characteristics, tree/shrub diversity and crop diversity were used as explanatory variables in a discriminant analysis of soil erosion (4 classes).

To determine if the status of farms and farmers had changed over time, paired *t*-tests were carried out to compare farm, wealth and social characteristics between 2000 and 2005. For a spatial analysis of the changes in agro-biodiversity and soil erosion between 2000 and 2005, the differences in agro-biodiversity and soil erosion between the years were grouped into three classes: decrease, no change and increase between 2000 and 2005. Discriminant analyses were carried out to see whether farm, wealth, development and topographic characteristics contributed to the separation between farms in the different change classes.

All log-normal transformed data were first subjected to stepwise discriminant (STEPDISC) analysis to select the classification variables that best discriminated among the different agro-biodiversity and soil erosion classes. Next, canonical discriminant analysis (CANDISC) was used to derive discriminant functions which determined if the distinctions among the classes were statistically significant and which variables contributed significantly to these functions. The thresholds (T) for the selection of variables correlating significantly to discriminant function1 were taken as $T = 0.6 / \sqrt{(eigenvalue)}$ for the analysis with agro-biodiversity as class variable, and $T = 0.2 / \sqrt{(eigenvalue)}$ for the other discriminant analyses (Afifi and Clark, 1984). The choice of these thresholds resulted in similar variables selected by the canonical discriminant and the stepwise discriminant analyses.

3 Results

3.1 Status of agro-biodiversity and soil degradation in 2005

3.1.1 Status of agro-biodiversity

Agro-biodiversity in relation to social characteristics

Chi-square tests revealed that more off-farm employment opportunities were associated with a higher agro-biodiversity class (low, medium and high) in 2005 (χ^2 = 30.81, DF = 4, P=0.001). However, farmer's education was not associated with agro-biodiversity (χ^2 = 7.59, DF = 2, P > 0.05).

Agro-biodiversity in relation to quantitative explanatory variables

The three agro-biodiversity classes (low, medium and high) were significantly separated by the explanatory variables (canonical discriminant analysis, Wilks'Lambda value = 0.08; P < 0.001; Figure 2). The first canonical function was significant (P < 0.001) and accounted for 97% of the total variance. The farm characteristics total N (%), available P (mg kg^{-1}), crop types (number $farm^{-1}$), animal manure (kg ha^{-1}) and crop selection criteria (number $farm^{-1}$) were positively associated with agro-biodiversity in the first canonical function and contributed significantly (P < 0.05) to the separation of the three agro-biodiversity classes (Table 2). Farms in the high agro-biodiversity class had 52% higher available P (mg kg^{-1}), 39% higher total N (%), 47% more crop types (number $farm^{-1}$), 71% higher animal manure use (kg $farm^{-1}$), 53% more animals (number $farm^{-1}$) and 42% more crop selection criteria (number $farm^{-1}$) than farms in the low agro-biodiversity class.

Similarly, caloric crop yield (Mcal $farm^{-1}$), animal ownership (number $farm^{-1}$), farm distance from the nearest town (km) and elevation (m) contributed significantly (P < 0.05) to the discrimination among the agro-biodiversity classes and were positively associated with the first canonical function (Table 2). Compared with farms in the low agro-biodiversity class, those in the high agro-biodiversity class had 19% higher total caloric crop yield (Mcal $farm^{-1}$), especially in farms located at high elevation and far from the nearest town (Table 2).

Wealth characteristics, inorganic fertilizer use (kg $farm^{-1}$) and credit sources (number $farm^{-1}$), were negatively associated with the first canonical function but contributed significantly to the distinction among the three agro-biodiversity classes (Table 2). The inorganic fertilizer use (kg $farm^{-1}$) and access to credit sources (number $farm^{-1}$) were 65 and 74% lower, respectively, for farms in the high compared to the low agro-biodiversity class.

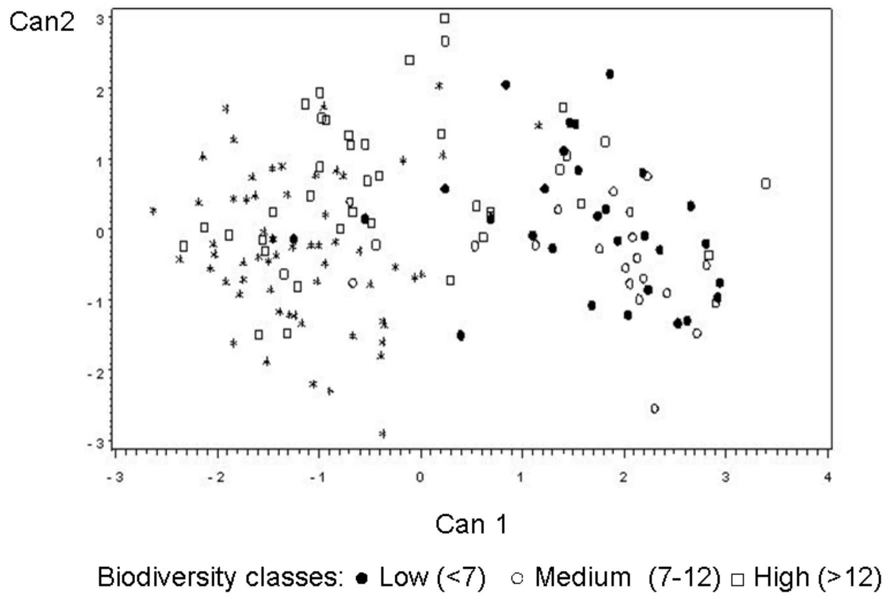


Figure 2. First and second canonical function from canonical discriminant analysis separating biodiversity classes (number of tree/shrub species and number of crop varieties) in 2005 in Tigray, northern Ethiopia.

Agro-biodiversity and land use types

Farms with low agro-biodiversity were mostly located in areas with (medium) intensively cultivated land use (Figure 3). This was especially true for farms located close to the towns of Adwa and Edaga Arbi. Farms classified in the low agro-biodiversity class hardly fell in the sparsely cultivated land use class. Sparsely cultivated land use coincided mainly with farms in the high agro-biodiversity class, particularly in region IV, located at high elevation (Figure 1) and far from the nearest town and major road. Farms in the medium agro-biodiversity class had a mix of land use types (Figure 3).

3.1.2 Status of soil degradation

Soil degradation in relation to social characteristics

Farms where farmers had more off-farm employment opportunities fell in higher soil erosion classes than farms where farmers had limited employment opportunities (χ^2 = 20.60, DF = 8, P < 0.05). No significance association was revealed between soil erosion classes and farm family education (χ^2 = 8.44, DF = 4, P > 0.05).

Table 2. Variables significantly contributing to the separation between biodiversity classes (low, medium and high) in 2005.

Classification variable	Pooled within standardized oefficients	Mean values of characteristics per biodiversity class		
	Canonical function 1	Low (n=74)	Medium (n=27)	High (n=50)
Crop types (number $farm^{-1}$) [*] [a]	0.51	3.2 (±0.1)	4.2 (±0.2)	5.9 (±0.1)
Crop selection criteria (number $farm^{-1}$) [*]	0.36	3.9 (±0.1)	5.8 (±0.2)	6.7 (±0.2)
Caloric crop yield (Mcal $farm^{-1}$) [*] [b]	0.29	6106.7 (±68.2)	6859.7 (±115.9)	7497.1 (±139.6)
Weed species (number $farm^{-1}$)	–0.15	4.5 (±0.1)	3.6 (±0.2)	3.5 (±0.2)
Insect pest species (number $farm^{-1}$)	–0.19	2.6 (±0.1)	2.2 (±0.2)	1.8 (±0.1)
Available soil P (mg kg^{-1})[*]	0.27	12.2 (±0.6)	19.7 (±1.9)	25.4 (±1.2)
Soil organic matter (%)	0.20	1.8 (±0.1)	2.3 (±0.2)	3.4 (±0.2)
Total soil N (%) [*]	0.25	0.2 (±0.01)	0.2 (±0.01)	0.3 (±0.01)
Animal manure (kg $farm^{-1}$) [*]	0.49	266.9 (±20.7)	557.4 (±39.8)	922.0 (±32.8)
Inorganic fertilizer (kg $farm^{-1}$) [*]	–0.36	79.4 (±4.0)	50.9 (±5.7)	24.7 (±4.2)
Animals (number $farm^{-1}$) [*]	0.38	12.7 (±0.7)	23.2 (±1.2)	27.1 (±0.8)
Credit sources (number $farm^{-1}$) [*]	–0.33	2.1 (±0.04)	1.9 (±0.09)	1.2 (±0.06)
Slope (%)	–0.04	5.2 (±0.8)	6.3 (±1.4)	3.4 (±0.5)
Elevation (m) [*]	0.21	1990.7 (±4.1)	2069.3 (±25.8)	2121.0 (±18.1)
Town distance (km) [*]	0.26	4.2 (±0.3)	7.9 (±0.8)	10.2 (±0.6)
Road distance (km)	0.18	2.7 (±0.4)	4.8 (±0.6)	6.0 (±0.4)

[a] [*] $P < 0.05$; Threshold = 0.6/√ (8.749) = 0.203.

[b] The trend in calories yields in different biodiversity classes was similar for all crops except for maize, which had a caloric yield of 814.0, 712.3 and 407.0 Mcal $farm^{-1}$ on farms with low, medium and high biodiversity, respectively, partially due to the larger number of maize plants on low-biodiversity farms. Each farm has 1 ha land.

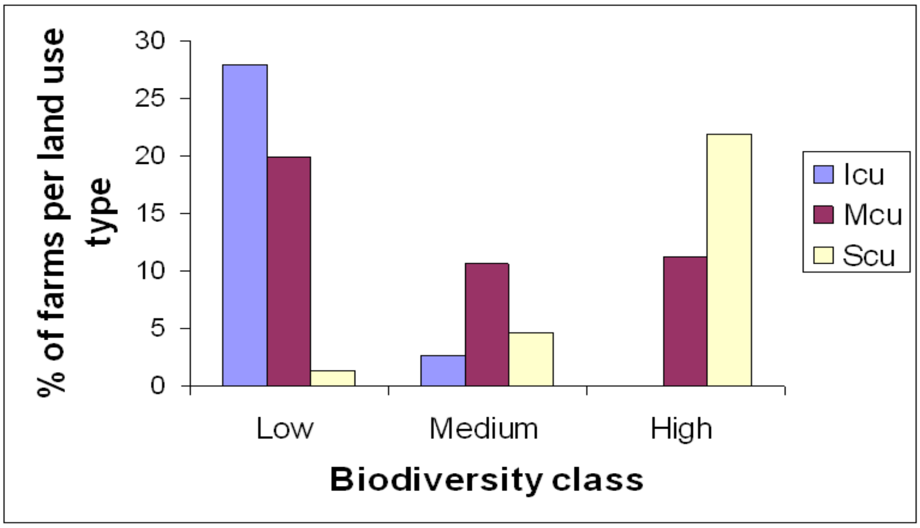


Figure 3. Relation between biodiversity classes and agricultural land use types for selected farms (n = 151) in the Tigray study area in northern Ethiopia. Land use types: Scu = Sparsely cultivated; Mcu = Moderately cultivated; Icu = Intensively cultivated.

Soil degradation in relation to quantitative explanatory variables

The explanatory variables (farm and topographic characteristics) significantly distinguished two groups among the four soil erosion classes, namely low and medium versus high and extremely high soil erosion (canonical discriminant analysis, Wilks' Lambda value = 0.30; $P < 0.001$; Figure 4). The first canonical function of the discriminant analysis was significant ($P < 0.001$) and explained 84.29% of the variance. Insect pest species (number farm^{-1}) and farm slope (%) were positively associated with the first canonical function and contributed significantly ($P < 0.001$) to the discrimination among the soil erosion groups (Table 3). The higher the slope (%) of farms, the higher was the soil erosion severity at those farms, and the more severe the soil erosion, the larger was the number of insect pest species (number farm^{-1}).

The farm characteristics soil OM content (%) and crop selection criteria (number farm^{-1}) were negatively associated with the first canonical function, which significantly ($P < 0.001$) separated the soil erosion classes (Table 3). This indicated that there was less soil erosion on farms with a higher soil OM content (%) and number of crop selection criteria (number farm^{-1}) (Table 2).

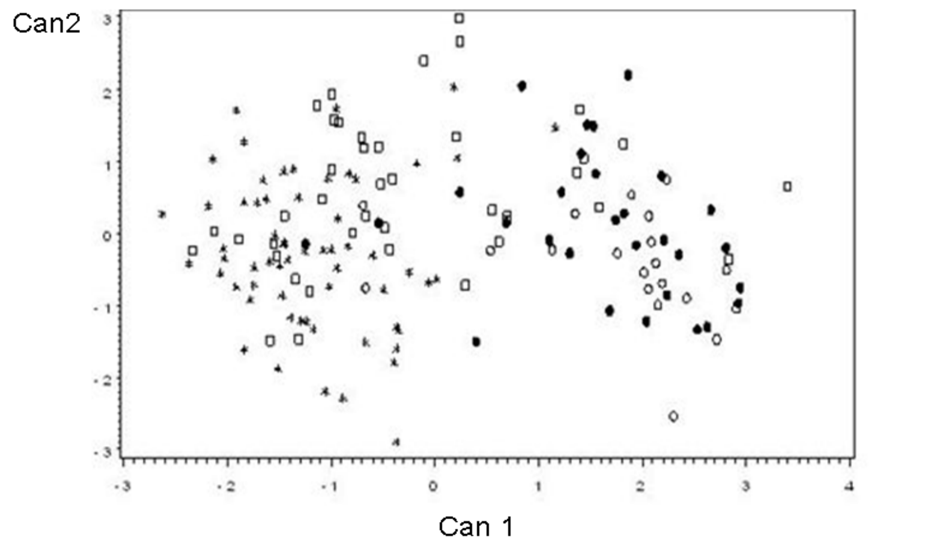


Figure 4. First and second canonical functions from canonical discriminant analysis separating soil erosion classes in 2005 in Tigray, northern Ethiopia.

3.2 Temporal change between 2000 and 2005

3.2.1 Changes in farm and wealth characteristics

Between 2000 and 2005, crop diversity (number farm^{-1}) (paired *t*-test, $t = 6.46$, $P < 0.001$, n=151), animal ownership (number farm^{-1}) (paired *t*-test, $t = 4.23$, $P < 0.001$, n=151) and crop selection criteria (number farm^{-1}) (paired *t*-test, $t = 2.05$, $P < 0.05$, n=151) decreased significantly (Table 4). Inorganic fertilizer use (kg farm^{-1}) increased significantly (paired *t* - test, $t = -3.40$, $P < 0.01$, n=151) between 2000 and 2005. There was no significant difference ($P > 0.05$) between 2000 and 2005 in the number of tree/shrub species (number farm^{-1}), soil erosion (category), crop types (number farm^{-1}), soil types (number farm^{-1}), credit sources (number farm^{-1}), weed species (number farm^{-1}) and insect pest species (number farm^{-1}).

3.2.2 Agro-biodiversity and soil degradation changes (2000-2005)

Decreases in biodiversity were observed at farms where native species were removed and/or few high-yielding crops were cultivated. Increases in biodiversity occurred only when farms had returned to the use of a variety of landraces. Biodiversity change (decrease, no change or increase) was separated into distinct groups by the explanatory

Table 3. Variables significantly contributing to the separation of the soil erosion classes (low, moderate, high and extremely high) in 2005.

Classification Variable	Pooled within standardized coefficients	Mean values of variables per soil erosion class			
	Canonical function 1	Low (n=29)	Moderate (n=20)	High (n=41)	Extremely high (n=61)
Tree/shrub species (number $farm^{-1}$)	–0.24	11.2 (±0.5)	11.1 (±0.7)	7.4 (±0.6)	5.3 (±0.3)
Crop varieties (number $farm^{-1}$)	–0.25	8.7 (±0.6)	8.4 (±0.6)	5.4 (±0.4)	4.0 (±0.2)
Crop selection criteria (number $farm^{-1}$) *	–0.27	6.5 (±0.3)	6.7 (±.3)	4.9 (±0.2)	4.2 (±0.1)
Caloric crop yield (Mcal $farm^{-1}$)	–0.04	7282.5 (±195.4)	7353.1 (±282.3)	6551.9 (±116.1)	6312.8 (±89.1)
Weed species (number $farm^{-1}$)	0.08	2.0 (±0.2)	3.2 (±0.3)	3.9 (±0.2)	4.5 (±0.1)
Pest species (number $farm^{-1}$) *	0.31	2.0 (±0.2)	1.4 (±0.2)	2.4 (±0.1)	2.5 (±0.1)
Available soil P (mg kg^{-1})	–0.15	23.8 (±1.6)	21.9 (±2.0)	18.6 (±1.6)	13.3 (±0.8)
Soil organic matter (%)*	–0.27	3.2 (±0.3)	3.1 (±0.4)	2.2 (±0.2)	2.0 (±0.1)
Total soil N (%)	–0.16	0.3 (±0.01)	0.3 (±0.02)	0.2 (±0.01)	0.2 (±0.01)
Animal manure (kg $farm^{-1}$)	–0.20	762.1 (±59.1)	835.0 (±67.9)	562.2 (±54.2)	312.3 (±29.2)
Inorganic fertilizer (kg $farm^{-1}$)	0.03	38.3 (±6.2)	22.5 (±7.7)	54.9 (±6.4)	76.6 (±4.2)
Animals (number $farm^{-1}$)	–0.16	25.9 (±1.5)	25.5 (±1.5)	19.6 (±1.2)	14.1 (±0.9)
Credit sources (number $farm^{-1}$)	0.21	1.3 (±0.09)	1.3 (±0.12)	1.7 (±0.07)	2.1 (±0.06)
Slope (%)*	0.29	3.9 (±0.7)	2.4 (±0.7)	5.1 (±0.9)	5.8 (±0.9)
Elevation (m)	–0.21	2128.9 (±24.8)	2098.4 (±29.9)	2038.8 (±17.2)	1998.9 (±6.8)
Town distance (km)	–0.01	10.8 (±0.8)	8.5 (±1.0)	6.3 (±0.7)	4.8 (±0.4)
Road distance (km)	–0.03	6.1 (±0.5)	5.4 (±0.6)	4.7 (±0.5)	2.5 (±0.4)

* $P < 0.05$; Threshold = 0.2/√ (0.5728) = 0.263.

Table 4. Mean and standard deviation of all variables assessed in 2000 and 2005 in the Tigray study area in northern Ethiopia.

Variable	Unit	Mean ± SD	
		2000	2005
Tree/shrub species	number $farm^{-1}$	7.9 (± 3.2)	7.8 (± 3.7)
Crop varieties *[a]	number $farm^{-1}$	7.0 (± 3.0)	5.9 (± 2.9)
Crop types	number $farm^{-1}$	4.5 (± 1.4)	4.5 (± 1.9)
Crop selection criteria *	number $farm^{-1}$	6.4 (± 1.7)	5.2 (± 1.7)
Caloric crop yield	Mcal $farm^{-1}$	[b]	6701.7 (± 969.0)
Weed species	number $farm^{-1}$	3.9 (± 1.2)	4.0 (± 1.3)
Pest species	number $farm^{-1}$	2.2 (± 0.8)	2.2 (± 0.9)
Available soil P	mg kg^{-1}	[b]	17.9 (± 9.5)
Soil OM	%	[b]	2.4 (± 1.4)
Total soil N	%	[b]	0.21 (± 0.1)
Animal manure	kg ha^{-1}	[b]	535.8 (± 354.8)
Soil erosion	category $farm^{-1}$	3.6 (± 1.2)	3.9 (± 1.2)
Inorganic fertilizer *	kg ha^{-1}	36.8 (± 46.0)	49.7 (± 41.1)
Animals *	number $farm^{-1}$	22.4 (± 5.3)	19.4 (± 8.9)
Credit sources	number $farm^{-1}$	1.8 (± 0.6)	1.7 (± 0.6)
Employment	number $farm^{-1}$	[b]	1.3 (± 0.5)
Education	category $farm^{-1}$ (yes=1; no=0)	[b]	0.1 (± 0.3)

[a] * Significantly different between 2000 and 2005.

[b] farm characteristic not acquired in 2000.

variables (canonical discriminant analsysis, Wilks' Lambda value = 0.61; $P < 0.001$; Figure 5). Of the total variance, 95.02% was accounted for by the first canonical function, which was significant ($P < 0.001$). The farm characteristics crop type (number $farm^{-1}$), crop selection criteria (number $farm^{-1}$), and animal ownership (number $farm^{-1}$), and the development drivers farm distance from the nearest town (km) and road (km) significantly contributed ($P < 0.05$; Table 5) to the distinction among agro-biodiversity change classes and were positively associated with the first canonical function (Table 5). This implies that where agro-biodiversity increased, this was associated with an increase in crop types (number $farm^{-1}$), crop selection criteria (number $farm^{-1}$) and animals (number $farm^{-1}$). An increase in agro-biodiversity was also observed on farms located far from the nearest town and major road, mainly in region IV (Figure 1). Inorganic fertilizer use (kg $farm^{-1}$) also contributed significantly ($P < 0.05$; Table 5) to the distinction among agro-biodiversity change classes between

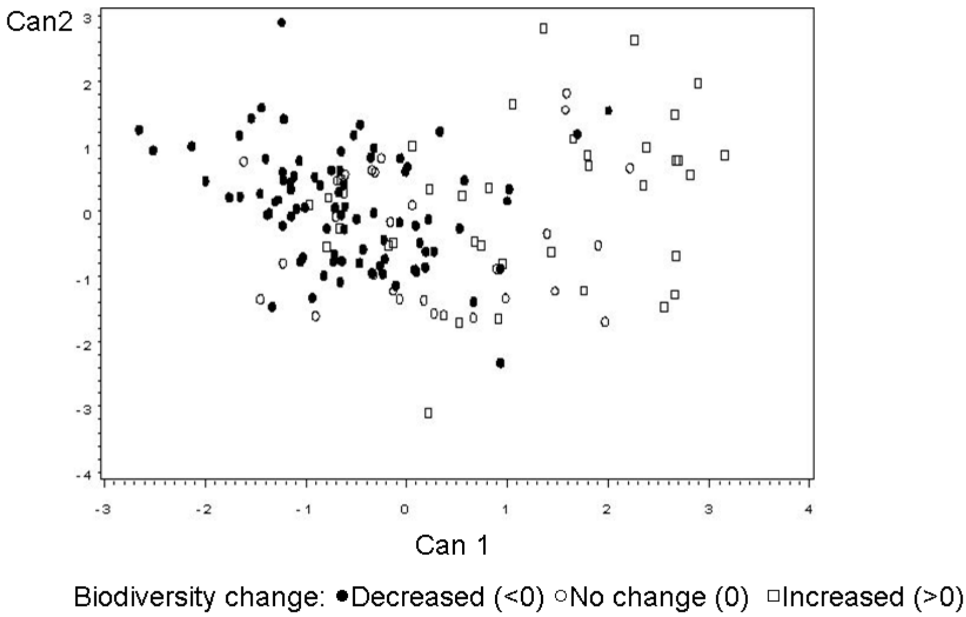


Figure 5. First and second canonical function of canonical discriminant analysis separating biodiversity change classes between 2000 and 2005 for the Tigray study area in northern Ethiopia.

2000 and 2005 but was negatively associated with the first canonical function (Table 5). More inorganic fertilizer was used (kg farm^{-1}) (Table 2 and 4) on farms where agro-biodiversity had decreased between 2000 and 2005.

Classes for changes in soil erosion (decrease, no change and increase) between 2000 and 2005 were not significantly separated by the explanatory variables included (canonical discriminant analysis, Wilks' Lambda value = 0.77; $P > 0.05$; Figure not shown), possibly because different soil erosion estimation methods were used in 2000 (visual assessment) and 2005 (USLE method).

3.3 Spatial distribution of agro-biodiversity in 2000 and 2005

Overall tree/shrub diversity did not change significantly between 2000 and 2005 (Table 4), and neither did the spatial distribution of the numbers of tree/shrub species (Figure 6). The number of crop varieties decreased significantly (Table 4), the changes taking place mainly at farms located close to a road (Figure 6 c and d). Proximity of farms to a town was associated with low agro-biodiversity, both in 2000 and 2005 (Figure 6 a – d). Particularly farms close to the towns of Adwa in the North-Western and Edga Arbi in the Eastern part of the study area showed a decrease in agro-biodiversity between 2000 and 2005 (Figure 6 c and d).

Table 5. Variables significantly contributing to the separation among change in biodiversity classes (decrease, no change and increase) between 2000 and 2005.

Classification variable	Pooled within standardized coefficients	Mean values of variables per biodiversity difference class		
	Canonical function 1	Decrease (n= 84)	No change (n=31)	Increase (n=36)
Crop type (number farm^{-1}) *	0.21	3.9 (±0.2)	4.4 (±0.2)	4.9 (±0.3)
Crop selection criteria (number farm^{-1})*	0.50	4.9 (±0.2)	5.3 (±0.3)	5.6 (±0.3)
Weed species (number farm^{-1})	–0.11	4.2 (±0.1)	3.8 (±0.2)	3.6 (±0.3)
Pest species (number farm^{-1})	–0.14	2.3 (±0.1)	2.2 (±0.2)	2.1 (±0.2)
Inorganic fertilizer (kg farm^{-1}) *	–0.33	66.5 (±4.3)	46.8 (±6.9)	40.3 (±6.26)
Animals (number farm^{-1}) *	0.37	16.5 (±1.0)	20.3 (±1.4)	25.2 (±1.1)
Credit sources (number farm^{-1})	–0.16	1.9 (±0.1)	1.7 (±0.1)	1.4 (±0.1)
Slope (%)	–0.16	4.7 (±0.7)	5.1 (±1.1)	4.7 (±0.9)
Elevation (m)	0.15	2009.1 (±6.3)	2045.6 (±18.1)	2140.2 (±26.2)
Town distance (km) *	0.45	5.1 (±0.3)	7.1 (±0.8)	10.6 (±0.8)
Road distance (km) *	0.36	3.1 (±0.3)	4.6 (±0.6)	6.3 (±0.5)

* $P < 0.05$; Threshold = 0.2/√ (1.5207) = 0.162

4 Discussion

4.1 Spatial and temporal variation in agro-biodiversity and soil degradation

This study integrated field measurements, farm surveys and GIS analysis of 151 farms to assess agro-biodiversity and soil degradation in relation to their proximate causes in a longitudinal study with observations in two years. The spatial and temporal analysis of our results demonstrate a decrease in agro-biodiversity, particularly in the number of crop varieties, on 84 farms, an increase on 36 farms and no change on 31 farms (Figure 5 and Table 5) This decrease occurred mainly at farms where inorganic fertilizer use and the number of credit sources was relatively high (Table 5). Those

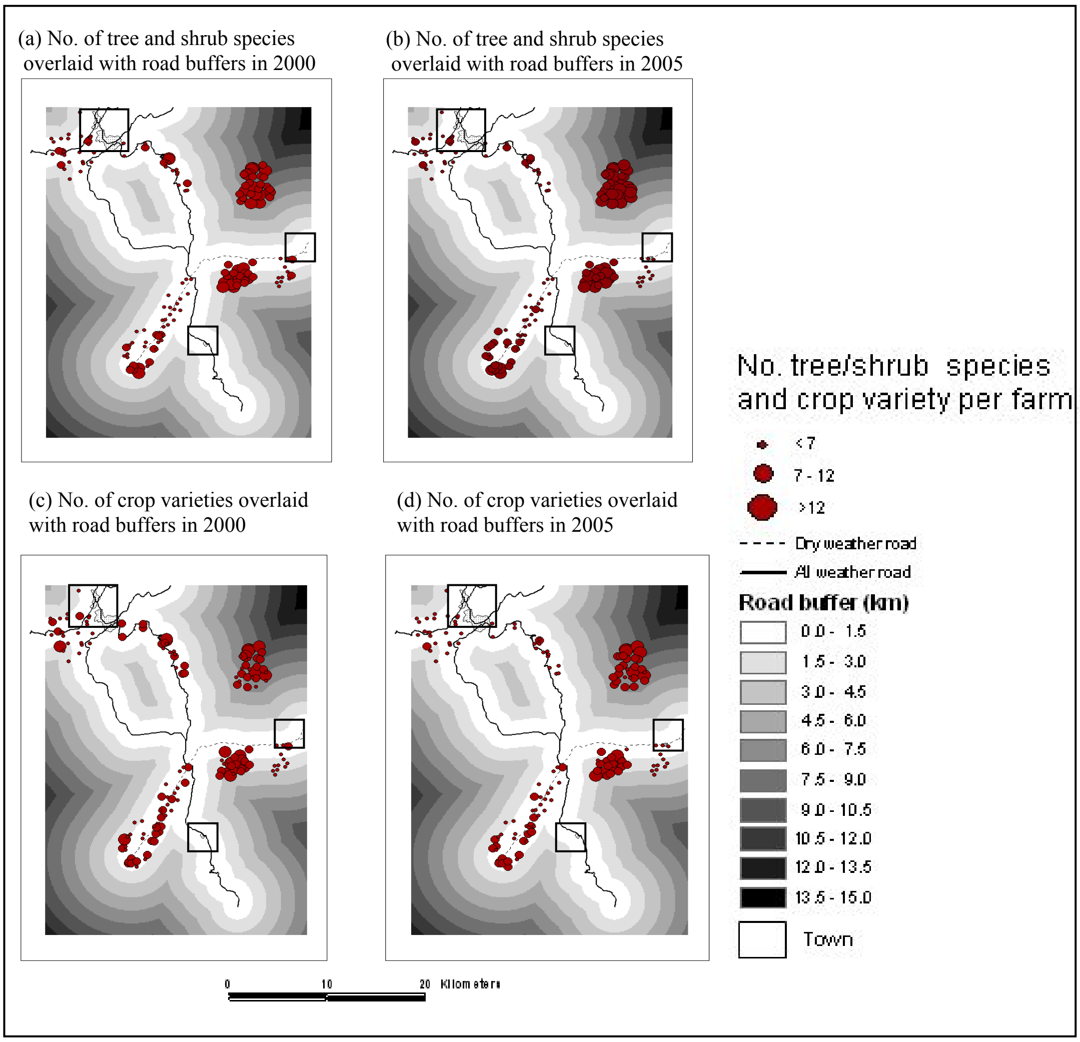


Figure 6. Spatial distribution of tree and shrub species in 2000 (a) and 2005 (b) and number of crop varieties in 2000 (c) and 2005 (d) for the Tigray study area in northern Ethiopia.

farms were mostly located close to towns and major roads (Figure 6). Overall biodiversity of the farm population as a whole did not decrease significantly (Table 4). This points to a major danger in averaging over space and emphasizes the importance of assessing biodiversity at specific locations over time. No changes in soil erosion, the indicator of soil resource degradation, were detected. However, this analysis suffers from the fact that soil erosion was estimated by two different methods, viz. visual in 2000 and by calculation in 2005.

The study demonstrates that agro-biodiversity had decreased between 2000 and 2005 on farms close to the development drivers towns and major roads, and on farms with better access to credit and with higher fertilizer use. Decreases in biodiversity between 2000 and 2005 were associated with decreases in crop types, crop selection criteria and number of farm animals (Table 5). This indicates that intensification of agricultural practices with higher external inputs is detrimental to on-farm biodiversity, a process which is most prevalent close to towns and roads, at lower elevations. Brush et al. (1992) working with potato-based systems in the Andes also found that farms closer to towns and markets were more influenced by the introduction of modern crop varieties compared to those further away and showed decreased biodiversity close to towns. The decrease in the number of crop varieties found in our study suggests that, in addition to the enhancement of external resource use, the development process is also one of specialization or simplification. Surprisingly, farms which exhibited this intensification pattern and associated low biodiversity values were not positively but negatively associated with the production of food calories (data 2005; Table 2). This relationship held for all crops at the farms visited, except for maize, which had a larger total caloric content at intensively cultivated farms, partially because more maize was grown at these farms. The general negative association between biodiversity and total caloric yield suggests that intensification, while taking place, does not appear to have the intended positive effect of increasing productivity, while exhibiting a range of undesirable side effects, including loss of crop diversity, on-farm trees, livestock, and soil P and N reserves. A similar conclusion was drawn by Mozumder and Berrens (2007) who showed that short term crop yield improvement strategies based on indiscriminate use of inorganic fertilizer enhances loss of biodiversity.

Increases in agro-biodiversity were limited to a return to a larger number of crop varieties (landraces) at farms far from the nearest development drivers (town and road) and at higher elevation with higher numbers of planted crop types, numbers of crop selection criteria and animal manure application rates. These farms were predominantly located in region IV (Figure 1) far from regional centers. There, farmers still practice traditional farming by growing diversified crop types selected by a range of criteria (e.g., yield, early maturity, drought resistance, market value, weed resistance, insect pest resistance, straw quality, treshability and beverage quality) (Hadgu et al., 2008a). Lack of access to markets forces these farmers to adopt subsistence strategies which rely on sustained maintenance of internal resources by highly diversified systems. Similar results were found in other studies: in Mexico (Van Dusen, 2000), in Ethiopia (Benin et al., 2003). and in different placesat various locations in the Andes (Brush et al., 1992).

The plants in these diversified cropping systems likely had diversified resource utilization traits, such as plant architecture, rooting depth, soil cover, and allocation of photosynthates (Russell, 2002). These cropping systems included regularly spaced acacia trees, and resulted in higher caloric crop yields. Higher overall productivity per unit area can be obtained when different species efficiently utilize nutrients, water and light because of their interspecific differences, resulting in complimentarity and facilitation (Tilman et al., 1996; Picasso et al., 2008).

Further evidence of agricultural land use changes being the cause of agro-biodiversity decline is provided by the GIS analysis of land use types and biodiversity in 2005. Results (Figure 3) demonstrate that the sparsely cultivated land use type is positively associated with high agro-biodiversity, while the intensively cultivated land use type is associated with medium and particularly with low agro-biodiversity. Earlier results (Hadgu et al., 2008c) showed that removal of the traditional tree species associated with intensification also removes significantly positive effects on yield of crops. Thus, a greater reliance on external nutrients first has to overcome this loss of ecosystem service, which may be one of the factors explaining lower caloric production in the more intensive systems in this study.

Similar to findings for 2000 (Hadgu et al., 2008a), soil erosion in 2005 was positively associated with slope and closeness to towns and roads (Table 4 and Figure 3). These locations are dominated by the intensively cultivated land use type resulting from cutting of trees in farm lands (Hadgu et al., 2008a). The significant increase of the number of pest species as stated by farmers on sites with higher erosion may be associated with this simplification of cropping systems. The data do not allow conclusions on this point. A negative association was observed between soil erosion, and soil OM and number of crop selection criteria. Pimentel and Kounang (1998) indicate that low soil OM facilitates water run off due to reduced water holding capacity of the soil. The consequence of high soil erosion frequently is low crop productivity as essential soil nutrients are lost in the process of soil erosion (Mokma and Sietz, 1992). Whether soil deterioration associated with intensification indeed explains the low caloric productivity we found, should be examined in more detail to devise more appropriate intensification strategies.

4.2 Comparison with other studies

Unlike our study, which assessed spatial variation in both crop and non-crop diversity in relation to their proximate drivers, most other studies in Ethiopia resulted in a description of (genetic) diversity in individual crops without consideration of external causes of the changes in diversity. Those studies concerned varietal diversity in sorghum (*Sorghum bicolor*) in Eastern Ethiopia (Mulatu and Belete, 2001; Mekbib, 2008) and in central and northern Ethiopia (Teshome et al., 1999), wheat (*Triticum* spp.) in central and Southern Ethiopia (Kebebew et al., 2001) and in northern Ethiopia (Di Falco et al., 2007), finger millet (*Eleusine coracana*) in northern Ethiopia (Tsehaye et al., 2006), and tef (*Eragrostis tef*) in central and northern Ethiopia (Assefa et al., 2001). A notable exception to these descriptive studies in Ethiopia is a study by Benin et al. (2003), which revealed determinants of cereal crop diversity. They found higher diversity on farms far from the nearest towns or markets, with higher livestock assets and higher education of family members. These results confirm those of our study, which included a range of crops, except that we did not find a significant effect of education.

Higher on-farm biodiversity in traditionally managed as compared to intensified agricultural production systems was also revealed in Ghana (Awanyo, 2007), Nigeria (Netting and Stone, 1996), Tanzania (Keller et al., 2006) and Peru (Pinedo-Vasquez et al., 2002). The last authors showed that traditional smallholder farming systems can manage ecological, agricultural and social processes while conserving agro-biodiversity. Netting and Stone (1996) and Keller et al. (2006) attributed the loss of agro-biodiversity to changes in land use resulting from socio-cultural and economic changes, such as expansion of urban areas and use of modern crop varieties. Biodiversity decline on agricultural lands was also reported from the central Himalaya in India mainly because of changes in agricultural land use practices (Maikhuri et al., 2001), and rapid socio-economic changes (replacement of mixed crops with uniform cash crops, changes in food habits, changes in social integration) and cultural changes (changes in traditional wisdom, faith and beliefs) (Nautiyal et al., 2008). Working in Sierra Norte de Puebla (SNP), a mountainous region of Mexico, Van Dusen and Taylor (2005) concluded that market integration, crop specialization and labor shortage contribute to the reduction in farm biodiversity. However, Conelly and Chaiken (2000) in Hamisi, in western Kenya argue that land use intensification and the use of modern crop varieties do not contribute to the loss of biodiversity but play a role in maintaining biodiversity in agricultural lands. As farmers in Hamisi, in western Kenya do not have large scale irrigable lands and are not led by market forces to focus on production of a single or narrow range of crops, agricultural intensification does not lead to specialization and reduction of agro-diversity (Conelly and Chaiken, 2000).

4.3 Implications

This study provides for the first time information on status and dynamics of agro-biodiversity and soil degradation in one of the centers of diversity in Tigray, northern Ethiopia. Lack of information has thus far prevented policy analysts from taking such information into account. Increasing population pressure and associated food demands, and globalization (CSA, 2004) may be expected to continue to drive land use changes from traditional agricultural management to increased reliance on external resources. As indicated by our results, such land use changes are a main cause of agro-biodiversity loss, without unequivocal positive effects on caloric production. Agricultural production by smallholder resource-poor farmers can not be sustainable by depending on high input agricultural technologies because of the rising prices of inorganic fertilizer and uncertainties associated with environmental changes. The challenge is how to optimize agricultural productivity in a sustainable way while conserving agro-biodiversity in agricultural landscapes. Decision makers and land use planners should, therefore, consider agro-biodiversity as natural capital from which agriculture gains ecosystems services, such as soil fertility, protection against soil erosion, water retention and pest control (MEA, 2005). Diversification of land use and farming strategies appear to be essential for future policies, as results of this research and previous studies (Hadgu et al., 2008a,b,c) show the positive contribution of agro-biodiversity to production. Policies that emphasize farm-internal resource optimization may well be more adapted to uncertain futures than policies that emphasize adoption of high external input technology packages.

5 Conclusions

This study revealed a significant loss of agro-biodiversity in agricultural landscapes between 2000 and 2005 in Tigray, northern Ethiopia. The loss of agro-biodiversity was higher on farms with higher inorganic fertilizer use and number of credit sources, which were mainly located close to towns and major roads. Agro-biodiversity was positively associated with number of crop types, crop selection criteria, and animals per farm. These farms were mainly located far from towns and major roads at high altitude locations. On-farm biodiversity contributed to soil fertility and crop productivity. At a regional scale, intensively cultivated land use (with few or no trees/shrubs) was associated with reduced agro-biodiversity. Reduced agro-biodiversity went hand-in-hand with higher soil erosion and lower soil organic matter content, signs of unsustainability. Relationships among agro-biodiversity, productivity and sustainability documented in this study can help to improve food security while maintaining agro-biodiversity resources in developing countries like Ethiopia.

6 Acknowledgments

Financial support was provided by an IITA-Lukas Brader Fellowship and a NUFFIC fellowship to the first author. We thank IITA for providing IITA- Lukas Brader Fellowship and Mr B. Oyewole, for logistic support, and Dr Morag Ferguson and Dr Michael Pillay, for being IITA supervisors. We also thank Dr Gerrit F. Epema for his assistance in the beginning of this research.

References

Afifi, A.A., Clark, V., 1984. Computer-aided multivariate analysis. Van Nostrand Reinhold Company, New York.

Assefa, K., Tefera, H., Merker, A., Kefyalew, T., Hundera, F., 2001. Quantitative trait diversity in tef [*Eragrostis tef* (Zucc.) Trotter] germplasm from Central and northern Ethiopia. Genet. Resour. Crop Ev.. 48, 53 – 61.

Awanyo, L., 2007. A Janus-faced biodiversity change and the partiality of ecological knowledge in a world biodiversity hotspot in Ghana: Implications for biodiversity rehabilitation. Geoforum. 38, 739 – 751.

Benin, S., Smale, M., Gebremedhin, B., Pender, J., Ehui, S., 2003. The determinants of cereal crop diversity on farms in the Ethiopian highlands. EPTD discussion paper No. 105. International Food Policy Research Institute, Washington, D.C.

Brush, S., Taylor, J.E. Bellon, M.R., 1992. Biological diversity and technology adoption in Andean potato agriculture. J. Dev. Econ. 39, 365 – 387.

Borlaug, N.E., 1996. Lost crops of Africa. National Academy Press, Washington DC.

Chapin III, F.S., Zavaleta, E. S., Eviner, V.T., Naylor, R.L., Vitousek, P.M., Reynolds, H.L., Hooper, D.U., Lavorel, S., Sala, O.E., Hobbie, S.E., Mack, M.C., Díaz, S., 2000. Consequences of changing biodiversity. Nature. 405, 234 – 242.

Conelly, W.T., Chaiken, M.S., 2000. Intensive Farming, Agro-Diversity, and Food Security Under Conditions of Extreme Population Pressure in Western Kenya. Human Ecol. 28, 19 – 51.

CSA, 2004. Statistical Abstracts. Ethiopian Central Statistical Authority (CSA), Addis Ababa.

Di Falco, S., Chavas, J.-P., Smale, M., 2007. Farmer management of production risk on degraded lands: the role of wheat variety diversity in the Tigray region, Ethiopia. Agric. Econ. 36, 147 – 156.

Drinkwater, L.E., Wagoner, P., Sarrantonio, M., 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature. 396, 262 – 265.

Deurloo HA, Haileselassie T., 1994. Rehabilitation of Degraded and Degrading Areas of Tigray, Ethiopia, Survey on Farm Practices based on Local Knowledge. Wageningen Agricultural University, Wageningen.

Edwards, S., Tadesse, M., Demissew, S., Hedberg, I., 2000. Flora of Ethiopia and Eritrea. Addis Ababa University, Addis Ababa.

FAO, 2003. Food energy - methods of analysis and conversion factors. FAO, Rome.Feoli, E., Vuerichm L.G., Woldu, Z., 2002. Processes of environmental degradation and opportunities for rehabilitation in Adwa, northern Ethiopia. Landscape Ecol. 17, 315 – 325.

Hadgu, K.M., Epema, G.F., van Bruggen, A.H.C., 2008a. Biodiversity and Sustainability in Agricultural landscapes in Tigray, northern Ethiopia. Landscape Urban Plan. (submitted)

Hadgu, K.M., Kooistra L, Rossing W.A.H., van Bruggen, A.H.C., 2008b. Detection of land use/ land cover changes by remote sensing and associated drivers for the period 1964-2005 in the highlands of Tigray, Ethiopia. Agric. Ecosyst. Environ. (submitted)

Hadgu, K.M., Kooistra, L., Rossing, W.A.H., van Bruggen, A.H.C., 2008c. Assessing the effect of *Acacia albida* based land use systems on barley yield at field and regional scale in the highlands of Tigray, northern Ethiopia. Agrofor. Syst. (submitted)

Hurni, H., 1985. Soil conservation manual for Ethiopia. A field guide for conservation implementation. Soil Conservation Research Project, Addis Ababa.

Kebebew, F., Tsehaye, Y., McNeilly, T., 2001. Diversity of durum wheat (*Triticum durum* Desf.) at *in situ* conservation sites in North Shewa and Bale, Ethiopia. J. Agric.l Sci. 136, 383 – 392.

Keller, G.B., Mndiga, H., Maass, B.L., 2006. Diversity and genetic erosion of traditional vegetables in Tanzania from the farmer's point of view. Plant Genet. Resour. 3, 400 – 413.

Mekbib, F., 2008. Genetic erosion of sorghum (*Sorghum bicolor* (L.) Moench) in the centre of diversity, Ethiopia. Genet Resour. Crop Evol. 55, 351 – 364.

Maikhuri, R.K., Rao, K.S., Senwal, R.L., 2001. Changing scenario of Himalayan agroecosystems: loss of agrobiodiversity, an indicator of environmental change in Central Himalaya, India. Environ. 21, 23 – 39.

McNeely, J.A., Scherr, S.J., 2003. Ecoagriculture: Strategies to Feed the World and Save Wild Biodiversity. Island Press, Washington, DC.

Mokma, D.L., Sietz, M.A., 1992. Effects of soil erosion on corn yields on Marlette soils in South-Central Michigan. J. Soil Water Conserv. 47, 325 – 327.

MEA, 2005. Ecosystems and Human Well-being: Biodiversity Synthesis. In: Millennium Ecosystem Assessment (MEA). World Resources Institute, Washington, DC.

MoNRDEP, 1990. Soil Analysis Laboratory Manual. Ministry of Natural Resources Development and Environmental Protection (MoNRDEP), Addis Ababa

Mooney, H.A., Cooper, A., Reid, W., 2005. Confronting the human dilemma. Science. 434, 561 – 562.

Mozumder, P., Berrens, R.P., 2007. Inorganic fertilizer use and biodiversity risk: An empirical investigation. Ecol. Econ. 62, 538 – 543.

Mulatu, E., Belete, K., 2001. Participatory varietal selection in lowland sorghum in

eastern Ethiopia: impact on adoption and genetic diversity. Expl. Agric. 37, 211 – 229.
Nautiyal, S., Bisht, V., Rao, K.S., Maikhuri, R.K., 2008. The Role of Cultural Values in Agrobiodiversity Conservation: A Case Study from Uttarakhand, Himalaya. J. Hum. Ecol. 23, 1 – 6.
Netting, R.M., Stone, M.P., 1996. Agro-diversity on a farming frontier: Kofyar smallholders on the Benue plains of central Nigeria. J. Int. Afr. Inst. 66, 52 – 70.
Russell, A.E., 2002. Relationships between crop-species diversity and soil characteristics in southwest Indian agroecosystems. Agric. Ecosyst. Environ. 92, 235 – 249.
Picasso, V.D., Brummer, E.C., Liebman, M., Dixon, P.M., Wilsey, B.J., 2008. Crop Species Diversity Affects Productivity and Weed Suppression in Perennial Polycultures under Two Management Strategies. Crop Sci. 48, 331 – 342.
Pimentel, D., Kounang, N.,1998. Ecology of Soil Erosion in Ecosystems. Ecosyst. 1, 416 – 426.
Pinedo-Vasquez, M., Pasqualle, J.B.Del Castillo Torres, D., Coffey, K., 2002. A tradition of change: the dynamic relationship between biodiversity and society in sector Muyuy, Peru. Environ. Sci. Policy. 5, 43 – 53.
Sarraute, J.L., Vonder, O.W., 1994. Rehabilitation of Degraded and Degrading Areas of Tigray, Ethiopia: landsurface, landcover and change detection classifications based on remote sensing. Wageningen Agricultural University, Wageningen.
SAS, 1999. SAS/STAT User's manual. Volume I. SAS Institute Inc., Cary.
Swift, M.J., Izac, A.M.N., van Noordwijk, M., 2004. Biodiversity and ecosystem services in agricultural landscapes - are we asking the right questions? Agric. Ecosyst. Environ. 104, 113 – 124.
Teshome, A., Fahrig, L., Torrance, J. K., Lambert, J. D., Arnason, Z. J., Baum, B.R.,1999. Maintenance of Sorghum *(Sorghum bicolor, P*oaceae) landrace diversity by farmers' selection in Ethiopia. Econ. Botany. 53, 79-88.
Thrupp, L.A., 2000. Linking agricultural biodiversity and food security: the valuable role of agrobiodiversity for sustainable agriculture. Int. Aff.. 76, 265 – 281.
Tilman, D., Wedin, D., Knops, J., 1996. Productivity and sustainability influenced by biodiversity in grassland ecosystems. Nature. 379, 718 – 720.
Tilman, D., Reich, P., Knops, J., Wedin, D., Mielke, T., Lehman, C., 2001. Diversity and productivity in a long-term grassland experiment. Science. 294, 843 – 845.
Tscharntke, T., Klein, A.M., Steffan-Dewenter, I., Thies, C., 2005. Landscape perspectives on agricultural intensification and biodiversity - ecosystem service management. Ecol. Lett. 8, 857 – 874.

Tsehaye, Y., Berg, T., Tsegaye, B., Tanto, T., 2006. Farmers' management of finger millet (*Eleusine coracana* L.) diversity in Tigray, Ethiopia and implications for on-farm conservation. Biodivers. Conserv. 15, 4289 – 4308.

Vandermeer, J., Lawrence, D., Symstad, A., Hobbie, S., 2002. Effects of biodiversity on ecosystem functioning in managed ecosystems. In: Loreau, M., Naeem, S., Inchausti, P. (Eds.), Biodiversity and Ecosystem Functioning. Oxford University Press, Oxford, pp. 157 – 168.

Van Dusen, E., 2000. In situ conservation of crop genetic resources in the Mexican *Milpa* system. Doctoral dissertation. University of California-Davis, Davis.

Van Dusen, M.E., Taylor, J.E., 2005. Missing markets and crop diversity: evidence from Mexico. Environ. Dev. Econ.. 10, 513 – 531.

Wischmeier, W.H., Smith, D.D., 1978. Predicting rainfall erosion losses: a guide to conservation planning. Agriculture Handbook 537. United States Department of Agriculture, Washington DC.

WRI, 2005. The Wealth of the Poor: Managing Ecosystems to Fight Poverty. World Resources Institute (WRI), Washington, DC.

Zhu, Y.Y., Chen, H., Fan, J., Wang, Y., Li, Y., Chen, J., Fan, J., Yang, S., Hu, L., Leung, H., Mew, T.W. Teng, P.S., Wang, Z., Mundt, C.C., 2000. Genetic diversity and disease control in rice. Nature. 406, 718 – 722.

Chapter 5

Assessing the effect of *Acacia albida* based land use systems on barley yield at field and regional scale in the highlands of Tigray, northern Ethiopia

K.M. Hadgu[a,b,c], L. Kooistra[c] W.A.H. Rossing[b], A.H.C. van Bruggen[b]

[a] Faculty of Natural Resources and Agriculture , Mekelle University, P.O. Box 231, Mekelle, Tigray, Ethiopia
[b] Biological Farming Systems, Department of Plant Sciences, Wageningen University, Marijkeweg 22, 6709 PG Wageningen, The Netherlands
[c] Geoinformatics and Remote Sensing, Department of Environmental Sciences, Wageningen University, Droevendaalsesteeg 3, 6708 PB Wageningen, The Netherlands

(Submitted to Agroforestry Systems)

Abstract

Implications of changes in traditional *A. albida* based land use systems on productivity were investigated in Tigray, northern Ethiopia. The *A. albida* based land use systems in relation to productivity was explored in 77 fields and 81 farms at field and regional scales, respectively. Barley yield and soil fertility increased when field locations were closer to an *A. albida* trunk in the *A. albida* alone (AA) and *A. albida* + livestock (AL) land use systems. However, the *A. albida* + Eucalyptus (AE) land use system showed a decreasing trend in barley yield and soil fertility as distance from *A. albida* trunk decreased. At regional scales, higher *A. albida* tree density per farm and sparsely cultivated land use types increased potential ecosystem services (barley yield). This study suggests that local biodiversity components (e.g., *A. albida* trees) can increase crop yield and soil fertility significantly when grown within and around farm lands.

Keywords: *A. albida*; biodiversity; ecosystem-service; land-use; productivity.

1 Introduction

Ensuring sustainable agricultural productivity to reduce poverty, while minimizing environmental degradation (e.g., biodiversity loss) is one of the main research goals of the UN Millennium Project (Sachs and McArthur, 2005; UN Millennium Project, 2005). As a response to this, approaches have been developed that promote best use of science and technology to increase agricultural productivity especially in Sub-Saharan Africa through the use of inorganic fertilizer and adoption of market oriented agricultural productivity strategies (IAC, 2004). A recent report by IAASTD (2008) proposed ways of increasing agricultural productivity by taking into account the diversified bio-physical resources of small scale farms, usually negatively affected by environmental changes, and where the potential for improved agricultural productivity is low. As addressed in this paper, sustainable increase in agricultural productivity requires an approach which reverses the current negative influence of agriculture on biodiversity (MEA, 2005).

Various authors have pointed out the potential of tree-based cropping systems for increasing crop productivity in arid and nutrient-deficient smallholder farming systems (Paoletti et al., 1992; Ong and Leakey, 1999; Rao and Mathuva, 2000). However, tree-crop interactions can have both positive and negative effects on the structure and functioning of the agro-ecosystem (Ong, 1995; García-Barrios and Ong, 2004). Trees can compete with crops for light, water and nutrients and decrease crop yield when density and size of trees increase (Akonde et al., 1996; Cannell et al., 1996; Miller et al., 2001; García-Barrios, 2003). Trees often affect soil water content, either increasing (Caldwell and Richards, 1989; Dawson, 1993) or decreasing them (Smith et al., 1999; Odhiambo et al., 2001), and thereby influencing nutrient transport to crop roots and root growth (Radersma et al., 2004). Although trees can increase the potential soil water-holding capacity, they have also negative effects on the actual water volume available in the tree-crop-soil system. For example, as much as 50% of rainfall intercepted by the canopy can evaporate without reaching the soil when tree density is high (Ong et al., 1996). However, trees and crops differ greatly in size, life form, phenology and capacity to capture and use efficiently above-and below-ground resources (Goldberg, 1990). Thus, their intra-and inter-specific competition can differ strongly. A tree modifies or improves growth of another tree or crop by changing the biophysical conditions in order to establish a better potential environment for the latter one (Hunter and Aarssen, 1988; Rhoades, 1997). System productivity can be increased by trees through reducing nutrient losses through leaching into the subsoil, reduced soil erosion, protection against wind (Rao et al., 1998) and reducing weed populations and their aggressiveness (Liebman and Gallandt, 1997), resistant to cyclic environmental changes and efficiently utilizing and recycling resources (Ong et al., 1996), and increasing available nutrients for crops by root exudates or rhizosphere effects (Radersma and Grierson, 2004). Trees may also affect soil water content, either positively (Caldwell and Richards, 1989; Dawson, 1993) or negatively (Smith et al., 1999; Odhiambo et al., 2001), and thereby influence nutrient transport to crop roots and root growth (Radersma et al., 2004).

Like in other developing countries, smallholder farms in Ethiopia are under pressure as a result of intensification and agro-ecosystem simplification (Worede, 1991 and 1997). This could become a serious threat to the sustainability of agricultural productivity with negative consequences such as severe soil erosion, fertility decline and water scarcity (Hurni, 1993; Shiferaw and Holden, 2000; Dejene, 2003). Within the Tigray region in northern Ethiopia, farmers keep *Acacia albida* Del. (Syn. *Faiderbhia albida* (Del.) A Chev.) trees in and around their farm land in order to improve soil fertility and increase crop yields. This tree has a special phenology as it sheds its leaves during the rainy season and keeps them during the dry season, i.e. from October to June in the northern tropics. As a result, *A. albida* sheds its leaves when ploughing begins and thereby *A. albida* barely competes for light and water during the crop growing season. Furthermore, *A. albida* trees provide nutrients from their leaves incorporated into the soil and through N fixation (Rao et al. 1998). In addition, the trees serve as fence and fuel, and provide fodder and shade to the livestock. This means that the presence of *A. albida* within the traditional small holder farming system provides ecosystem services which can be categorized as provisioning services (including food production), regulating services (e.g. climate regulation, nutrient cycling, minimize soil erosion), and supporting services (e.g. biodiversity) (Costanza et al., 1997; Daily, 1997; MEA, 2003).

Several studies (Poschen, 1986; Kamara and Haque, 1992; Asfaw and Ågren, 2007) have shown the positive effect of *A. albida* trees on crop yield for different crops (e.g., maize, sorghum) of traditional smallholder farming systems in Ethiopia. These studies compared yield under the tree with yield at larger distances from the *A. albida* tree at field scale. However, no information was available on the influence of *A. albida* on barley productivity at increasing distance from a tree and under different *A. albida* based land use systems. Land use intensification in Ethiopia has included the use of inorganic fertilizer and planting of *Eucalypt* species for fuel wood and house construction. This process causes a shift away from the traditional *A. albida* based farming practices including livestock. The intensification process affects biodiversity at the regional scale (Hadgu et al., 2008a) and could also influence *A albida* density and its yield benefits.

The objective of this paper is to investigate implications of changes in traditional *A. albida* based land use systems on productivity for the Tigray region in northern Ethiopia. Biodiversity as used in this study includes number of trees and shrubs in and around agricultural fields at field and regional scale, and productivity is measured as barley yield. The hypotheses addressed in this study are: (i) closer to an *A. albida* tree and at high *A. albida* tree density, barley yield and soil properties (total N, available P, soil organic matter, pH and soil moisture) are affected positively and (ii) *A. albida* based land use systems are associated with low intensity agricultural land use types.

2 Materials and methods

2.1 Study location

The study was undertaken in the highlands of Tigray in northern Ethiopia (Figure 1). The study area (4° 82' – 5° 10' N and 15° 66' – 15° 28' E) is located South-East to the town of Adwa and covers an area of about 30 by 40 km at an elevation of 1300 – 2800 m. The climate of the area is semi-arid, with two rainy seasons, the main season starting in late June and lasting until September, and a minor season between March and April. The average annual rainfall ranges from 740 mm at 1500 m to 900 mm at 2000 m (Deurloo and Haileselassie, 1994). Wide variation in rainfall from year to year

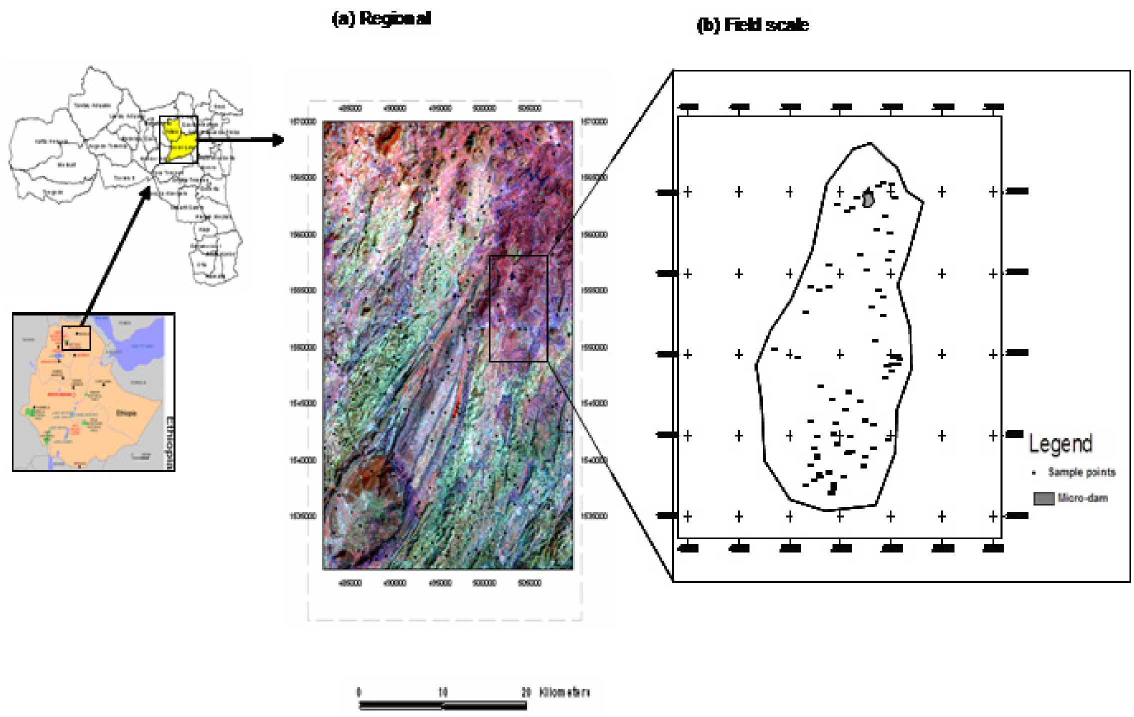


Figure 1. Location of study area: false color composite of bands 4, 5 and 3 of 2005 Landsat ETM+ at regional scale (a) and sub area with field scale sample points (b) in Tigray, northern Ethiopia.

is characteristic for the area. Soils are categorized as Cambisols, Fluvisols, Xerosols, Vertisols and Luvisols (Sarraute and Vonder, 1994). The study area is considered as one of the most densely populated areas in Ethiopia (Feoli et al., 2002). Land use within the area consists of four dominant classes (Hadgu et al., 2008a): woodland, shrub land, scrubland and agriculture. The typical agricultural practice in the study area is a mixed crop-livestock small holder farming system. Within this farming system different degrees of agricultural intensification can be identified ranging from sparsely cultivated (Scu) to intensively cultivated (Icu) areas (Table 1) (Hadgu et al., 2008a). *A. albida* trees are present throughout the region with varying densities (Figure 2) often as remnants of natural land cover types (e.g., woodland, shrub land). The relation between biodiversity and productivity of the smallholder systems within the study area was assessed at the field scale and extrapolated to the regional scale based on the land use classification. To investigate the contribution of *A. albida* based land use systems on barley yield productivity, we distinguished measured field data and farm survey data which correspond to field scale and regional scale, respectively.

2.2 Field measurements

Site selection for field data acquisition was achieved through participatory identification of a region (sub-region of the study region) with good examples of *A. albida* tree based farming practices. In selecting the sub-region (Figure 1b) with good *A. albida* tree based farming practices, a tour was made in the whole study region together with extension agents. Actual information on the farming practices of the region were collected from farmers (n=38) by interviewing key informants, group discussions and joint field excursions to select key areas with good examples of *A. albida* faming systems. In addition, topographic maps coupled with farmers' sketches contributed in identifying the sub-region with *A. albida* faming systems. In the same

Table 1. Agricultural land use types for the study area in Tigray, *northern Ethiopia*.

Land use type	Description
Sparsely cultivated land (SCu)	Between 20 and 40% of the mapping unit is under cultivation while the remaining area is covered by trees, shrubs or herbs.
Moderately cultivated land (MCu)	Between 40 and 70% of the mapping unit is under annual and perennial crop while the remaining area is covered by trees, shrubs or herbs.
Intensively cultivated land (ICu)	Over 70% of the land is under annual and perennial crops while the remaining area is covered by trees, shrubs or herbs.

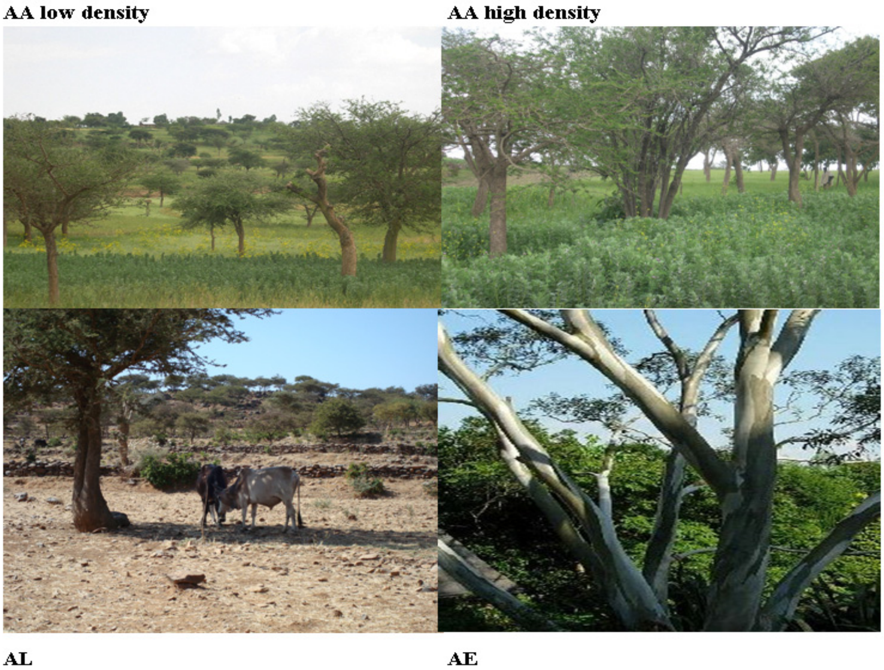


Figure 2. Different *Acacia albida* land use systems in the Tigray study area in northern Ethiopia with *Acacia albida* alone (AA), *Acacia albida* and livestock (AL) and *Acacia albida* and Eucalyptus (AE).

and/or fodder and with *A. albida* growing adjacent to *Eucalyptus* species were also identified. The approach followed to select a sub-region was similar to the Rapid Rural Appraisal (RRA) (Messerschmidt, 1995) and Participatory Rural Appraisal (PRA) methods (Chambers and Guijt, 1995). As a result, a sub-region (Figure 1b) of approximately 6 by 8 km was chosen for the field scale analysis (4° 82' – 5° 10' N and 15° 66' – 15° 28' E). This sub-region is located in the North-Eastern part of the study area (Figure 1b) and has an elevation between 2000 and 2400 m.

Based on farmers' information, 77 barley fields were selected within this sub region (Figure 1b). Within each field, observations were made on one *A. albida* tree separated from the nearest *A. albida* tree by at least 50 m to establish the effect of an individual tree on crop and soil characteristics. On the fields, the measurements were made at 1, 25 and 50m from a solitary *A. albida* tree to investigate if locations close to *A. albida* trunk in AA and AL systems contribute to yield benefits, while in combination with Eucalypt these yield benefits are absent. On each field (n=77), slope was also measured by clinometers. Land use type for the sampled fields in the sub-region was classified using the land use classification by Hadgu et al. (2008a).

The relation between barley yield and soil properties (total N, OM, available P, soil moisture and soil pH) at different distances from an *A. albida* tree within a field was investigated for 77 locations. We assumed that trees and livestock can increase nutrient availability in agricultural fields by transporting nutrients from the subsoil and by manuring, respectively. Therefore, sampling occurred in strata corresponding to three different *A. albida* land use systems (Figure 2):

1. *A. albida* alone (AA): only *A. albida* is present along field boundaries or within fields without interference of other tree species or livestock;
2. *A. albida* and livestock (AL): the presence of *A. albida* is combined with livestock which use the tree for shading and/or fodder;
3. *A. albida* and Eucalypt (AE): fields are enclosed by *A. albida* which grow adjacent to *Eucalyptus camaldulensis*.

Within the study area, fields with AA and AL land use systems were located on more gentle slopes and at lower altitudes than fields with the AE land use system. Most fields with an AE land use system were located close to a micro –dam and were irrigated. In addition, inorganic fertilizer was applied on these fields, particularly in fields located in the Northern part of the field scale study area (Figure 1b). In contrast, irrigation and inorganic fertilizers were not applied on fields far from the micro-dams; most of them located in the Southern part of the study area.

For each of the 77 selected fields, barley and soil samples were collected at 1 m, 25 m and 50 m from the *A. albida* trunk. As a result, sampling of the fields was performed in a split plot design with the three land use systems (AA, AL and AE) as a main-plot and the distances from the center of *A. albida* trunk (1 m, 25 m and 50 m) as sub-plot. The number of sampled fields was almost equally divided over the three land use systems: AA (n=23), AL (n=27) and AE (n=27).

Barley samples were taken by harvesting all above-ground crop material within a 1 × 1 m quadrant. Within this quadrant, soil samples were collected from the top 0 – 15 cm plough layer and stored in labeled and sealed plastic bags. Canopy characteristics of the *A. albida* trees were determined and their coordinates acquired using a hand-held GPS. The sampled *A. albida* trees had a mean canopy width of 12.43 m (± 0.57 m), a height of 5.89 m (± 0.09 m) and a diameter at breast height (DBH) of 0.62 m (± 0.07 m).

The harvested barley crop material was oven-dried at 70 °C for 48 hours and weighed to calculate the total dry biomass (kg ha^{-1}). Grain was separated from the straw by threshing and grain yield (kg ha^{-1}) was determined for each sample. Total barley biomass was well correlated with barley yield (R^2 of 0.6). Therefore, statistical analysis results will only be presented for barley yield.

Soil samples were sieved through a 2 mm sieve, air dried and analyzed according to the methods described in MoNRDEP (1990). Total nitrogen content (%) was determined using the Kjeldahl method. The Walkley and Black method was used to determine the organic matter content (%) and available phosphorus was determined by (mg kg^{-1}) by the Olsen method. Finally, the soil samples were analyzed for pH (in a 1:2.5 soil: solution extract with water) and soil moisture content. Data were log transformed before statistical analysis.

2.3 Farm survey

In an earlier study, 151 farms were selected within the complete study area (Figure 1) based on a stratified random sampling method from 4 sampling strata based on intensity of land use, natural vegetation and altitude derived from a Digital Elevation Model (DEM), aerial photographs and topographic maps. In each sub-stratum, sample farms were selected randomly (Hadgu et al., in prep). Every farm was surveyed in 2005 including interviews with farmers, and two to three transects were made across farmers' fields. For every farm, field locations were recorded using a hand held GPS (Garmin eTrex Summit 2000) and crops, farmer's estimates of their yield, tree and shrub species and general management in and around the sampled farms were recorded (Hadgu et al., in prep).

Of the full set of farms only farms with barley were taken into account in this study, resulting in a dataset of 81 farms. Barley yield was estimated at farm level based on farmers yield estimates. No data were collected on quantitative soil characteristics nor on yield as a function of distance from trees. For each farm, four categories of characteristics were derived from the results of the survey (categories 1 and 2) or from GIS analysis (categories 3 and 4):

1) livestock density: three classes of livestock density (number cattle per farm household) were derived from the questionnaire of the 2005 farm survey (Hadgu et al., in prep): no livestock (NL), low livestock (1 – 2 $farm^{-1}$; LL) and high livestock (> 2 $farm^{-1}$; HL);
2) inorganic fertilizer use: three classes of inorganic fertilizer use (kg ha^{-1}) were derived from the questionnaire of the 2005 farm survey (Hadgu et al., in prep): no fertilizer (NF), low fertilizer use (1-25 kg ha^{-1}; LF) and high fertilizer use (> 25 kg ha^{-1}; HF);
3) *A. albida* density: tree density was derived from the 2005 land use map of the study area (Hadgu et al., 2008a). High *A. albida* density (HA), medium *A. albida* density (MA) and low *A. albida* density (LA) were observed with more sparsely cultivated land, moderately cultivated land and intensively cultivated land, respectively;
4) presence of *Eucalyptus camaldulensis*: within the study area, presence of Eucalypt is largely associated with urban areas. Using a spatial buffer of 5 km around major towns in a GIS, farms within the buffer were categorized as having a Eucalyptus

dominated land use (HE) whereas farms located outside the 5 km buffer were categorized as farms with low Eucalyptus land use (LE).

2.4 Data analysis

A mixed model analysis (SAS, 1999) was performed for the field scale data set to compare barley yield of different *A. albida* land use systems at various distances from the sampled *A. albida* tree. Similarly, a mixed model analysis was carried out for the soil characteristics, as dependent variables, of the *A. albida* land use systems at different distances from the *A. albida* trunk. Using the split-plot design, *A. albida* land use system (main plot) and distance from the center of the *A. albida* trunk (sub-plot) were considered as fixed effects. Slope of a field was treated as random effect, but was found be be insignificant ($P > 0.05$). Type III sums of squares were computed in the test for fixed effects. Significance of fixed effects was tested using Wald's F-test. To evaluate which specific interactions between distance from the *A. albida* trunk and land use systems contributed significantly, mean estimates from the mixed model output were presented separately. Multiple regression with forward selection (SAS, 1999) was used to investigate the relationship between barley yield and soil properties.

The fields in which measurements were made, were classified into land use land cover (LULC) classes described for the area in a previous study (Hadgu et al., 2008a). A LULC map for 2005 was available which had been classified from Enhanced Landsat Thematic Mapper Plus (ETM+) satellite imagery using maximum likelihood classification. The LULC map was overlaid with the 77 field locations at 1 m distance from the center of *A. albida* trunk and relations between LULC type and *A. Albida* based land use system at these points were analyzed. Field locations with positional inaccuracies (n = 7) were left out of the analysis. In addition, the field locations were overlaid with an elevation map derived from the Shuttle Radar Topographic Mission (SRTM) to relate *A. albida* based land use system to altitude. All spatial analysis procedures were carried out in ArcGIS 9.2 (ESRI, Redlands, CA, USA).

Using the data from the farm survey, the relation between *A. albida* and barley yield was analyzed using Canonical Correspondence Analysis (CCA) in CANOCO 4.5 (Ter Braak and Smilauer, 2002). The CCA analysis was elaborated for the 81 farms for which barley yield was analyzed in relation to the four categories of farm characteristics, *A. albida* density, presence of *Eucalyptus,* livestock density, and inorganic fertilizer use. Altitude of the farm was taken into account as a co-variable. A Monte Carlo permutation test was used to reveal the effect of the explanatory variables on barley yield. As the survey samples were collected randomly, unrestricted permutations with a total of 499 permutations as recommended in the software (Ter

Braak and Smilauer, 2002) was performed. For the CCA analysis, the four explanatory variables were coded into dummy variables. In addition, three categories of farm altitude (low, intermediate and high) were included as covariable.

To estimate added ecosystem service (in this case added barley yield), a simple spatial graphical analysis was carried out with three spatial density configurations of *A. albida* within 1 hectare of land, corresponding to low, moderate and high spatial *A. albida* tree densities. These three tree densities were assumed to correspond to intensively, moderately and sparsely cultivated land use types (Table 1). Starting from an average farm size of 1 ha with four adjacent fields, we assumed fields to consist of regular grids of trees, with trunks at 12 m distance. We calculated yield benefits from *A. albida* as the mean of the benefits at 1m and at 25 m from the trunk in the AA land use system and applied this to circles of barley around each tree. The overall yield benefit or added ecosystem service for this idealized sparsely cultivated land use system (with a high density of trees) was calculated. Trees were then removed from the field at random, each tree reducing yield by a fixed amount equivalent to its area of influence, until the fields were cleared and only the edges contained trees (medium density of trees). Additional yield losses were calculated after further removal of trees down to trees just at the corners of the fields (low density) and no trees at all. Added ecosystem services (contributions to barley yield) were plotted versus tree density at different configurations.

3 Results

3.1 Productivity and land use systems at field scale

Barley yield was significantly affected by distance from the center of *A. albida* trunk (Dist) and by the interaction of distance and land use systems (Dist*Manag) (Table 2). Significantly higher barley yields ($P < 0.05$) were found at 1 m distance from the tree compared to yields at 25 m and 50 m for land use systems AA and AL (Table 3 and Figure 3). In contrast in the AE land use systems, barley yields did not change significantly with distance from the tree although average yields were lowest under the tree (Table 3 and Figure 3).
The effect of *A. albida* land use system and distance from *A. albida* trunk on soil properties is shown in Table 2. The interaction was significant for total N ($P < 0.05$), available P ($P < 0.001$), and soil moisture ($P < 0.0001$). In all cases mean values decreased with distance from the tree for AA and AL, and were more erratic for AE. Organic matter was significantly affected only by distance from the tree irrespective of Acacia based land use system. For available P, the interaction could clearly be

attributed to high available P concentrations at 1 m from the tree in the AL land use system (Table 3). Soil moisture showed sharply decreasing trends with distance for AA and AL, and increasing trends for AE (Table 3). Soil pH did not show any response to distance of Acacia based land use system. Stepwise regression analysis of barley yield on soil properties indicated that soil moisture significantly affected barley yield in the AA ($P < 0.01$) and the AL ($P < 0.001$) land use systems. In contrast, barley yield was not significantly related with other soil properties (Table 4).

Table 2. Test of fixed effects on barley yield, total N, OM, available P, soil moisture and soil pH for the 2005 field locations (n=77) in Tigray, Ethiopia.

	Source	Num DF	Den DF	Type III F	P-value
Barley yield					
	Manag	2	9.47	1.71	0.2316
	Dist	2	17.3	9.44	0.0017
	Dist * Manag	4	17.4	6.58	0.0021
Total N					
	Manag	2	10.3	0.76	0.4911
	Dist	2	210	0.18	0.8377
	Dist * Manag	4	210	3.22	0.0135
OM					
	Manag	2	7.86	2.23	0.1711
	Dist	2	212	3.48	0.0325
	Dist * Manag	4	212	0.14	0.9692
Available P					
	Manag	2	222	4.18	0.0164
	Dist	2	219	4.46	0.0127
	Dist * Manag	4	219	4.99	0.0007
Moist					
	Manag	2	8.21	1.84	0.2182
	Dist	2	17.1	18.83	<0.0001
	Dist * Manag	4	17.1	34.41	<0.0001
pH					
	Manag	2	13	1.60	0.2400
	Dist	2	215	0.69	0.5003
	Dist * Manag	4	215	0.66	0.6188

Note: Manag is land use system of *Acacia albida* (*Acacia albida* alone (AA), *Acacia albida* and livestock (AL) or *Acacia albida* and Eucalyptus (AE); Dist is distance from the center of *Acacia albida* tree trunk.

Table 3. Mean estimates and standard error from mixed model analysis for barley yield , total N, organic matter (OM), available P, soil moisture and pH for the 2005 field locations (n = 77) in Tigray, Ethiopia.

		Barley yield (kg ha^{-1})		Total N (%)		OM (%)		Available P (mg kg^{-1})		Soil moisture (%)		Soil pH	
Manag	Dist (m)	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
AA	1	1395.93	81.509	0.15	0.01653	2.13	0.2157	20.09	3.8081	0.98	0.0138	6.43	0.3208
AA	25	991.63	81.509	0.14	0.01653	1.89	0.2157	17.87	3.8081	0.90	0.0138	6.45	0.3208
AA	50	939.84	81.509	0.12	0.01653	1.78	0.2157	14.75	3.8081	0.84	0.0138	6.44	0.3208
AL	1	1344.97	75.106	0.17	0.01535	2.36	0.2019	39.02	3.5197	0.97	0.0127	6.63	0.2959
AL	25	1024.21	75.106	0.14	0.01535	2.29	0.2019	19.15	3.5197	0.88	0.0127	7.38	0.2959
AL	50	881.14	75.106	0.14	0.01535	2.01	0.2019	17.15	3.5197	0.82	0.0127	6.66	0.2959
AE	1	1097.64	75.073	0.14	0.01535	2.40	0.2018	15.80	3.5186	0.83	0.0127	6.60	0.2959
AE	25	1248.46	75.073	0.16	0.01535	2.36	0.2018	22.58	3.5186	0.90	0.0127	6.61	0.2959
AE	50	1246.27	75.073	0.18	0.01535	2.07	0.2018	18.04	3.5186	0.93	0.0127	6.61	0.2959

Note: Manag is land use system of *Acacia albida* (*Acacia albida* alone (AA), *Acacia albida* and livestock (AL) or *Acacia albida* and Eucalyptus (AE)); Dist is distance from the center of an *Acacia albida* tree trunk.

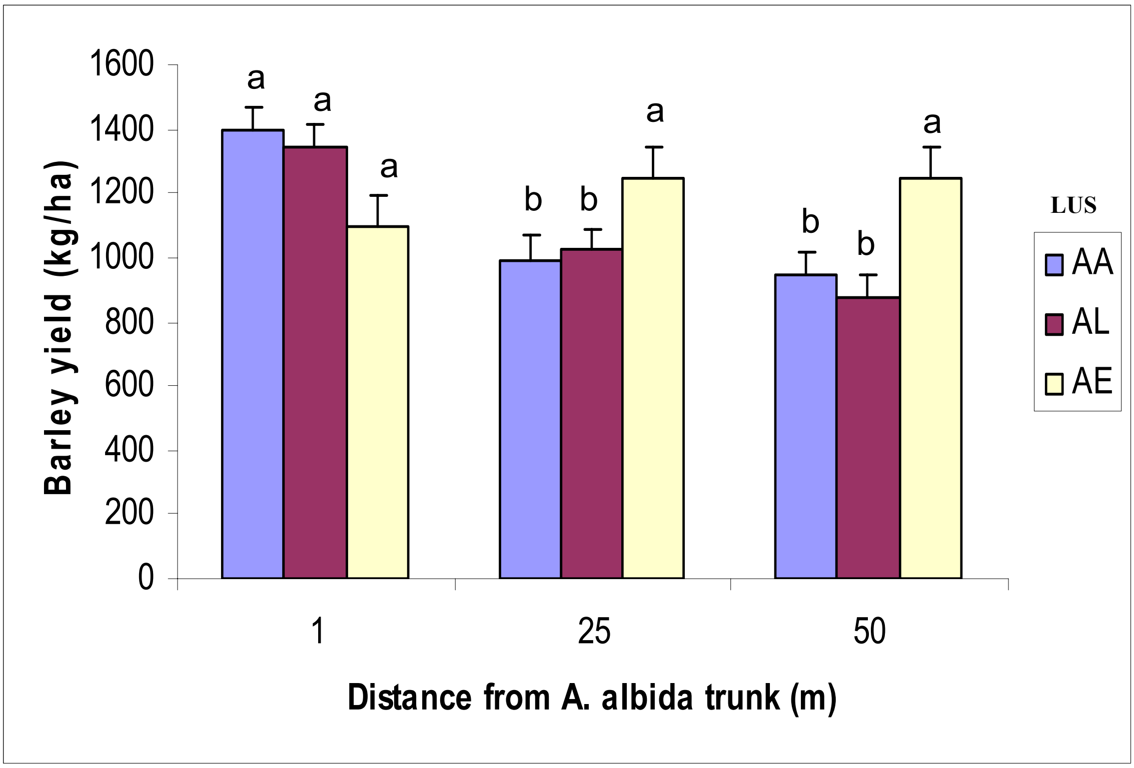


Figure 3. Mean (±SE) barley yield (kg ha^{-1}) at increasing distance from the centre of an *Acacia albida* trunk and for three land use system (*Acacia albida* only, *Acacia albida* and livestock, and *Acacia albida* & Eucalyptus) for 77 field locations sampled in 2005 in Tigray, northern Ethiopia.

Note: Land use systems (LUS) with the same letter are not significantly different.

The GIS analysis showed that land use systems AA and AL were mainly associated with sparsely cultivated and moderately cultivated land use classes, respectively (Figure 4 and 5). The AE land use system was associated with all three agricultural land uses types (sparsely cultivated, moderately cultivated and intensively cultivated). Most locations with AE land use system were also associated with the use of high yielding varieties and inorganic fertilizers, mainly in irrigated areas at an elevation of 2100 – 2200 m (Figure 4b).

Table 4. Multiple regression (forward selection) of soil properties and their contribution to barley yield for each land use system in 2005 in Tigray, northern Ethiopia.

Land use system	Variable Entered	Number Vars IN	Partial R-Square	C(p)	F value	Pr>F
AA (n=69)	Moisture	1	0.1417	1.0597	11.06	0.0014
AL n=81)	Moisture	1	0.1310	1.9932	11.91	0.0009
	P	2	0.0348	0.8287	3.26	0.0751

Note: Total N, OM, available P, soil Moisture content and pH were entered to the regression model but none of them were significant for the AE land use system.

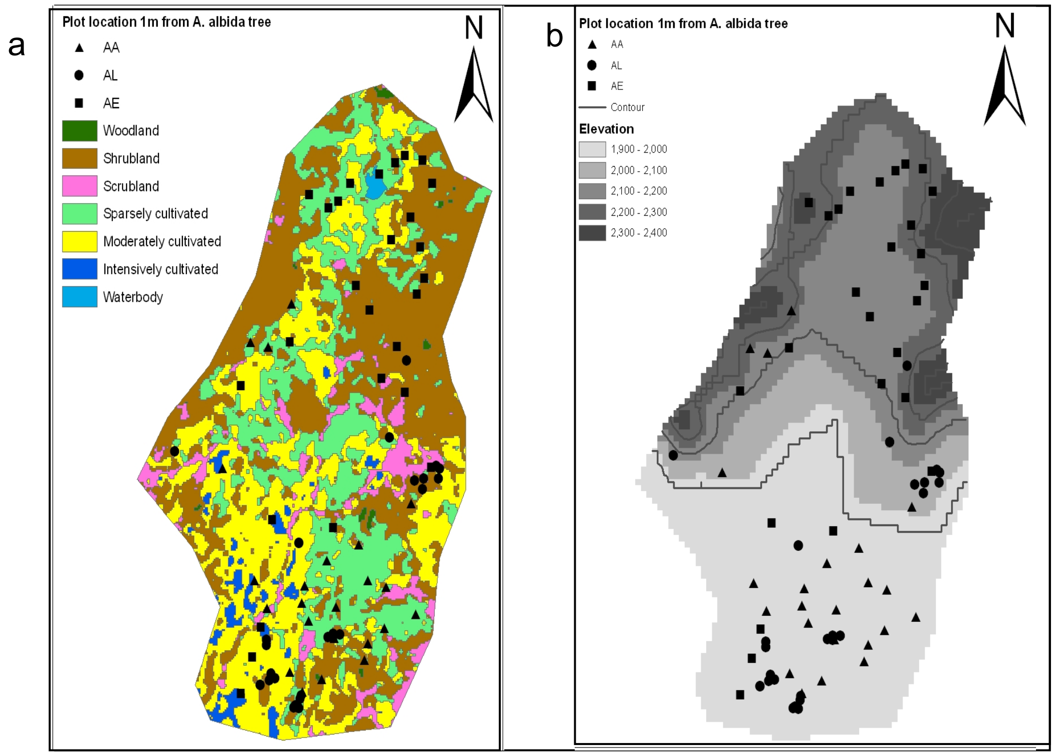


Figure 4. Overlay of field locations with *A. albida* trees with (a) 2005 LULC map and (b) elevation map for the study area in Tigray, northern Ethiopia.

Note: Land use system of *Acacia albida* alone (AA), *Acacia albida* and livestock (AL) and *Acacia albida* and Eucalyptus (AE).

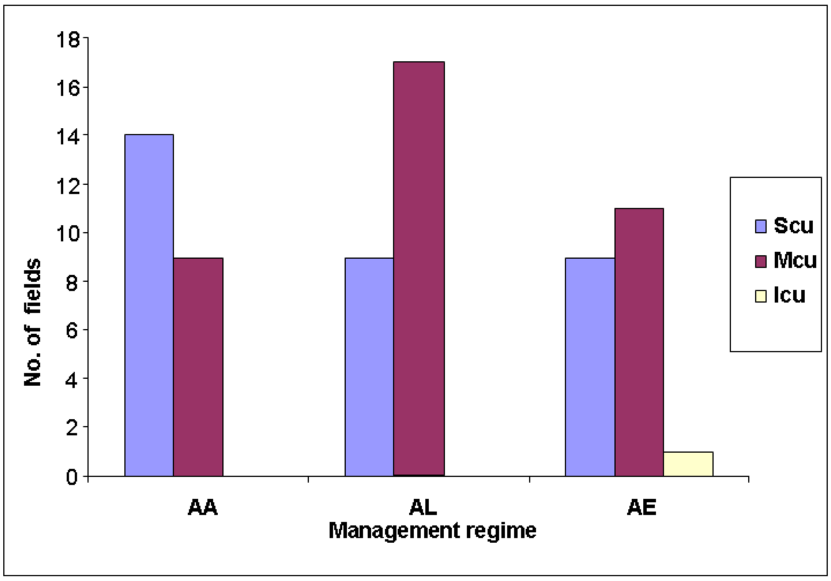


Figure 5. Relation between agricultural land use types and land use system derived from field scale observations for 2005 in Tigray, northern Ethiopia.

Note: Land use system of *Acacia albida* alone (AA), *Acacia albida* and livestock (AL) and *Acacia albida* and Eucalyptus (AE); Land use types: Scu = Sparsely cultivated; Mcu = Moderately cultivated; Icu = Intensively cultivated.

3.2 Productivity and farm characteristics at regional scale

Canonical correspondence analysis showed clear relations between barley productivity and farm characteristics (Figure 6). The first axis of the ordination diagram represents mainly the tree densities of *A. albida* and *Eucalyptus*, while the second axis represents the effect of live stock density and inorganic fertilizer use. Barley yield was positively associated with *A. albida* density, where the highest barley yield (class 3) was strongly related to a high *A. albida* density (HA), whereas low yield (class 1) was associated with a low *A. albida* density (LA).High barley yield was negatively associated with locations with Eucalypt domination (HE), while intermediate barley yield (class 2) was associated with intermediate *A. albida* tree density (MA) and with high fertilizer input (HF). Livestock density was associated to a lower extent with barley yield class. LULC types and the spatial distribution of *A. albida* based land use systems were clearly related (Figure 7). The sparsely cultivated class (Scu) was associated with farms having a high density of *A. albida* and low dominance of Eucalypt, while the intensively cultivated areas (Icu) were characterized by low *A. albida* densities and higher Eucalypt influence.

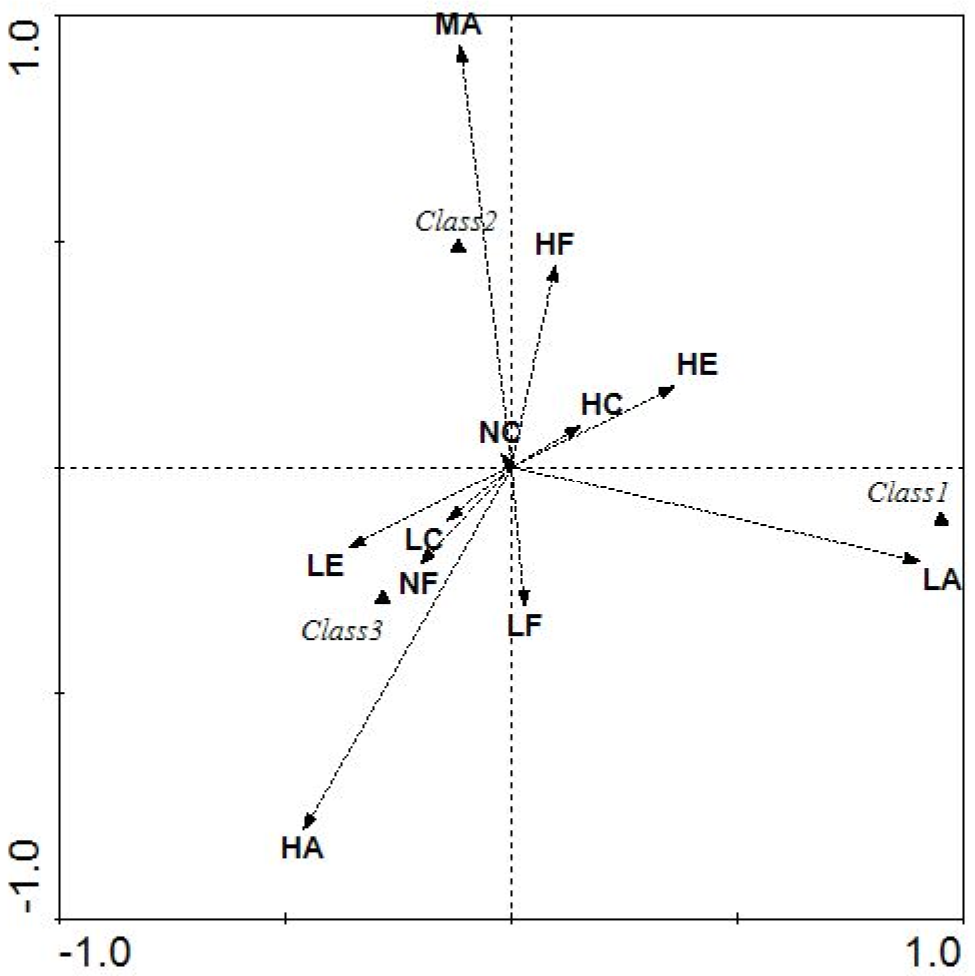


Figure 6. Ordination diagram (Canonical correspondence analysis, CCA) of response variable barley yield and environmental variables represented with triangles and arrows respectively. The length of the arrow and its closeness to the CCA axes is a measure of its strength. Response variables are barley yield of Class 1 (< 500 kg ha^{-1}), Class 2 (500 – 1000 kg ha^{-1}) and Class 3 (>1000 kg ha^{-1}). Explanatory categories are: no fertilizer (NF; 0 kg ha^{-1}), low fertilizer use (LF; 1 – 25 kg ha^{-1}), high fertilizer use (HF; >25 kg ha^{-1}), no livestock (NC; no catte farm^{-1}), low livestock (LC; 1 – 2 catte farm^{-1}), high livestock (HC; >2 catte farm^{-1}), low Eucalyptus farm characteristics (LE; low Eucalyptus farm^{-1}), Eucalyptus dominated farm characteristics (HE; high Eucalyptus farm^{-1}), low *A. albida* density (LA; low *A. albida* farm^{-1}), medium *A. albida* density (MA; medium *A. albida* farm^{-1}) and high *A. albida* density (HA; high *A. albida* farm^{-1}).

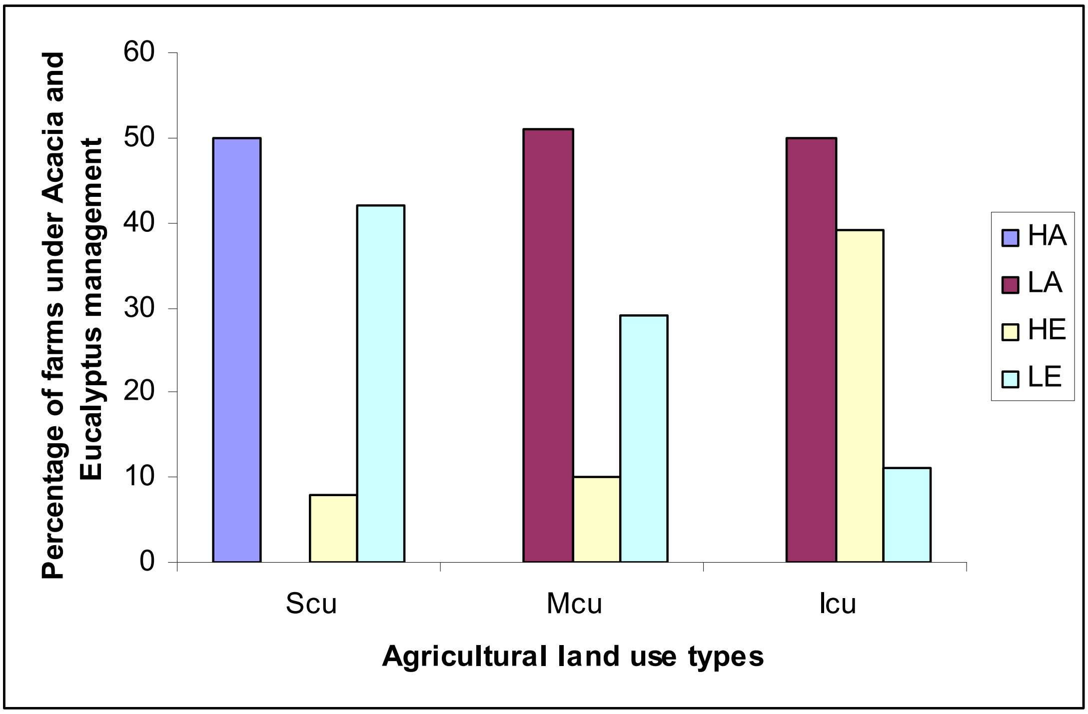


Figure 7. *Acacia albida* density and Eucalyptus tree farm characteristics in relation to agricultural land use types at regional scale in Tigray, northern Ethiopia.

Note: Scu = Sparsely cultivated; Mcu = Moderately cultivated; Icu = Intensively cultivated; HA = High dominance of *A. albida*; LA = Low dominance of *A. albida* , HE = High dominance of Eucalyptus and LE = Low dominance of Eucalyptus.

Figure 8 describes the consequences of *A. albida* tree removal from hypothetical calculations based on our data. The overall yield benefit or added ecosystem service for the idealized sparsely cultivated land use system (high tree density) at T1 is shown as E3 (100%) in Figure 8. Removing trees from inside of the field at random until point T2 was reached, resulted in a reduction in yield benefit from 100% in E3 to 40% in E2, or 65.9 kg ha^{-1} $tree^{-1}$. Further removal of trees down to trees just at the corners of the fields (T3) and complete clearing took away less yield benefit, as the zone of influence of the trees became progressively lower.

4 Discussion

The study presented in this paper integrates field measurements and farm survey data to demonstrate the effect of different *A. albida* based land use systems on barley yield. For the AA and AL land use systems, significantly higher barley yield, and soil

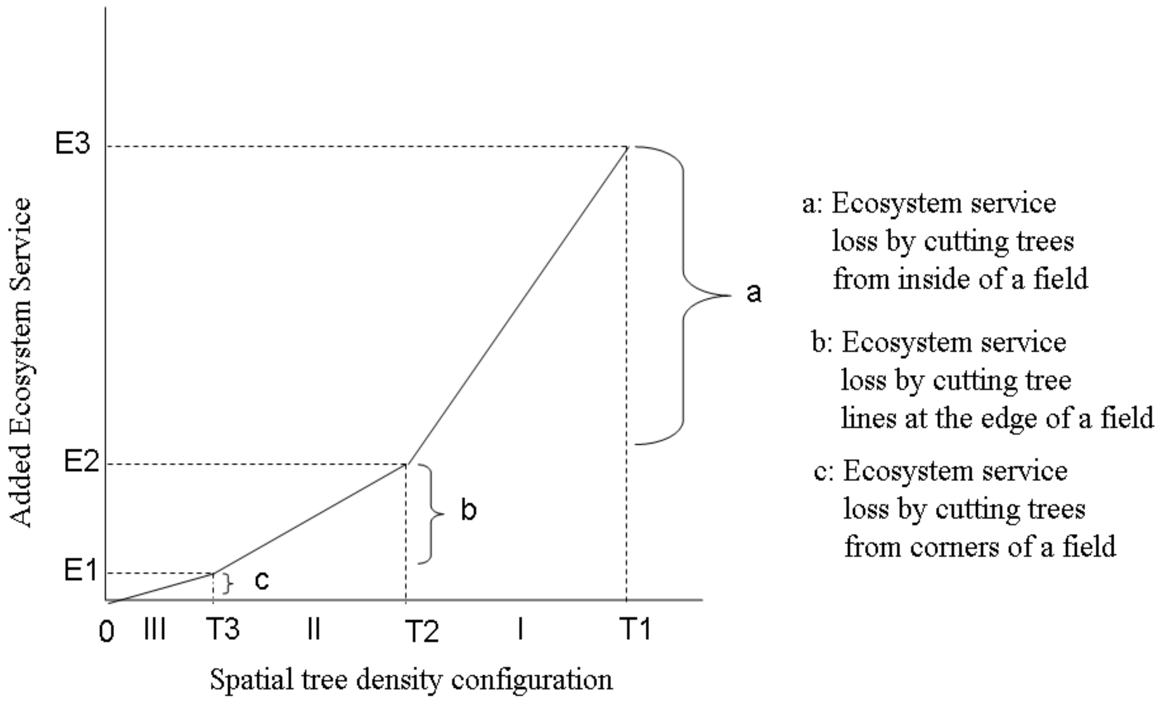


Figure 8. Theoretical model for added ecosystem service of increasing *A. albida* tree density on barley yield at farm level where E1, E2 and E3 refer to increasing barley yield levels for three spatial density configurations of *A. albida* on the corner, edge and within an agricultural fields.

moisture content were found close to the *A. albida* tree trunk compared to outside the canopy (Table 3 and Figure 3). These results confirm the effect of A. albida on productivity found in other studies in Ethiopian smallholder farming systems. Poschen (1986), revealed a 56% increase in grain yields of combined maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench) crops under *A. albida* trees as compared to crop yields outside the tree canopy. Kamara and Haque (1992) investigated soil fertility in vertisols, and demonstrated that organic matter, N, P and available water capacity were higher under *A. albida* canopies than outside. Similar results were found in other African countries, including Niger (Vandenbeldt and Williams, 1992; Kho et al., 2001; Payne et al., 1998) and Tanzania (Chamshama et al., 1998). These studies demonstrated that *A. albida* trees contributed to yield increases in sorghum, maize and millet and enhanced soil fertility, mainly levels of total nitrogen and available phosphorus. Clear differences in total N, soil organic matter and available P under and away from the canopy were also found in our study (Table 2) but variation in data precluded statistical significance. This can also be because of the large distance between sampling points (1, 25 and 50 m away from an *A. albida* trunk) and collection of soil samples after crop harvest, as we did not have a chance to collect soil samples in the beginning of crop growth

These effects are attributed to *A. albida*'s N fixation (Rao et al., 1998) and its effect on less water demand, by shedding its leaves, during the cropping season and reducing crop wilting during dry periods (Rhoades, 1995). In the AL land use system available P was higher closer to the *A. albida* trunk, possibly due to the effect of manure from the livestock.

In contrast, results for the Eucalyptus dominated land use system (AE) indicated that barley yields under *A. albida* in the vicinity of Eucalypt trees did not differ from those in the open field, indicating that the benefits of *A. albida* were offset by Eucalypt. On the contrary, an increasing trend in barley yield was observed with increasing distance from the *A. albida* trunk (Figure 3). Also soil fertility parameters were affected in a different way than in AA and AL systems. In the AE land use system, significantly lower total N, available P and soil moisture were observed under the *A. albida* trunk than further away. Whereas, higher OM was found at closer distance from the *A. albida* trunk in the AE land use system. Crop yield comparison under and outside of a sole Eucalyptus tree canopy, without adjacent *A. albida* growth, was carried out in other studies. Asfaw and Ågren (2007) reported a higher organic C but lower available P and total N under a Eucalyptus tree canopy than outside the canopy. Malik and Sharma (1990) observed a decrease of 47% in mustard and 34% in wheat yields at 10 meter distance from Eucalyptus tree strips. Singh and Kohli (1992) indicated that yield of chickpea, lentil, wheat and cauliflower decreased by more than a half in a 12-m-wide strip to *Eucalyptus* shelterbelts. Similarly, barley yield under the AE land use system in our study decreased as the distance to *A. albida* next to a *Eucalyptus* tree decreased. This effect can be attributed to the high nutrient and water demand of Eucalyptus trees (Sanginga and Swift, 1992) growing adjacent to *A .albida* in the AE land use system. Moreover, allelopathic substances released from leaves or litter of Eucalyptus (Poore and Fries, 1985) may also hinder growth of a barley crop. A higher OM was observed under *A. albida* canopy than farther away in the AE land use system (Table 3). The higher OM under the canopy of the AE land use system may be related to the slow decomposition rate of Eucalyptus litter (Adams and Attiwill, 1986). Unlike the AA and AL land use systems, lower available P was observed at a decreasing distance from the center of *A. albida* trunk for the AE land use system. The fact that Eucalyptus trees reduce vesicular-arbuscular mycorrhizal (VAM) fungal growth and reduces available plant P uptake (Siqueira et al., 1991) may contribute to lower available P in the AE land use system. Moreover, lower soil moisture was observed as distance from the center of *A. albida* trunk decreased in the AE land use system, possibly because of negative effects of eucalyptus on moisture availability for crops growing close to the tree (Sanginga and Swift, 1992). Other studies in Ethiopia indicated decreasing crop output because of the negative hydrological impacts of eucalyptus trees growing close to crops (Malik and Sharma, 1990; Saxena, 1991; Calder et al., 1993). Apparently, our choice of systems, with *A. albida* and Eucalypt growing in mixed stands dampened negative effects of pure Eucalypt stands. This suggests there may be room for optimization of Eucalypt deployment.

Combination of GIS-based land use classification and field measurement results revealed a relationship between land use types and land use systems (Figure 4a and 5). Taking into account any inaccuracies in land use classifications (Hadgu et al., 2008a) and GPS measurements, sparsely cultivated land (also called agroforestry land use type) and moderately cultivated land use types were mainly associated with the AA and AL land use system, respectively. The yield increase in the AA and AL land use system could therefore be attributed to the presence of more trees and shrubs, especially with more *A. albida* trees, in and around agricultural fields of the sparsely cultivated (agroforestry) land use type (Hadgu et al., 2008b). Although the surface area occupied by intensively cultivated land was relatively low compared to surface area occupied by sparsely and moderately cultivated lands, the AE land use system, associated with low barley yield and soil fertility, was mainly observed in intensively cultivated land use type. This implies that less trees/shrubs are present in the AE land use system as compared to the AA and AL land use system. The association of intensively cultivated land use type and AE land use system can be because most AE land use system is practiced close to a micro-dam, located in the northern part of the study area (Figure 1b). Moreover, farmers in the AE land use system practice irrigation farming, use inorganic fertilizer and plant Eucalyptus in and around their agricultural fields to raise their farm income mainly because of their proximity to the micro-dam. In contrast, traditional farming practices (agroforestry systems) without application of inorganic fertilizer is still practiced in fields with the AA and AL land use system.

The farm survey data confirmed the results found at the field scale. From the farm survey data it was apparent that higher barley yield (Class 3) was strongly associated with high *A. albida* tree dominance (Figure 6) which in turn was strongly associated with sparsely cultivated land use type (Figure 7). High yield was also associated with low Eucalypt density and with no or low fertilizer inputs. Low barley yield (Class 1) was observed in farms with low *A. albida* presence. These results could be associated with intensification policies, which emphasize use of fertilizer and often lead to land clearing. There are different explanations for the relatively low yields in intensively cultivated land. One is that the intensification technology is not used properly. We have no data on timing of fertilizer application. Another explanation is that the fertilizer levels used are not compensating for the loss of *A. albida* mediated yield benefits. Our study does not lead to conclusions but raises the question whether current intensification strategies are sufficiently taking into account local natural resources.

The results of the regional farm surveys showed much more clearly than the field data the relation between low *A. albida* densities and Mcu and Icu land use types (Figure 7). Also, they demonstrate that there is an intensification trajectory from Scu to Mcu and Icu which is characterized by less Acacia and more Eucalypt. This can be partly explained by the nature of the different datasets from field and regional scales. The dataset from the field was collected from less intensified parts than the farm survey dataset. Similar to our observations at field scale (Figure 5), also at regional scale, the sparsely cultivated land use type was association with high *A. albida* densities whereas the intensively cultivated land use type was associated with high Eucalyptus dominated farm characteristics (Figure 7).

A longitudinal analysis in the same study area across 41 years by Hadgu et al. (2008a) indicated that intensively cultivated and moderately cultivated land use types increased at the expense of declining sparsely cultivated land use type. Taking this into consideration, the graphical analysis (Figure 8) also revealed that the highest ecosystem loss by cutting trees from sparsely cultivated land use type (I in Figure 8) followed by cutting trees from moderately (II in Figure 8) and intensively cultivated (III in Figure 8) land use types.

5 Conclusions

This study integrates field and regional scales to explore the implication of *A. albida* land use system and land use types on productivity, in this case barley yield. The results of this study revealed increased barley yield and soil fertility as the distance to an *A. albida* trunk decreased in the AA and AL land use system. On the contrary, barley yield and soil fertility showed a decreasing trend as the distance to an *A. albida* trunk decreased in the AE land use system. The study also demonstrated that higher ecosystem service, in terms of barley yield, can be rendered by having more *A. albida* trees within a field than at the edge or corner of a field. Higher ecosystem service can also be gained from sparsely cultivated land use types than intensively and moderately cultivated land use types. This study suggests that productivity of crops and soils can be increased by appropriate use of local biodiversity resources, for example, *A. albida* trees. Land use planners and decision makers should, therefore, integrate locally available resources in planning and implementing rural developments.

6 Acknowledgements

Financial support was provided by an IITA-Lukas Bader Fellowship and a NUFFIC fellowship to the first author. We thank IITA for providing the IITA- Lukas Brader Fellowship. We also thank Mr B. Oyewole, for logistic support, and Dr Morag Ferguson and Dr Michael Pillay, for being IITA supervisors.

References

Adams, M.A., Attiwill, P.M., 1986. Nutrient cycling and nitrogen mineralization in eucalypt forests of southeastern Australia. II. Indices of nitrogen mineralization. Plant Soil. 92, 341 – 362.

Akonde, T.P., Leihner, D.E., Steinmuller, N., 1996. Alley cropping on an Ultisol in subhumid Benin. Part 1. Longterm effect on maize, cassava and tree productivity. Agrofor. Syst. 34, 1 – 12.

Asfaw. Z., Ågren, G.I., 2007. Farmers' local knowledge and topsoil properties of agroforestry practices in Sidama, Southern Ethiopia. Agrofor. Syst. 71, 35 – 48.

Calder, I.R., Hall, R.K., Prasanna, K.T., 1993. Hydrological impact of Eucalyptus plantation in India. J. Hydrol. 150, 635–648.

Caldwell, M.M., Richards, J.H., 1989. Hydraulic lift: water efflux from upper roots improves effectiveness of water uptake by roots. Oecologia. 75, 1 – 5.

Cannell, M.G.R., Van Noordwijk, M., Ong, C.K., 1996. The central agroforestry hypothesis: the trees must acquire resources that the crop would not otherwise acquire. Agrofor. Syst. 34, 27 – 31.

Chambers, R., Guijt, I., 1995. PRA - five years later. Where are we now? Forest, Trees and People Newsletter. 26/27, 4 – 13.

Chamshama, S.A.O., Mugasha, A.G., Kløvstad, A., Haveraaen, O., Maliondo, S.M.S., 1998. Growth and yield of maize alley cropped with *Leucaena leucocephala* and *Faidherbia albida*in Morogoro, Tanzania. Agrofor. Syst. 40, 215 – 225.

Costanza, R., Dárge, R., De Groot, R.S., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton. P., Van den Belt. M., 1997. The value of the world's ecosystem services and natural capital. Nature. 387, 253 – 260.

Daily, G.C., 1997. Introduction: What are ecosystem services? In: Daily, G.C. (Ed.), Nature's services: societal dependence on natural ecosystems. Island Press, Washington, pp 1 – 10.

Dawson, J.F., 1993. Hydraulic lift and water use by plants: implications for water balance, performance and plant-plant interactions. Oecologia. 95, 565 – 574.

Dejene, A., 2003. Integrated Natural Resources Management to Enhance Food Security: The Case for Community-Based Approaches in Ethiopia. Environment and Natural Resources Working Paper No. 16. FAO, Rome.

Deurloo, H.A., Haileselassie, T., 1994. Rehabilitation of Degraded and Degrading Areas of Tigray, Ethiopia, Survey on Farm Practices based on Local Knowledge. Wageningen Agricultural University, Wageningen.

Feoli, E., Vuerich, L.G., Woldu, Z., 2002. Processes of environmental degradation and opportunities for rehabilitation in Adwa, northern Ethiopia. Landscape Ecol. 17, 315 – 325.

García-Barrios, L., 2003. Plant-plant interactions in tropical agriculture. In: Vandermeer, J. (Ed), Tropical Agroecosystems. CRC Press, NewYork, pp. 1 – 58.

García-Barrios, L., Ong, C.K., 2004. Ecological interactions, management lessons and design tools in tropical agroforestry systems. Agrofor. Syst. 61, 221–236.

Goldberg, D. 1990. Components of Resource Competition in Plant Communities. In: Grace, J.B., Tilman, D. (Eds.) Perspectives on Plant Competition. Academic Press, New York, pp 27 – 49.

Hadgu, K.M., Kooistra, L., Rossing, W.A., Van Bruggen, A.H.C. 2008a. Detection of land use/ land cover changes by remote sensing and associated drivers for the period 1964 – 2005 in the highlands of Tigray, Ethiopia. Agric. Ecosyst. Environ. (Submitted)

Hadgu, K.M., Epema, G. F., Van Bruggen, A.H.C. 2008b. Biodiversity and Sustainability in Agricultural landscapes in Tigray, northern Ethiopia. Landscape Urban Plan. (Submitted)

Hunter, A.F., Aarssen, L.W., 1988. Plants helping plants. Biosci. 38, 34 – 40.

Hurni, H., 1993. Land degradation, famine and land resource scenarios in Ethiopia. In: Pimentel, D. (Ed.), World soil erosion and conservation, Cambridge University Press, Cambridge, pp 27 – 61.

IAASTD, 2008. Synthesis Report of IAASTD. International Assessment of Agricultural Science and Technology for Development (IAASTD). Island Press, Washington, DC.

IAC, 2004. Realizing the promise and potential of African agriculture: science and technology strategies for improving agricultural productivity and food security in Africa. InterAcademy Council (IAC), Amsterdam.

Kamara, C.S., Haque, I., 1992. *Faidherbia albida* and its effects on Ethiopian highland Vertisols. Agrofor. Syst. 18, 17 – 29.

Kho, R.M., Yacouba, B., Yayé, M., Katkoré, B., Moussa, A., Iktam., A.,Mayaki., A., 2001. Separating the effects of trees on crops: the case of *Faidherbia albida* and

millet in Niger. Agrofor. Syst. 52, 219 – 238.
Liebman, M., Gallandt, E.R., 1997. Many little hammers: ecology management of crop-weed interactions. In: Jackson, L.E. (Ed.), Ecology in Agriculture. Academic press, New York, pp 291 – 343.
Malik, R.S., Sharma, S.K., 1990. Moisture extraction and crop yield as a function of distance in a row of *eucalyptus tereticornis*. Agrofor. Syst. 12, 187–195.
MEA, 2003. Ecosystems and human well-being a framework for assessment. In: Alcamo, J., Bennett, E.M. (Eds.), Millennium Ecosystem Assessment. Island Press, Washington, DC.
MEA, 2005. Ecosystems and human well-being: Current state and trends. In: Hassan, R., Scholes, R. (Eds.), Millennium Ecosystem Assessment. Island Press, Washington, DC.
Messerschmidt, D., 1995. Rapid Rural Appraisal for Community Forestry. The RA process and Rapid Diagnostic Tools. IIED, London.
Miller, A.W., Pallardy, S.G., 2001. Resource competition across the crop-tree interface in a maize-silver maple temperate alley cropping stand in Missouri. Agrofor. Syst. 53, 247 – 259.
MoNRDEP, 1990. Soil Analysis Laboratory Manual. Ministry of Natural Resources Development and Environmental Protection (MoNRDEP), Addis Ababa.
Odhiambo, H.O., Ong, C.K., Deans, J.D., Wilson, J., Khan, A.A.H., Sprent, J.I., 2001. Roots, soil water and crop yield: tree crop interactions in a semi-arid agroforestry systems in Kenya. Plant Soil. 235, 221 – 233.
Ong, C.K., 1995. The 'dark side' of intercropping: manipulation of soil resources. In: Sinoquent, H., Cruz, P. (Eds.), Ecophysiology of Tropical Intercropping. Institute National de la Recherche Agronomique, Paris, pp. 45 – 65.
Ong, C.K., Black, C.R., Marshall, F.M., Corlett, J.E., 1996. Principles of resource capture and utilization of light and water. In: Ong, C.K., Huxley, P. (Eds.), Tree-crop Interactions: A physiological Approach. CAB International, Wallingford, pp. 73 – 158.
Ong, C.K., Leakey, R.R.B., 1999. Why tree-crop interactions in agroforestry appear at odds with tree-grass interactions in tropical savannahs**.** Agrofor. Syst. 45, 109 – 129.
Paoletti, M.G., Pimentel. D., Stinneff, B.R., Stinneff, D., 1992. Agroecosystem biodiversity: matching prod'uction and conservation biology. Agric. Ecosyst. Environ. 40, 3 – 23.
Payne, W.A., Williams, J.H., Maì Moussa, K.A., Stern, R.D., 1998. Crop Diversification in the Sahel through Use of Environmental Changes near *Faidherbia albida* (Del.) A. Chev. Crop Sci. 38, 1585 – 1591.

Poore, M.E.D., Fries, C., 1985. The ecological effects of eucalyptus. Forestry Paper No. 59. FAO, Rome.

Poschen, P.,1986. An evaluation of the *Acacia albida*-based agroforestry practices in the Hararghe highlands of Eastern Ethiopia. Agrofor. Syst. 4, 129 – 143.

Radersma, S., Lusiana, B., Noordwijk, M.V., 2004. Simulation of soil drying induced phosphorus deficiency and phosphorus mobilization as determinants of maize growth near tree lines on Ferralsol. Field Crops Res. 91, 171 – 184.

Radersma, S., Grierson, P.F., 2004. Phosphorus mobilization in agroforestry: organic anions, phosphatase activity and phosphorus fractions in the rhizosphere. Plant Soil. 259, 209 – 219.

Rao, M.R., Nair, P.K.R., Ong, C.K., 1998. Biophysical interactions in tropical agroforestry systems. Agrofor. Syst. 38, 3 – 50.

Rao, M.R., Mathuva, M.N., 2000. Legumes for improving maize yields and income in semi-arid Kenya. Agric. Ecosyst. Environ. 78, 123 – 137.

Rhoades, C.C., 1995. Seasonal pattern of nitrogen mineralization and soil moisture beneath *Faidherbia albida* (syn *Acacia albida)* in central Malawi. Agrofor. Syst. 29, 133 – 145.

Rhoades, C.C., 1997. Single-tree influences on soil properties in agroforestry:lessons from natural forest and savanna ecosystems. Agrofor. Syst. 35, 71 – 94.

Sachs, J.D., McArthur, J.W., 2005. The Millennium Project: a plan for meeting the Millennium Development Goals. The Lancet. 365, 347 – 353.

Sanginga, N., Swift, M.J., 1992. Nutritional effects of Eucalyptus litter on the growth of maize (*Zea mays*). Agric. Ecosyst. Environ. 41, 55 – 65.

Sarraute, J.L., Vonder, O.W., 1994. Rehabilitation of Degraded and Degrading Areas of Tigray, Ethiopia: landsurface, landcover and change detection classifications based on remote sensing. Wageningen Agricultural University, Wageningen.

SAS, 1999. SAS/STAT User's manual. Volume I. SAS Institute Inc., Cary.

Saxena, N.C., 1991. Crop losses and their economic implications due to growing of eucalyptus on field bunds - a pilot study. Agrofor. Syst. 16, 231 – 245.

Shiferaw, B., Holden, S.T., 2000. Policy instruments for sustainable land management: The case of highland smallholders in Ethiopia . Agric. Econ. 22, 217 – 232.

Smith, D.M., Jackson, N.A., Roberts, J.M., Ong, C.K., 1999. Root distributions in a Grevillea robusta – maize agroforestry system in semi-arid Kenya. Plant Soil. 211, 91 – 205.

Singh, D., Kohli, R.K., 1992. Impact of Eucalyptus tereticornis Sm. shelterbelts on crops. Agrofor. Syst. 20, 253 – 266.

Siqueira, J.O., Nair, M.G., Hammerschmidt, R., Safir, G.R., 1991. Significance of phenolic compounds in plant-soil-microbial systems. Crit. Rev. Plant Sci. 10, 63 – 121.

Ter Braak, C.J.F., Smilauer, P., 2002. CANOCO Reference manual and CanoDraw for Windows User's guide: Software for Canonical Community Ordination (version 4.5). Microcomputer Power, New York.

UN Millennium Project, 2005. Investing in Development: A Practical Plan toAchieve the Millennium Development Goals. Earthscan, New York.

Vandenbeldt, R.J., Williams, J.H., 1992. The effect of soil surface temperature on the growth of millet in relation to the effect of *Faidherbia albida* trees. Agric. Forest Meteorol. 60, 93 – 100.

Worede, M., 1991. An Ethiopian perspective on conservation and utilization of plant genetic resources. In: Engels, J.M.M., Hawkes, J.G., Worede, M. (Eds.), Plant Genetic Resources of Ethiopia. Cambridge University Press, Cambridge, pp 3 – 19.

Worede, M., 1997. Ethiopian in situ conservation. In: Maxted, N., Ford-lloyd, B.V., Hawkes, J.G. (Eds.). Plant Genetic Conservation: the in situ approach. Chapman and Hall, London, pp. 290 – 301.

Chapter 6

Synthesis and conclusions

1 Introduction

Environmental degradation (e.g. soil erosion and decrease in natural vegetation) and deterioration of agricultural productivity are increasing in Tigray, northern Ethiopia, mainly because of intensification of agricultural production in response to an increasing population and increasing demand for food, animal feed and woody biomass. Intensification commonly involves the cutting of trees in fields, planting of *Eucalyptus* spp. around fields, and growing modern crop cultivars in pure stands rather than traditional crops and land races in mixtures. Although inorganic fertilizer use has been stimulated, actual fertilizer use is minimal due to their high costs (Shiferaw and Holden, 1999). Agricultural intensification is frequently associated with increased erosion (Nyssen, 1997).

To protect the environment from being eroded and to optimize agricultural productivity, understanding of underlying processes such as changes in land use/land cover (LULC), agro-biodiversity reduction and farming practices and their interrelations areis necessary. At the beginning of this research, limited spatial and temporal information on LULC, agro-biodiversity and agricultural practices was available for the Tigray region. Moreover, there was limited understanding on the agro-biodiversity-productivity-sustainability relationship in agricultural landscapes. Especially in developing countries like Ethiopia where 85% of the population directly depends on agriculture this knowledge is essential to direct developments in traditional agro-ecosystems (Shiferaw and Holden, 1999; CSA, 2004).

Therefore, this thesis addressed LULC, agro-biodiversity, sustainability and agricultural productivity, and their relationship at various spatial and temporal scales in the heterogeneous tropical highland region of Tigray. Spatial and temporal approaches were adopted to understand variation in relation to various geographic, developmental and agricultural drivers and provide recommendations for future sustainable land use management in the study region. The research objectives were:

1. To detect LULC changes based on a time series of remote sensing data and identify drivers of the changes at a regional scale **(Chapter 2);**
2. To identify and analyze factors affecting agro-biodiversity and sustainability (with soil erosion as indicator), focusing on relationships between agro-biodiversity, physical environment, crop production characteristics and measures of wealth at farm and regional scales **(Chapter 3)**;
3. To study spatial and temporal variation in agro-biodiversity and soil degradation in relation to farm, productivity, wealth, social, and development drivers and topographic characteristics between 2000 and 2005 at farm and regional scale **(Chapter 4)**; and

4. To investigate the effects of *Acacia albida* based land use systems on crop productivity at field and regional scales **(Chapter 5)**.

The objectives and major results of the research are discussed in section 6.2. In section 6.3, the contributions of this research to sustainable land use management are presented. Section 6.4 provides implications and recommendations, and section 6.5 presents the main conclusions of the research. Research outlooks are summarized in section 6.6.

2 Research objectives and major results of this thesis

Objective 1:
To detect LULC changes based on a time series of remote sensing data and identify drivers of the changes at a regional scale.

Assessing LULC patterns is an important step in sustainable land use planning, especially in developing countries which are facing rapid LULC changes (Brandt and Townsend, 2006). Increased availability of remotely sensed data provides an opportunity to analyze historical and current LULC patterns. Chapter 2 provides an approach that can help to improve understanding of LULC changes and their drivers for heterogeneous landscapes of the tropical highlands. A spatially explicit multiple logistic regression approach was adopted to assess LULC changes and their drivers at regional scale, from time-series of remote sensing data (1964, 1994 and 2005). Between 1964 and 1994, a sharp reduction in natural habitats and an increase in agricultural land were demonstrated (Table 3 and Figure 4 in Chapter 2). The sharp reduction in natural habitats can mainly be attributed to changes in land use policies during the 1964 – 1994 period. A nation-wide change in land distribution took place in 1975 and resulted in a change of ownership from relatively few landlords to many individual farmers (Abegaz, 2004). This change contributed considerably to cutting of trees and shrubs from both natural habitats and agricultural lands, especially in locations far from the nearest major road. In addition, war, drought and famine in this period contributed to the destruction of natural habitats, which was more severe in remote areas compared to areas close to roads (Keller, 1992; Amacher et al., 2004). In the same period (1964-1994), expansion and intensification of agricultural land increased (Table 6 and Figure 4 in Chapter 2) due to an increase in population density.

Between 1994 and 2005, changes in density and location of natural habitats were associated with proximity to settlements, high altitude and steep slopes. At locations with high altitude and steep slopes, conversion of natural habitats to agricultural lands and other LULC types was the greatest, especially close to settlements (Table 6 and Figure 4 in Chapter 2). Population pressure, in both rural and urban areas, was again the main driver of changes (increases) in agricultural land as well as agricultural intensification (Table 6 in Chapter 2).

The approaches used in chapter 2 (Figure 2 in Chapter 2), namely processing of a time-series of remotely sensed data coupled with spatially explicit regression resulted in a description of LULC changes and explanation of the changes in relation to their drivers. The results gave a better insight in the trends of LULC changes which can help to predict their future consequences.

Objective 2:

To identify and analyze factors affecting agro-biodiversity and sustainability (with soil erosion as indicator), focusing on relationships between agro-biodiversity, physical environment, crop production characteristics and measures of wealth at farm and regional scales.

Several definitions for sustainable agriculture have been presented in the literature, among others ‘A way of farming that will continually protect the environment, conserve resources, and enhance the health and safety of farm-workers and consumers, while producing needed food supplies at a profit for farmers’ or ‘An agriculture that is ecologically sound, economically viable, socially just, and humane’ (Gliessman, 2001). Sustainability has also been defined as the ability of an agro-ecosystem to maintain productivity when subject to a major disturbing force. These definitions imply that a given level of productivity can be maintained over time, and involves the ability of farm management to maintain agro-ecosystem functions (Conway, 1987). In this thesis, one major indicator of sustainability was selected to represent other aspects of sustainability, namely soil erosion, as this is a clear sign of non-sustainability which is visible in the study area and which seems to be associated with the observed loss of agro-biodiversity.

For sustainable agricultural production and maintenance of ecosystems, information on the status of agro-biodiversity in agricultural landscapes is necessary (Thrupp, 2000). However, there is a limited understanding of the status and interrelation of agro-biodiversity and sustainability in agricultural landscapes of Tigray. In Chapter 3, agro-biodiversity (number of tree- and shrub species, and crop varieties and landraces) and sustainability (as indicated by soil erosion) were assessed in relation to farm, farmer, and development drivers and physical characteristics at farm and regional scales in Tigray. This study showed that there was greater agro-biodiversity (combined crop and tree/shrub diversity) at higher altitudes, and at farms with more crop- soil types per farm. When more than one plant species grow in a particular area, soil nutrients and other resources can be utilized more efficiently because of the different inter- and intra-specific characteristics of the crop and non-crop plants (Altieri, 1994 and 1999). Farmers who have an array of crop selection criteria tend to maintain greater agro-biodiversity by planting different crops and varieties or landraces to fulfill their diversified demands (e.g., yield, early maturity, drought resistance, market value, weed resistance, insect pest resistance, straw quality, threshability and beverage quality). Diverse crops and varieties use microhabitats with different nutrients, moisture and other resources (Altieri, 1999). This enhances the stability and sustainability of the food production system.

In line with this trend, non-sustainability (measured by soil erosion) was negatively associated with number of soil types per farm, number of crop types per farm, number of crop selection criteria and number of animals per farm. Moreover, severe soil erosion was associated with low soil fertility, and was not encountered on farms with a high diversity of tree- and shrub species and crop varies. Soil erosion was significantly more severe on farms where inorganic fertilizer was used. Similarly, Matson et al. (1997) showed that increased use of high agricultural inputs (i.e., inorganic fertilizer) can have negative local consequences, such as increased soil erosion, reduced soil fertility and agro-biodiversity loss. Contrary to other research results (Belsky and Blumenthal, 1997), high numbers of animals per farm were not associated with increased erosion. Relatively more animals are kept in remote areas, where crop and animal production apparently are still balanced within the farm. However, the average animal densities per farm of 1 ha (2 oxen, 4 sheep, 2 goats, 1 beehive and 10 chickens) call for further analysis to show to which extent common lands are threatened.

Spatial analysis of agro-biodiversity and non-sustainability (soil erosion intensity) indicated that agro-biodiversity was reduced and soil erosion was worse at farms close to the nearest town and major road. This could be partially attributed to the adoption of new, intensive agricultural technologies that are usually used first in farms accessible from towns and major roads. In addition, the proximity of markets promotes the cutting and sale of trees for firewood and construction purposes. This premise is supported by the observed increase in intensively cultivated land use types close to towns and major roads (Chapter 2).

Objective 3:

To study spatial and temporal variation in agro-biodiversity and soil degradation in relation to farm, productivity, wealth, social, development drivers and topographic characteristics between 2000 and 2005 at farm and regional scale.

A reduction in natural habitats and an increase in agricultural lands were documented at a regional scale in the highlands of Tigray for a period of 41 years (Chapter 2). In chapter 4, variation in spatial and temporal agro-biodiversity and soil erosion were investigated at both farm and regional scales in the same study area.

This study revealed that there was a decrease in agro-biodiversity between 2000 and 2005 (Figure 4 and Table 5 in Chapter 4), mainly at farms with high inorganic fertilizer use and a large number of credit sources (Table 5 in Chapter 4) located close to the nearest town or major road (Figure 5 in Chapter 4). Spatially explicit land use classification and agro-biodiversity analysis revealed that sparsely cultivated and intensively cultivated land use types were associated with high and low agro-biodiversity, respectively (Figure 6 in Chapter 4). As a result, intensively cultivated land, where trees and shrubs have been cut, provides fewer ecosystem services such as natural soil fertility (Chapter 5).

In 2000, farms located close to towns and major roads had relatively low agro-biodiversity which was associated with intensive agricultural practices, such as the use of high yielding crop varieties and inorganic fertilizers (Chapter 3). Higher agro-biodiversity was positively associated with extensive agricultural practices, including the planting of many diversified crops for a range of crop selection criteria and the use of animal manure, mainly located in region IV (Figure 1 in Chapter 4) and far from the nearest town and major road. High agro-biodiversity was also associated with higher available P and total N contents in the soil, resulting in higher crop caloric yields than at locations with lower agro-biodiversity. Higher overall yield can be obtained from a unit area when different crops or landraces are grown in mixtures in the same field, and utilize nutrients, water and light efficiently due to their differences in plant architecture and resource capture, resulting in complementation or facilitation of plant growth (Tilman et al., 1996; Picasso et al., 2008). Agro-biodiversity was reduced when farmers had access to credit and used inorganic fertilizers. Thus, the decrease in agro-biodiversity could be attributed to the planting of few high-yielding crops with high market value, coupled with the application of inorganic fertilizer, mainly at farms close to towns and major roads.

In 2005, soil erosion was more severe at farms on steep slopes (Table 4 and Figure 3 in Chapter 4) and at locations close to towns and major roads with intensively cultivated land where most trees and shrubs had been cut (Chapter 2). Soil erosion was less severe in areas with high soil OM content, where a multitude of crops were grown for a range of purposes. Low soil OM content restricts the water holding capacity of the soil and facilitates water run off (Pimentel and Kounang, 1998). The consequence of high soil erosion can be low crop productivity as essential soil nutrients are lost in the process (Mokma and Sietz, 1992).

Objective 4:

To investigate the effects of Acacia albida based land use systems on crop productivity *at field and regional scales.*

Smallholder farming in Tigray is under pressure because of declining soil fertility, increasing soil erosion, population pressure and water scarcity (Hurni, 1993; Shiferaw and Holden, 1999). To explore the underlying reasons for these problems, land use, agro-biodiversity, farming practices and soil degradation were assessed at different spatial and temporal scales in chapters 2, 3 and 4. However, there was still limited information on the contribution of trees to agricultural productivity in Tigray. In chapter 5, the effects of different *Acacia albida* land use systems on barley productivity were assessed at field and regional spatial scales.

At the field scale, higher barley yields and end-of-season soil moisture contents were observed at locations close to an *A. albida* tree trunk compared to locations outside of the canopy in land use systems with *A. albida* alone (AA) and *A. albida* plus livestock (AL) (Table 3 and Figure 3 in Chapter 5). Higher total soil N was also demonstrated under the *A. albida* canopy than farther away in the AA land use system (Table 2 in Chapter 5). The increased N content was likely due to N fixation by *A. albida* (Rao et al., 1998) and water conservation by shedding its leaves during the wet season when crops are planted (Rhoades, 1995). In the AL land use system available P was higher in close proximity to the *A. albida* trunk, possibly due to the effect of manure from the livestock seeking shade under the tree.

However, when *Eucalyptus* sp. was grown adjacent to an *A. albida* tree (AE), barley yields under the *A. albida* canopy did not differ from those in the open field, indicating that the benefits of *A. albida* were offset by *Eucalyptus*. Barley yield was even higher at increasing distance from the *A. albida* trunk in AE land use systems (Figure 3 in Chapter 5). In these systems, significantly lower total N, available P and soil moisture were observed under the *A. albida* trunk than further away. This effect can be attributed to the high nutrient and water demand of *Eucalyptus* trees (Sanginga and Swift, 1992). Moreover, allelopathic substances released from leaves or litter of *Eucalyptus* (Poore and Fries, 1985) may hinder the growth of a barley crop. While the presence of *Eucalyptus* resulted in a higher soil OM content (Table 3 in Chapter 5) because of the slow decomposition rate of *Eucalyptus* litter (Adams and Attiwill, 1986), availability of N and P was reduced possibly by allelopathic effects on various microorganisms. *Eucalyptus* trees also reduce vesicular-arbuscular mycorrhizal (VAM) fungal growth, negatively affecting the P uptake by neighbouring plants (Siqueira et al., 1991).

AA and AL land use systems were mainly associated with sparsely cultivated (Scu) and moderately cultivated (Mcu) land use types (Figure 4a and 5 in Chapter 5). Scu and Mcu land use types were also associated with higher productivity because of the presence of more *A. albida* trees in and around agricultural fields (Chapter 4). The intensively cultivated land use type (Icu), characterized by presence of fewer or no trees and shrubs, was more common in the AE land use system. This land use system is frequently encountered close to micro-dams (Figure 1b in Chapter 5), stimulating the use of irrigation and inorganic fertilizer. Despite the use of irrigation and inorganic fertilizer in AE systems, regional scale analyses revealed higher barley yields at lower *Eucalyptus* and higher *A. albida* densities, with no or little inorganic fertilizer use (Figure 6 in Chapter 5). Higher *A. albida* density was associated with the Scu land use type (Figure 7 in Chapter 5) and traditional mixed farming practices. Intensification of land use from Scu to Mcu and Icu (Chapter 2) likely led to a reduction in ecosystem services that *A. albida* can provide (Figure 8 in Chapter 5).

3 Contributions of the research to sustainable land use management

In line with the diversity-productivity and diversity-sustainability hypotheses, several studies indicate higher productivity and sustainability (stability and resilience) at higher species diversity, mainly for grassland ecosystems (Tilman et al., 1996; Tilman and Downing, 1996; Dukes, 2001; Tilman et al., 2001; Tilman et al., 2006; Tylianakis et al., 2008; Verheyen et al., 2008). Most of these studies focused on the field or farm scale, and there is still a knowledge gap on the effects of scaling up from field or farm level to the regional scale (Loreau et al., 2001). Moreover, there is limited information on the agro-biodiversity-productivity-sustainability relationship in agricultural landscapes, especially in developing countries like Ethiopia where agriculture is the main form of land use (Shiferaw and Holden, 1999; CSA, 2004). In this thesis, agro-biodiversity, productivity and sustainability relationships were assessed at different spatial and temporal scales, so that we may (prudently) extrapolate to the future.

3.1 Biodiversity-productivity-sustainability relationships

The human population in Ethiopia is expected to double in 2030, at a growth rate of 2.7% annually, as compared to the present population (Sonneveld and Keyzer, 2003; CSA, 2004). Food demand is expected to grow even faster, 3.6% annually, (Sonneveld and Keyzer, 2003; UN Millennium Project, 2005) because of the increase in population and changes in diet associated with urbanization. To increase food production in Ethiopia, Sonneveld and Keyzer (2003) predicted that agricultural lands will expand and land use will intensify. Rosegrant et al. (2005) estimated that land under cereal production in Africa will increase from 102.9 Mha in 1997 to 135.3 Mha in 2025. This will continue the process of conversion from natural habitats to agricultural lands to feed the increasing population, and may result in a doubling or tripling of inorganic fertilizer application, a twofold increase in water use and a threefold increase in pesticide sprays (Hole et al., 2005). Trewavas (2001) argues that increased food production should be limited to the cropland currently in use in order to conserve the present ecosystems. These opposed opinions reflect the apparent conflicts between agricultural production and agro-biodiversity conservation. Policy makers and land use planners, as well as stakeholders in agricultural production and nature conservation, need to reconcile these differences in opinion on the basis of scientific evidence about the complementarities of agro-biodiversity conservation and agricultural production, in order to accommodate the continuing and growing demand for agricultural products and the need for agro-biodiversity ecosystem services (Thrupp, 2000; Scherr and McNeely, 2008).

This thesis contributes to an understanding of the agro-biodiversity-productivity-sustainability relationships in agricultural landscapes in Tigray. The relative agro-biodiversity (compared to the maximum number of tree/shrub species and crop varieties observed) assessed at 151 farms was positively correlated with crop productivity at those farms (Figure 1). The main reason for this was probably the contribution of N-fixing trees and shrubs to N nutrition by crops plants (Chapter 5). In addition, traditional farming systems in areas with high agro-biodiversity are commonly mixed farming systems with plant and animal production, and the use of crop and varietal mixtures. Crop mixtures can be more productive due to complementarities among diversified crop and non-crop species facilitating soil fertility enhancement, soil nutrient capture and stabilization of soil structure (Naeem et al., 1994; Naeem et al., 1996; Tilman et al., 1996; Tilman and Downing, 1996; Yachi and Loreau, 1999; Bullock et al., 2001; Picasso et al., 2008). This implies that agro-biodiversity friendly agricultural landscapes can maintain ecosystem services and improve agricultural productivity (MA, 2005).

Conversely, non-sustainability (measured by soil erosion) was higher at lower relative agro-biodiversity at these same 151 farms (Figure 1). The inverse association between relative non-sustainability and agro-biodiversity (Figure 1) could be attributed to low organic matter content in the soils of intensively used land (Table 3 in Chapter 4), which facilitates water run off and reduces water holding capacity (Pimentel and Kounang, 1998).

3.2 Land use, agro-biodiversity, and productivity relationships at different spatial scales

This thesis provides an insight in the relationship among land use, agro-biodiversity and productivity at different spatial scales in Tigray. Our research revealed higher

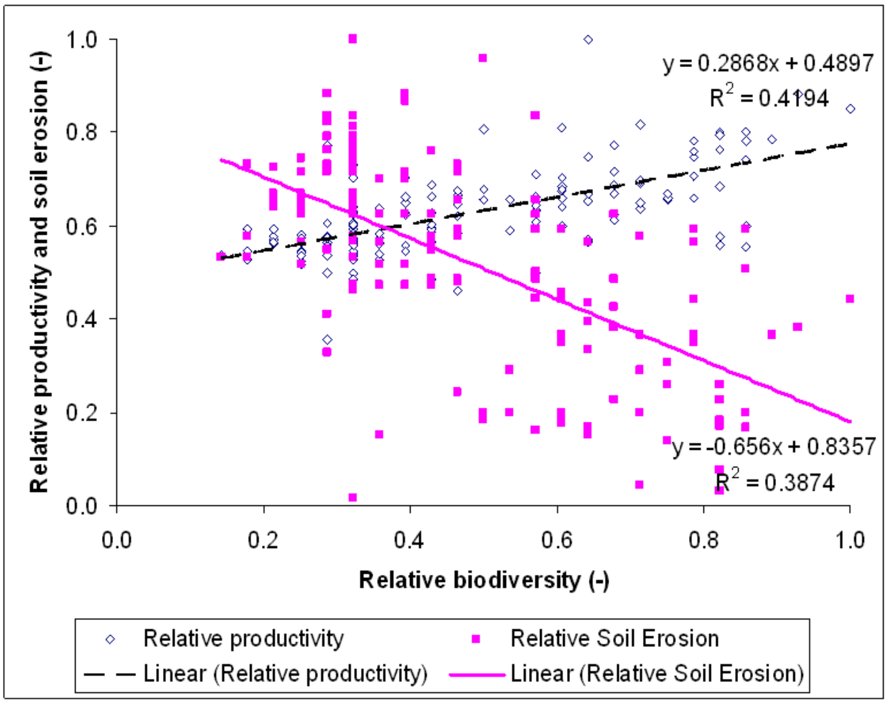


Figure 1. Relationship between relative agro-biodiversity, productivity and soil erosion (compared to the maximum of these variables in the data set) in Tigray, northern Ethiopia (calculated from data in Chapter 4).

agro-biodiversity and productivity on less intensively cultivated land (sparsely cultivated land use type; Table 1 in Chapter 5) observed at field and regional scale (Chapter 5) and at farm and regional scales (Figure 6 in Chapter 4). In spite of the contribution of agro-biodiversity to productivity, expansion and intensification of agricultural lands has continued at the expense of natural habitats over the past 41 years (Table 3 in Chapter 2). The main reason has been the increase in population coupled with the increasing demand for food, animal feed, fuel and construction material. Natural habitats, particularly at high altitudes and on steep terrains in Tigray, have declined dramatically (especially in the period 1964-1994, but continuing thereafter) due to the expansion of settlements and the associated increase in tree cutting for fuel wood and construction purposes. Because of the declining wood availability, cow dung is used for cooking which may have an impact on soil fertility and reduce productivity (EPA, 1997; Abegaz et al., 2007). Moreover, removal of natural habitat and on-farm shrubs and trees can lead to deterioration of soil quality and enhance soil erosion (Chapter 4).

4 Implications and recommendations

Land use change, mainly expansion and intensification of agricultural lands due to an increase in human population (Chapter 2), was shown to be the main driver of agro-biodiversity loss (Chapter 4). Faced with an increasing food demand, agricultural policies in Tigray will likely promote yield increasing, high input agricultural technologies which may adversely influence diversity of agricultural land and natural habitats. The degradation of natural resources such as agro-biodiversity and productive soil (Chapter 4) and the rising prices of inorganic fertilizer may actually reduce agricultural productivity and/or increase the costs of agricultural production (UN Millennium Project, 2005) at small farms in Tigray. The cost of inorganic fertilizer is two to six times as high in Africa as that in Europe, North America and Asia (Sanchez, 2002). The high price of inorganic fertilizer will increase the cost of agricultural production, which will likely be realized below the potential of improved crops. Moreover, poor farmers will be dependent on loans for the purchase of external inputs, increasing the risk of bankruptcy in case of crop failure.

Results presented in this thesis reveal that intensively cultivated lands, with few or no trees in and around agricultural fields, were associated with low agricultural productivity (Chapter 5). Specifically, intensively cultivated land currently yields 6200 $kcal.ha^{-1}$, moderately cultivated land 6770 $kcal.ha^{-1}$, and sparsely cultivated land 7140 $kcal.ha^{-1}$ per year (calculated from data collected for Chapter 4). Assuming a farm size of 1 ha (the usual farm size in Tigray) and a household size of 8 people, this amounts to 2124, 2320 and 2446 cal per person per day for intensively, moderately and sparsely cultivated farms, respectively. Considering average grain losses of 20% in storage an average need of 2000 calories per day per person, this is barely enough to satisfy the needs of the rural people in Tigray. From this point of view, it is good that farmers on intensively cultivated land, close to cities and roads, have most off-farm employment opportunities (Chapter 4).

The challenge for land use planners and decision makers in Tigray is how to increase agricultural productivity in a sustainable way. Agro-biodiversity should be considered as natural capital from which agriculture gains ecosystem services such as soil fertility, protection against soil erosion, water retention, pollination and pest control (MA, 2005). Agro-biodiversity-based agricultural production systems, for example, agroforestry, should be promoted. Sanchez (2002) documented that leguminous trees and shrubs such as *Sesbania, Tephrosia, Crotalaria, Glyricidia* and *Cajanus* interplanted into maize resulted 100 to 200 Kg N ha^{-1} which is similar to the amount of N that is applied from inorganic fertilizer in intensive cropping systems. Leaf biomass transfer from leguminous trees/shrubs at field margins, roadsides and adjacent ecosystems added nutrients into the soil and doubled maize yields in sub-humid tropical Africa (Sanchez, 2002). Badgley et al. (2007) presented a literature review showing that intensive organic crop production leads to higher yields than conventional production in developing countries, and could feed the current and future human population by improving soil fertility without expanding the current agricultural area. In arid and semi-arid regions like Tigray, enough nitrogen can be fixed from leguminous crops and plants to replace the expensive inorganic fertilizer. Planting of legume crops in rotation, green manuring, intercropping and alley cropping with leguminous trees and shrubs can improve soil fertility and thereby agricultural productivity (Badgley et al., 2007). Even in a fertilizer-based approach, care should be taken not to ignore the soil fertility bonus provided by the traditional agro-forestry systems, which is considerable at the given production levels.

Despite the negative correlation between intensity of cultivation and caloric yields, intensively cultivated land use types increased in Tigray over a period of 41 years, accompanied by the cutting of trees inside and outside agricultural lands (Chapter 2). If this trend continues, productivity and ecosystem services will decline even further (Chapter 5). Communities located in the Eastern part of the study region (Figure 5 in Chapter 5) manage to maintain trees and shrubs, particularly N-fixing species such as *Acacia albida,* in and around their agricultural fields to enhance soil fertility, improve agricultural productivity, to provide fodder/shade for livestock and as live fences. To optimize the potential of *A. albida* trees to improve productivity and scale up from field to farm and regional scales, more detailed studies on *A. albida* tree density and agricultural productivity should be carried out. Remote sensing techniques using high resolution satellite images and automatic tree detection methods (Pitkänen, 2001; Pouliot, et al., 2002) can be used to map, quantify and explain the effects of *A. albida* trees on agricultural productivity. As *A. albida* trees can not be replaced easily once they have been cut, the potential of alternative, faster growing leguminous trees and shrubs must be evaluated for their potential contribution to crop productivity. Furthermore, ecosystem services that can be derived from trees and shrubs inside and outside agricultural lands should be modeled at different spatial scales (Van Keulen, 2007) in order to calculate the benefits of agro-biodiversity in economic terms. Availability of extension packages and credit sources only for modern seed-fertilizer agricultural technologies may contribute to the reductions in landraces that have been conserved and passed through generations. Agricultural policies should also avail extension packages and credit sources for landrace conservation and better market development for organically grown products.

In addition, maintenance or development of biodiversity based agricultural production systems should be integrated with natural habitat protection, instead of focusing only on farm level production systems. Natural habitats can provide ecosystem services (e.g., ground water aquifer recharging, flood reduction, sediment flow reduction, pollination and pest control) to adjacent agricultural landscapes. Cutting of trees from natural habitats should, therefore, be minimized by on-farm planting of trees for firewood and construction purposes. In degraded environments like Tigray conservation of declining agro-biodiversity (Chapter 3 and 4) and rehabilitation of natural habitats, especially on steep slopes and extreme (low and high) altitudes (Chapter 2) should be integrated in rural land use planning not only at field or farm scale but also at regional scale. Local farmers could be involved in sharing their knowledge of traditional farming practices and contributing to the protection and restoration of natural habitats, for example by raising their ecological, economic and social awareness through farmers' field school (FFS) (Rola et al., 2002).

5 Main conclusions

This thesis adopted a multi-scale approach to assess and explain land use/land cover (LULC), agro-biodiversity, productivity and sustainability distribution and change in Tigray, Ethiopia. The first study assessed LULC change and their drivers based on a time-series (1964-2005) of remotely sensed data at regional scale. In addition, spatially explicit multiple logistic regression was used to understand LULC changes in relation to the drivers of the change in spatial and temporal scale (1964-1994 and 1994-2005). This study revealed a dramatic decrease in natural habitats which was higher at locations further from major roads, between 1964 and 1994, mainly due to war, drought and famine. Natural habitat also declined between 1994 and 2005 in locations close to settlements and major roads, especially at steep slopes and high altitudes. Expansion and intensification of agricultural lands took place in both 1964-1994 and 1994-2005 due to increase in population growth. The use of modern agricultural technologies, such as the use of new cultivars in pure stands, at farms close to towns and roads was associated with declining agro-biodiversity and sustainability. Agro-biodiversity was maintained at high-altitude farms managed with traditional farming practices. These farms generally had higher productivity thanks to the pervasive presence of *Acacia albida* trees inside and on the borders of the agricultural fields

The research presented in this thesis demonstrated dramatic changes in LULC, loss of agro-biodiversity, reduction in agricultural productivity and sustainability through a combination of multi-scale approaches. Cutting of trees and shrubs for intensive land use contributed to the loss of agro-biodiversity and productivity. Agro-biodiversity and productivity were negatively correlated with soil erosion, associated high input agricultural technologies. These results led to the recommendation to seek an integrated approach to agro-biodiversity conservation and agricultural production to promote sustainable agricultural production and food security.

6 Research outlook

The work presented in this thesis can be considered to constitute the first steps in the methodological approach of quantitative analysis of agro-ecosystems, which consists of four consecutive steps to Describe, Explain, Explore and Design land-use systems (DEED; Tittonell, 2008). This study provided a multi-scale approach to Describe and Explain the status and processes in land-use, agro-biodiversity and productivity. In the subsequent Explore and Design steps, simulation models and exploratory tools could be used to generate alternative management options that could improve the agro-ecosystem performance under different scenarios of development of external drivers (e.g., economic developments). Several recent research efforts have demonstrated the usefulness of integrated simulation models to aid the (re)design of sustainable agroecosystems by means of exploratory studies that search ways to balance for instance crop-livestock interactions to improve resource use at farm and landscape scales (Dogliotti et al., 2005; Groot et al., 2007; Tittonell et al., 2007). The resulting frameworks not only assess productivity and profitability of land-use, but support the simultaneous exploration of multiple ecosystem services or functions that reflect ecological, economical and social aspects of production such as conservation of agro-biodiversity and maintenance of soil and water quality. Moreover, trade-offs between the various services and functions can be made explicit. These approaches are often integrated with GIS systems (e.g., Groot et al., 2007), that enable spatially explicit assessment and scaling up to higher scale levels, to show the complementarities among agro-biodiversity, productivity and sustainability at different scales.

References

Abegaz, B., 2004. Escaping Ethiopia's poverty trap: the case for a second agrarian reform. J. Mod. Afr. Stud. 42, 313 – 342.

Abegaz, A., Van Keulen, H., Haile, M., Oosting, S.J., 2007. Nutrient dynamics on smallholder farms in Teghane, Northern Highlands of Ethiopia. In: Botiono, A., Job, K., Joseph, K., Boaz, W. (Eds.), Advances in integrated soil fertility management in Sub-Saharan Africa: Challenges and Opportunities. Springer, Dordrecht.

Adams, M.A., Attiwill, P.M. 1986. Nutrient cycling and nitrogen mineralization in eucalypt forests of southeastern Australia. II. Indices of nitrogen mineralization.

Plant Soil. 92, 341 – 362.
Altieri, M.A., 1994. The ecological role of biodiversity in agriculture. In: Altieri, M.A. (Ed.), Biodiversity and pest management in agroecosystems. Hayworth Press, New York, pp. 3 – 9.
Altieri, M.A. 1999. The ecological role of biodiversity in agroecosystems. Agric. Ecosyst. Environ. 74, 19 – 31.
Amacher, G.S., Ersado, L., Hyde, W.F., Osorio, A., 2004. Tree planting in Tigray, Ethiopia: the importance of human disease and water microdams. Agroforest. Syst. 60, 211 – 225.
Badgley, C., Moghtader, J., Quintero, E., Zakem, E., Chappell, M.J., Avile´s-Va´zquez, K., Samulon, A., Perfecto, I., 2007. Organic agriculture and the global food supply. Renewable Agric.Food Syst.. 22, 86 – 108.
Belsky, A.J., Blumenthal, D.M., 1997. Effects of Livestock Grazing on Stand Dynamics and Soils in Upland Forests of the Interior West. Conserv. Biol. 11, 315 – 327.
Brandt, J., Townsend, P.A., 2006. Land use – land cover conversion, regeneration and degradation in the high elevation Bolivian Andes. Landscape Ecol. 21, 607 – 623.
Bullock, J.M., Pywell, R. F., Burke, M. J.W., Walker, K.J., 2001. Restoration of biodiversity enhances agricultural production. Ecology Letters. 4, 185 – 189.
Chapin III, F. S., Zavaleta, E.S., Eviner, V.T., Naylor, R.L., Vitousek, P.M., Reynolds, H.L., Hooper, D.U., Osvaldo, S.L., Sala, E., Hobbie, S.E., Mack, M.C., Díaz, S., 2000. Consequences of changing biodiversity. Nature. 405, 234 – 242.
CSA, 2004. Statistical Abstracts. Ethiopian Central Statistical Authority (CSA), Addis Ababa.
Conway, G.R., 1987. The properties of agroecosystems. Agr. Syst. 24, 95 – 117.
Dogliotti, S., M.K. van Ittersum, and W.A.H. Rossing., 2005. A method for exploring sustainable development options at farm scale: a case study for vegetable farms in South Uruguay. Agr. Syst. 86, 29 – 51.
Dukes, J.S., 2001. Biodiversity and invasibility in grassland microcosms. Oecologia. 126, 563 – 568.
EPA, 1997. Environmental Policy of the Federal Democratic Republic of Ethiopia. Environmental Protection Authority (EPA). Addis Ababa.
Gliessman, S., 2001. Agroecosystem Sustainability: Developing Practical Strategies. CRC Press LLC, Boca Raton, Florida, pp. 3 – 15.
Groot, J.C.J., Rossing, W.A.H., Jellema, A., Stobbelaar, D.J., Renting, H., Van Ittersum, M.K., 2007. Exploring multi-scale trade-offs between nature conservation, agricultural profits and landscape quality – a methodology to support discussions

on land-use perspectives. Agric.Ecosys.Enviro. 120, 58 – 69.

Hole, D.G., Perkins, A.J., Wilson, J.D., Alexander, I.H., Grice, P.V., Evans, A.D., 2005. Does organic farming benefit biodiversity? Biol. Conserv.. 122, 113 – 130.

Hurni, H., 1993. Land degradation, famine and land resources scenario in Ethiopia. In: D. Pimentel (Ed), World Soil Erosion and Conservation, Cambridge University Press, Cambridge, pp. 27 – 62.

Keller, E.J., 1992. Drought, War, and the Politics of Famine in Ethiopia and Eritrea. J. Mod. Afri. Stud. 30, 609 – 624.

Loreau, M., Naeem, S., Inchausti, P., Bengtsson, J., Grime, J. P., Hector, A., Hooper, D.U., Huston, M.A., Raffaelli, D., Schmid, B., Tilman, D., Wardle, D. A., 2001. Biodiversity and Ecosystem Functioning: Current Knowledge and Future Challenges. Science. 294, 804 – 808.

Matson, P.A., Parton, W.J., Power, A.G., Swift, M.J., 1997. Agricultural Intensification and Ecosystem Properties. Science. 277, 504 – 509.

Millennium Ecosystem Assessment (MA), 2005. Ecosystems and human well-being: synthesis. World Resources Institute, Washington, DC.

Mokma, D. J., and M. A. Sietz., 1992. Effects of soil erosion on corn yields on Marlette soils in South-central Michigan. J. Soil Water Conservation. 47, 325 – 27.

Naeem, S., Thompson, L.J., Lawler, S.P., Lawton, J.H., Woodfin, R.M., 1994. Declining biodiversity can alter the performance of ecosystems. Nature. 368, 734 – 737.

Naeem, S., Håkansson, K., Lawton, J.H., Crawley, M.J., Thompson, L.J., 1996. Biodiversity and Plant Productivity in a Model Assemblage of Plant Species. Oikos. 76, 259 – 264.

Nyssen, J., 1997. Vegetation and soil erosion in Dega Tembien (Tigray, Ethiopia). Bull. Jard. Bot. Nat. Belg. Bull. Nat. Plantentuin Belg. 66, 39 – 62.

Rao, M.R., Nair, P.K.R., Ong, C.K., 1998. Biophysical interactions in tropical agroforestry systems. Agrofor. Syst. 38, 3 – 50.

Rhoades, C.C., 1995. Seasonal pattern of nitrogen mineralization and soil moisture beneath *Faidherbia albida* (syn *Acacia albida)* in central Malawi. Agrofor. Syst. 29, 133 – 145.

Rola, A.C., Jamias, S. B., Quizon, J. B., 2002. Do Farmer Field School graduates retain and share what they learn? An investigation in Iloilo, Philippines. J. Int. Agric. Ext. Educ. 9, 65 – 76.

Rosegrant, M., Li, W., Clein, S. A., Sulser, T., Valmonte-Santos, R., 2005. Looking ahead: long-term prospects for Africa's agricultural development and food

security. International food policy research Institute,Washington, DC.
Picasso, V.D., Brummer, E.C., Liebman, M., Dixon, P.M., Wilsey, B.J., 2008. Crop Species Diversity Affects Productivity and Weed Suppression in Perennial Polycultures under Two Management Strategies. Crop Sci. 48, 331 – 342.
Pimentel, D., Kounang, N., 1998. Ecology of Soil Erosion in Ecosystems. Ecosyst. 1, 416 -4 26.
Pitkänen, J., 2001. Individual tree detection in digital aerial images by combining locally adaptive binarization and local maxima methods. Can. J. For. Res. 31, 832 – 844.
Poore, M.E.D., Fries, C., 1985. The ecological effects of eucalyptus. Forestry Paper No. 59 FAO, Rome.
Pouliot, D.A., King, D.J., Bell, F.W., Pitt, D.G., 2002. Automated tree crown detection and delineation in high-resolution digital camera imagery of coniferous forest regeneration. Remote Sens. Environ. 82, 322 – 334.
Sanchez, P.A., 2002. Soil Fertility and Hunger in Africa. Science. 295, 2019 – 2020.
Sanginga, N., Swift, M.J., 1992. Nutritional effects of Eucalyptus litter on the growth of maize (*Zea mays*). Agric. Ecosyst. Environ. 41, 55 – 65.
Scherr, S.J., McNeely, J.A., 2008. Biodiversity conservation and agricultural sustainability: towards a new paradigm of ‘ecoagriculture’ landscapes. Phil. Trans. R. Soc. B. 363, 477 – 494.
Shiferaw, B., Holden, S., 1999. Soil Erosion and Smallholders' Conservation Decisions in the Highlands of Ethiopia. World Dev. 27, 739 – 752.
Siqueira, J.O., Nair, M.G., Hammerschmidt, R., Safir, G.R., 1991. Significance of phenolic compounds in plant-soil-microbial systems. Crit. Rev. Plant. Sci. 10, 63 – 121.
Sonneveld, B.G.J.S., Keyzer, M.A., 2003. Land under pressure: soil conservation concerns and opportunities for Ethiopia. Land Degrad. Develop. 14, 5 – 23.
Thrupp, L.A., 2000. Linking agricultural biodiversity and food security: the valuable role of agrobiodiversity for sustainable agriculture. Int. Aff.. 76, 265 – 281.
Tilman, D., Downing, J.A., 1996. Biodiversity and stability in Grasslands. In: Samson, F.B., Knopf, F.L. (Eds.), 1996. Ecosystem Management: selected readings. Springer, New York. pp. 3 – 7.
Tilman, D., Wedin, D., Knops, J., 1996. Productivity and sustainability influenced by biodiversity in grassland ecosystems. Nature. 379, 718 – 720.
Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W.H., Simberloff, D., Swackhamer, D., 2001. Forecasting agriculturally driven global environmental change. Science 292, 281 – 284.

Tilman, D., Reich, P.B., Knops, J.M.H., 2006. Biodiversity and ecosystem stability in a decade-long grassland experiment. Nature. 441, 629 – 632.

Tittonell, P., 2008. Msimu wa Kupanda – targeting resources within diverse, heterogeneous and dynamic farming systems of East Africa. PhD Thesis Wageningen University.

Tittonell, P., van Wijk, M. T., Rufino, M. C., Vrugt, J. A., Giller, K. E., 2007. Analysing trade-offs in resource and labour allocation by smallholder farmers using inverse modelling techniques: A case-study from Kakamega district, western Kenya. Agr. Syst. 95, 76 – 95.

Trewavas, A., 2001. Urban myths of organic farming. Nature. 410, 409 – 410.

Tylianakis, J.M. , Rand, T.A., Kahmen, A., Klein, A.-M., Buchmann, N., Perner, J., Tscharntke, T., 2008. Resource heterogeneity moderates the biodiversity-function relationship in real world ecosystems. PLoS Biol.. 6, 947 – 956.

UN Millennium Project, Task Force on Hunger, 2005. Halving hunger: it can be done. Earthscan, London.

Van Keulen, H. 2007. Quantitative analyses of natural resource management options at different scales. Agr. Syst. 94, 768 – 783.

Verheyen, K.,Bulteel, H., Palmborg, C., Olivié, B., Nijs, I., Raes, D., Muys, B., 2008. Can complementarity in water use help to explain diversity–productivity relationships in experimental grassland plots? Oecologia. 156, 351 – 361.

Yachi, S., Loreau, M.,1999. Biodiversity and ecosystem productivity in a fluctuating environment: The insurance hypothesis. Ecology.96, 1463 – 1468.

Summary

Biodiversity encompasses the broad differences between ecosystem types, and the diversity of habitats and ecological processes occurring within each ecosystem type, in addition to species and genetic diversity. The diversity of life is of crucial value, probably giving greater resilience to ecosystems and organisms. Diversity of vegetation and associated organisms contributes to the formation and maintenance of soil structure and the retention of moisture and nutrient levels, and promotes the recycling of nutrients. Loss of biological diversity through clearing of vegetation has contributed to leaching of nutrients, loss of minerals and accelerated erosion of topsoil, reducing the land's productive capacity. Thus, in addition to its intrinsic value, biodiversity needs to be studied from a functional perspective.

Ethiopia is one of the eight world centers of origin and diversity of agricultural crops. The Tigray region in northern Ethiopia still has extensive areas of natural habitat and traditional agriculture. Trees in and around farm lands have been used and are still being managed by farmers, although the abundance of trees and shrubs on farms has been declining since the introduction of 'modern' crop production packages. In view of both the intrinsic and the functional aspects of biodiversity, this is reason for concern. There is also a growing concern about food security and sustainable agricultural production in Tigray. To increase agricultural productivity and ensure food security, it is necessary to know the processes underlying the food production problems such as changes in land use, agro-biodiversity and soil erosion.

The decline in agro-biodiversity and its drivers have not been quantified for the Tigray area. Spatial tools such as GIS and remote sensing provide good opportunities for describing changes in biodiversity at regional scales, inferred from land use/land cover assessment. Information on the relevance of agro-biodiversity for productivity at field and farm scale, in combination with information on the rate of decline of biodiversity at the regional scale is highly relevant for land use policies, and can stimulate new directions for improving resource use in Tigray.

Therefore, the overall aim of this thesis is to identify and analyze factors affecting land use/ land cover (LULC) changes and biodiversity, and relate these to agricultural productivity in Tigray. A multi-scale approach is used in this thesis. LULC dynamics are analyzed at a regional scale and explained in relation to their drivers for a period from 1964 to 2005 using remotely sensed data and spatially explicit multiple logistic regression models. At farm and regional scales, biodiversity and sustainability are described using an integrated field survey and GIS analysis of data collected in 2000. Moreover, spatial changes in biodiversity and land degradation are described for 2000 and 2005, and associated with agricultural productivity at farm and regional

scales. Finally, agricultural productivity is compared for different *Acacia albida* based land use systems both at field and regional scales.

At the regional scale, aerial photographs and Landsat satellite images are used to examine LULC changes for the period 1964-2005 (**Chapter 2**). LULC classifications are inferred and verified with ground data collected during surveys in 2005. Changes in LULC in the periods 1964-1994 and 1994-2005 are mapped and related to spatially explicit potential drivers in GIS. Agricultural land areas have increased significantly (from 10% in 1964 to 40 % in 2005) at the cost of the surface area for natural vegetation (woodland and shrub land) over a period of 41 years. Especially a significant decline in woodland areas is presented (from 28% in 1964 to 3% in 2005) with the largest changes in the period before 1994. The results from multiple logistic regression show that anthropogenic changes are the primary drivers for LULC changes. In the period between 1964 and 1994 woodland areas were primarily reduced in remote areas, likely due to war, drought and famine, whereas in recent decades until 2005 reductions in woodland and expansion and intensification of agriculture were associated with road construction, settlement expansions and population pressure.

Chapter 3 quantitatively examines the relationships between diversity of tree and shrub species and crop diversity (landraces) in relation to farm altitude, soil fertility, soil erosion, crop production characteristics, farmers' wealth parameters, and proximity to roads and urban areas in 2000. The objective of this study is to identify spatial and non-spatial factors affecting biodiversity and sustainability in the agricultural landscapes of the Tigray region. Soil erosion is considered as the main indicator of non-sustainability. One hundred eighty-eight farmers are interviewed and their fields are observed for crop and non-crop plant diversity. GIS buffering and proximity analyses of urban areas and roads are presented. Plant diversity increases significantly with altitude, soil quality class and number of crop selection criteria, while plant diversity declines as farmers' access to credit and inorganic fertilizer use increase. Plant and crop diversity are positively correlated with number of weed species and number of insect pests per farm but negatively with soil erosion class. Soil erosion is positively associated with inorganic fertilizer use and negatively with plant diversity and numbers of animals per household, as indigenous plants and landraces are purposefully maintained to feed the animals. Proximity of farms to urban areas and roads negatively affects biodiversity (tree and crop diversity) in agricultural landscapes.

In **Chapter 4**, spatial variation in agro-biodiversity and soil degradation is documented for 2005 in relation to farm, productivity, wealth, social, developmental and topographic characteristics at 151 of the 188 farms studied in 2000 (**Chapter 3**).

A significant decrease in agro-biodiversity is documented between 2000 and 2005, mainly associated with inorganic fertilizer use, number of credit sources and proximity to towns and major roads. Agro-biodiversity is higher at farms with higher soil fertility (available P and total N) and higher productivity (total caloric crop yield). Low soil organic matter, few crop selection criteria, and steep slopes contribute to soil erosion, and severe soil erosion is associated with a large number of insect pests. Sparsely and intensively cultivated land use types, as determined from satellite images, are associated with high and low agro-biodiversity classes as determined during on-farm surveys in 2005.

In **Chapter 5**, the question is addressed if presence of trees in and around farmlands can contribute to crop productivity. Barley yields are compared in different *Acacia albida* tree-based land use systems in 2005, namely *A. albida* as only tree species without livestock (AA), *A. albida* trees with livestock (AL), and *A. albida* and *Eucalyptus* trees (AE) in and around agricultural fields. Barley yield and soil fertility are compared at increasing distances from an *A. albida* trunk. Yield and soil fertility increase when field locations are under the *A. albida* canopy as compared to outside the canopy in the *A. albida* alone (AA) and *A. albida* + livestock (AL) land use systems. However, in the *A. albida* + *Eucalyptus* (AE) land use system barley yield and soil fertility are lower close to the *A. albida* trunk. At regional scales, higher *A. albida* tree densities per farm and sparsely cultivated land use types increase potential ecosystem services (barley yield).

In this thesis, significant changes in LULC, loss of biodiversity, and reductions in agricultural productivity and sustainability (as indicated by soil erosion) are demonstrated for the Tigray region in Ethiopia through the application of a multi-scale approach. Reductions in biodiversity and sustainability are negatively associated with soil erosion and current use of agricultural intensification technologies. Furthermore, this research documents that indigenous farming practices are associated with higher biodiversity and sustainability in agricultural landscapes at the current production levels in Tigray. This thesis also confirms a positive relationship between biodiversity and productivity at different spatial scales. This association can help to improve food security and agricultural productivity through conservation and proper utilization of biodiversity resources. However, continued cutting of trees (especially *A. albida* trees) from farmlands and adjacent natural habitats and replacement by eucalypts may result in intensively cultivated land use with negative consequences for biodiversity and agricultural productivity. Finally, the thesis recommends utilization of the complementarities between biodiversity conservation and agricultural production to promote sustainable agricultural production and food security.

Samenvatting

Biologische diversiteit of biodiversiteit heeft betrekking op de variatie tussen levende organismen in allerlei bronnen en de ecologische processen waar zij deel van uit maken. Biodiversiteit behelst de diversiteit binnen soorten, tussen soorten en van ecosystemen. De diversiteit van leven is een essentiële waarde welke vermoedelijk grotere veerkracht geeft aan ecosystemen en organismen. De diversiteit van vegetatie en de daarin levende organismen draagt bij aan het ontstaan en de ontwikkeling van bodemstructuur, het vasthouden van vocht en nutriënten, en het stimuleert het hergebruik van nutriënten binnen het systeem. Afname van de biologische diversiteit door verwijdering van de vegetatie draagt bij aan de uitspoeling van nutriënten, mineralen verlies en versnelde uitspoeling van de bovengrond waardoor de agrarische productiecapaciteit van de bodem vermindert. Dus naast haar intrinsieke waarde, dient biodiversiteit ook te worden bestudeert vanuit een functioneel perspectief.

Ethiopië is een van de acht mondiaal belangrijkste genencentra voor tal van landbouwgewassen. De Tigray provincie in het Noorden van Ethiopië bestaat nog steeds voor een groot deel uit gebieden met natuurlijke habitats en traditionele landbouw. In dit gebied werden bomen in en om percelen gebruikt door boeren en vaak wordt dit systeem ook nu nog onderhouden. Echter de algemene trend is dat het aantal bomen en struiken rond de boerderijen afneemt, mede onder invloed van de introductie van 'moderne' gewasproductiemethoden. Vanuit het perspectief van zowel de intrinsieke als functionele waarde van biodiversiteit geeft deze ontwikkeling reden tot ongerustheid. Daarnaast is er in Tigray groeiende aandacht voor voedselzekerheid en duurzame agrarische productie. Om de agrarische productiviteit te verhogen en voedselzekerheid te garanderen, is het nodig om de processen die aan de problemen van voedselproductie ten grondslag liggen te kennen en te bestuderen. Voorbeelden van deze processen zijn veranderingen in landgebruik, agro-biodiversiteit en bodemerosie.

De afname in agro-biodiversiteit en de onderliggende oorzaken zijn voor de provincie Tigray nog niet in beeld gebracht. Ruimtelijke technieken zoals Geografische Informatiesystemen (GIS) en remote sensing bieden goede mogelijkheden om veranderingen in biodiversiteit op regionale schaal af te leiden op basis van veranderingen in landgebruik. Informatie over het belang van agro-biodiversiteit voor productiviteit op veld- en boerderijschaal gecombineerd met inzicht in de afname van biodiversiteit op regionale schaal is van groot belang voor het opstellen van beleid voor planning van landgebruik. Daarnaast stimuleert deze kennis ook nieuwe richtingen voor duurzaam gebruik van natuurlijke hulpbronnen in Tigray.

Het doel van dit promotieonderzoek is dan ook om voor een studie gebied in de Tigray provincie in Ethiopië de factoren in beeld te brengen en te analyseren die van invloed zijn op landgebruik verandering en biodiversiteit, en deze factoren te relateren aan de agrarische productiviteit van het gebied.

De relatie tussen landgebruik, biodiversiteit en agrarische productiviteit wordt in dit proefschrift geanalyseerd op basis van een benadering waarbij verschillende ruimtelijke schaalniveaus met elkaar worden vergeleken. Hierbij worden remote sensing data toegepast om op regionale schaal de dynamiek van landgebruik te analyseren in de periode van 1964 tot 2005. Om de ruimtelijke veranderingen in landgebruik te verklaren worden multiple logistische regressiemodellen gebruikt om de belangrijkste sturende factoren te identificeren. Op boerderij en regionale schaal worden biodiversiteit en duurzaamheid beschreven aan de hand van uitgebreid veldonderzoek en een analyse van GIS data verzameld in 2000. Een vergelijkbaar veldonderzoek is uitgevoerd in het studiegebied in 2005. Ruimtelijke veranderingen in biodiversiteit en land degradatie in de periode tussen 2000 en 2005 worden beschreven en gerelateerd aan agrarische productiviteit op boerderij en regionale schaal. Tenslotte wordt een vergelijking gemaakt van de agrarische productiviteit voor verschillende op *Acacia albida* gebaseerde landgebruikssystemen op veld en regionale schaal.

Op regionale schaal zijn luchtfoto's en Landsat satelliet beelden gebruikt om de landgebruiksveranderingen voor Tigray over de periode 1964-2005 te karakteriseren (**Hoofdstuk 2**). Voor de classificatie van landgebruik zijn veldopnames van 2005 gebruikt om de classificatie methode te kalibreren en valideren. De resulterende landgebruikskaarten worden in GIS vergeleken met topografische kaarten. Veranderingen in landgebruik in de periodes 1964-1994 en 1994-2005 zijn gekarteerd en gerelateerd aan potentiële sturende factoren. Over een periode van 41 jaar is het agrarisch landgebruik significant toegenomen (van 10% in 1964 naar 40% in 2005) ten koste van de oppervlakte natuurlijke vegetatie (bos en struikvegetatie). Daarbij heeft vooral een significante verandering in het areaal bos plaatsgevonden (van 28% in 1964 naar 3% in 2005) met de grootste veranderingen in de periode voor 1994. De resultaten van de multiple logistische regressieanalyse laten zien dat menselijke invloeden de belangrijkste sturende factoren zijn voor deze veranderingen. In de periode tussen 1964 en 1994 is het oppervlak bos vooral afgenomen in afgelegen gebieden als gevolg van oorlog, droogte en hongersnood. In het laatste decennium tot 2005 is de reductie van bos en de uitbreiding en intensivering van landbouw vooral gerelateerd aan ontwikkeling van de infrastructuur, urbane uitbreiding en bevolkingsgroei.

In **hoofdstuk 3** wordt de relatie onderzocht tussen enerzijds de diversiteit van soorten bomen en struiken in combinatie met de diversiteit van agrarische gewassen en anderzijds gegevens uit een enquête onder agrariërs in Tigray in 2000. Doel van deze studie is het identificeren van ruimtelijke en niet-ruimtelijke factoren die de biodiversiteit en duurzaamheid van het agrarische landschap beïnvloeden. Hierbij is bodemerosie gebruikt als belangrijkste indicator voor duurzaamheid. In totaal zijn 181 agrariërs geïnterviewd en voor hun velden zijn schattingen gemaakt van natuurlijke en agrarische diversiteit (landrassen). De volgende eigenschappen zijn meegenomen in de analyse: topografische hoogte, bodemvruchtbaarheid, bodemerosie, gewasproductie karakteristieken, rijkdom karakteristieken en afstand tot infrastructuur en urbane gebieden. De laatste 2 eigenschappen zijn afgeleid door middel van een buffer en afstand analyse in GIS. Plantdiversiteit neemt significant toe voor de eigenschappen hoogte, bodemkwaliteitsklasse en het aantal gewas selectiecriteria. Een afname van de plantdiversiteit is gerelateerd aan de toegang tot bronnen van krediet en gebruik van kunstmest. Plant- en gewasdiversiteit zijn positief gecorreleerd aan het aantal onkruidsoorten en het aantal soorten insectenplagen per boerderij en negatief gecorreleerd met bodemerosieklasse. Bodemerosie is positief geassocieerd met kunstmestgebruik en negatief met plantdiversiteit en aantal stuks vee per huishouden. Afstand van de boerderij tot de urbane gebieden heeft een negatieve invloed op de biodiversiteit in het agrarische landschap.

Hoofdstuk 4 beschrijft de ruimtelijke variatie in agro-biodiversiteit en bodem degradatie voor het studie gebied in 2005. Verklarende variabelen hierbij zijn karakteristieken van bedrijf, productiviteit, rijkdom, sociale en ontwikkeling status en topografie zoals waargenomen voor 151 van de 181 boerderijen die ook in 2000 zijn bezocht (Hoofdstuk 3). Tussen 2000 en 2005 wordt een significante afname in agro-biodiversiteit waargenomen, welke vooral is gerelateerd aan kunstmest gebruik, aantal kredietbronnen en afstand tot steden en infrastructuur. De agro-biodiversiteit is hoger voor boerderijen met een hogere bodemvruchtbaarheid (beschikbare P en totale N) en hogere productiviteit (totale calorische gewas opbrengst). Lage bodem organische stof, een beperkt aantal gewasselectiecriteria en steile hellingen dragen bij aan bodem erosie, en ernstige bodemerosie is geassocieerd met een groot aantal plaagtypen. Gebieden met extensief en intensief agrarische landgebruik afgeleid uit remote sensing beelden van 2005 (hoofdstuk 2) zijn respectievelijk gerelateerd aan klassen met een hoge en lage agro-biodiversiteit.

Hoofdstuk 5 gaat in op de vraag of de aanwezigheid van bomen in en rond de boerderijpercelen bijdraagt aan de gewasproductiviteit. Hiertoe worden opbrengsten van gerst vergeleken voor verschillende landgebruiksystemen met *Acacia albida* als dominante boomsoort. Onderscheid wordt gemaakt tussen een management systeem met *A. albida* als enige soort en zonder vee (AA), een systeem met *A. albida* en met vee (AL), en een systeem met gemengde *A. albida* en *Eucalyptus* bomen in en rond het perceel (AE). Gerstopbrengst en bodemvruchtbaarheid zijn vergeleken op toenemende afstand vanaf de stam van de *A. albida* boom. Voor de opbrengst en vruchtbaarheid in het AA en AL systeem geldt dat deze op korte afstand van de boom hoger zijn en afnemen naarmate de afstand van de boom toeneemt. Voor het AE systeem geldt het omgekeerde; dichtbij de *A. albida* stam zijn opbrengst en bodem vruchtbaarheid relatief laag terwijl deze toenemen met toenemende afstand van de boom. Op regionale schaal en bij extensief agrarisch landgebruik zouden hogere dichtheden van *A. albida* per boerderij kunnen leiden tot een toename van de potentiële ecosysteem service in de vorm van gerstopbrengst.

Dit proefschrift laat zien dat voor het studiegebied in Tigray processen zoals veranderingen in landgebruik, verlies van biodiversiteit en afname van agrarische productiviteit en duurzaamheid kunnen worden gekarakteriseerd door het toepassen van een multi-schaal benadering (**hoofdstuk 6**). Afname van biodiversiteit en duurzaamheid zijn negatief geassocieerd met bodemerosie en het huidig gebruik van technieken voor landbouwkundige intensivering. Daarnaast laten de resultaten zien dat traditionele agrarische methoden zijn gerelateerd aan hogere biodiversiteit en duurzaamheid van het agrarisch landschap bij stabiele productieniveaus. Het proefschrift bevestigt de positieve relatie tussen biodiversiteit en productiviteit op verschillende ruimtelijke schaalniveaus. Deze bevindingen kunnen helpen in de verbetering van de agrarische productiviteit en voedselzekerheid door behoud en zorgvuldig gebruik van bestaande bronnen voor biodiversiteit. Voortschrijdende verwijdering van *A. albida* bomen zowel vanuit de agrarische percelen alsook uit de omliggende natuurlijke habitats en hun vervanging door eucalyptus resulteert in intensief gecultiveerde landschappen met negatieve gevolgen voor biodiversiteit en agrarische productie. Tenslotte wordt aanbevolen om gebruik te maken van de complementariteit tussen het behoud van biodiversiteit en agrarische productie om te komen tot duurzame productie en voedselzekerheid.

Acknowledgements

In the process of my PhD research work several people and institutions deserve gratitude for their countless support and guidance but only one name is allowed in the final PhD thesis book. Taking this opportunity, I would like to thank those who made this PhD thesis possible.

First of all, let me express my special gratitude to Prof. dr. ir. Ariena van Bruggen, my main supervisor, for opening all the doors of my scientific career. I would also like to thank her for initiating my IITA-Lukas Brader fellowship. I sincerely appreciate her meticulous support, scientific guidance and for the critical questions and challenges which motivated me to think critically during my PhD research period. I would also thank her for the enormous support and for her valuable time, including weekends and evenings, especially during the finalization of the thesis write-ups. It is unfair to only acknowledge her as a main supervisor as she was also available for me to discuss about my research results and problems. So, I thank her very much for her dedication and full support to my PhD research.

I am very grateful to Dr. ir. Walter Rossing and Dr. ir. Lammert Kooistra, my daily supervisors, for the priceless commitment, patience and encouragement during my PhD research work. I feel privileged to have them as my daily supervisors who were always available for me and allowed me to walk in to their offices whenever I had questions or difficulties. I owe them my special thanks for their very enthusiastic field visit to my research area and for their interests to travel on foot, including in the evenings of their visit, to see my research sites. I thank them also for helping me to get a NUFFIC fellowship for the last 10 months of my stay in Wageningen University. Dr. ir. Walter Rossing, I always appreciate your willingness to brainstorm, help and give me the opportunity to think on my own. I would also like to extend my appreciation to Dr. ir. Lammert Kooistra for his day to day discussions and comments, and for sharing his own scientific experiences. I will never forget his encouraging words: '*Do you see the light at the end of the tunnel*?'. My special thank you also goes to his very friendly family who invited me for a delicious dinner. I would also like to extend my special thanks to Dr. ir. Gerrit Epema for his support and guidance as a supervisor at the beginning of my PhD research.

I would like to express my sincere gratitude to the IITA – Lukas Brader Fellowship programme for providing a scholarship and research funds for four years, and to the Netherland Fellowship Programme (NUFFIC) for support for the last 10 months. Additional financial support for printing of the thesis was provided by the Dr. Judith Zwartz Foundation and the Fonds Landbouw Export-Bureau (LEB) Foundation.

Let me extend my utmost respect and gratitude to Prof. Dr. ir. Lukas Brader for initiating the IITA-Lukas Brader Fellowship programme with the objective of capacity building of young African scientists who can contribute to the realization of food security and poverty reduction in Africa. I can not thank him enough for visiting me in Wageningen and for his continued inspirations and encouragements. I am also indebted to Mr. Emannuel Banji Oyewole, IITA Training and Research office, for smoothing administrative matters and his very encouraging advice. My thanks also go to Dr. Morag Ferguson and Dr. Michael Pillay for being my IITA supervisors. I would also like to express my appreciation to IITA staff Ms. Maureen Omoniyodo, Chinyere Woods, Jenny Cramer, Pieter Windmeijer, Dr. Kim Sander and Eugene Agbicodo (IITA-Lukas Brader Fellow).

This PhD research would not have been finalized without the support of staff members and PhD students of the Biological Farming Systems (BFS) group and the Center for Geo-information and Remote Sensing (GIRS) group. I appreciate both BFS and GIRS members for giving me opportunities to present and discuss my research outputs during lab meetings and group discussions. I sincerely appreciate Mrs. I.C. van Schouwenburg for her very great support in editing and setting the layout of my thesis, to Mrs. C.G. Uithol for her administrative support, and to Mrs. G. Berkhout-van de Garde for handling the financial matters. I also extend my sincere appreciation to Dr. ir. J.C.J. Groot for assisting during my final hectic times and to Diego Flores and Ir. Bas Allema for being friends. My thanks also goes to Dr. ir. E.A. Lantinga, Dr. ir. J.J. Neeteson, ing. O.J. de Vos, H.D. Halm, D. Volker, Dr.ir. A. Jellema, Dr. ing. J. Scholberg, Sasha Semenov, C.L. Velazco, Ir. E. Speelman and F. Alliaume.

I am very indebted to Prof. dr. sc. nat. M.E. Schipman, from GIRS, for his support and for showing interest in my research with a very friendly approach. I would also like to extend my gratitude to A.J. Stoffers for her friendly approach and assistance with regard to office and computer arrangements, Dr. Jia Li for her advice and encouragement while sharing an office. For their support and facilitation at the GIRS group, my thank you goes to Prof. dr. ir. A.K. Bregt, Dr. J.G.P.W. Clevers, Dr. R. van Lammeren, J. Steiver, Drs. H.M. Bartholomeus, Ir. S. Mucher, Ing. W.Th. ten Haaf and all staff members and PhD students of the GIRS group.

Several people from Mekelle University, Ethiopia, contributed scientifically and morally to my PhD research work. I especially thank Dr. Mitiku Haile, Dr. Dereje Assefa, Dr. Kindeya Gebrehiwot, Dr. Fitsum Hagos, Zelalem Hadush, Mulugeta Sibhatleab and Haile Bezabih. I also thank Desta Gebremichael, Ezgimeles Tecleab, Berhane Haile, Guush Berhane, Solomie Abreha, Getachew Ebuy and Gebremedhin Gebreyesus for their encouragement and friendly support. My respect and special thanks go to the farmers of Tigray, staff of the Bureau of Agriculture and Relief Society of Tigray (REST) in central Tigray.

Last but not least, this PhD research would not have been possible without my beloved wife Sebli and my handsome son Noel. My family's love, patience and continued encouragement throughout the PhD research were formidable drives to my success. I would like to express my respect and gratitude to my parents for sending me to school and showing me the way ahead. I also owe many thanks to my family-in-law for giving me so much support and passion. Finally, I would like to thank my paranymphs Ir. Bas Alema and Solomie Abreha for reading the thesis and for their grateful help in the preparation of the PhD ceremony.

Curriculum Vitae

Kiros Meles Hadgu was born in Tigray, Ethiopia on 12 January 1976. In 1998, he finished his BSc degree in Dryland Agriculture and Natural Resources from Mekelle University, Ethiopia. He worked as a graduate assistant in teaching and research at Mekelle University for one year after finishing his BSc degree.

In 1999, he got a scholarship from the collaborative project 'Mekelle University-Larenstein International Agricultural College (MU-LIAC)' to study for the MSc degree at Wageningen University. After receiving the MSc degree from Wageningen University, he rejoined Mekelle University as a lecturer with teaching responsibilities mainly for 'land use planning and watershed management', 'geo-information technology' and 'remote sensing'. Parallel to teaching activities, he was also involved in research projects as a team leader in 'Geo-Database Development in Tigray', 'Impact of current and alternative land use scenarios on soil erosion in Eastern Tigray' and 'Land use assessment in the drylands of Ethiopia'.

In November 2004, he started a sandwich PhD study at Wageningen University sponsored by IITA-Lukas Brader Fellowship programme. During his stay at Mekelle University for his field work, he taught courses mainly 'GIS for post graduates in rural development', 'GIS and crop growth modeling for the post graduate programme in Crop and Horticultural Sciences', and 'GIS and remote sensing for the post graduate programme in Tropical Land Resources'. His PhD study 'Temporal and spatial changes in land use patterns and biodiversity in relation to farm productivity at multiple scales in Tigray, Ethiopia' was done under the supervision of the Biological Farming Systems (BFS) and Centre for Geo-Information and Remote Sensing (GIRS) groups of Wageningen University.

List of publications

Peer reviewed journals:

Hadgu, K.M., Kooistra, L., Rossing, W.A.H., Van Bruggen, A.H.C. 2008. Detection of land use/ land cover changes by remote sensing and associated drivers for the period 1964-2005 in the highlands of Tigray, Ethiopia. Agriculture, Ecosystems and Environment, in review.

Hadgu, K.M., Epema, F.G., Van Bruggen, A.H.C. 2008. Biodiversity and sustainability in agricultural landscapes in Tigray, northern Ethiopia. Landscape and Urban Planning, in review.

Hadgu, K.M., Kooistra L., K., Rossing, W.A.H., Van Bruggen, A.H.C. 2008. Assessing the effect of *Acacia albida* based management regimes on barley yield at field and landscape scale in the highlands of Tigray, northern Ethiopia. Agroforestry Systems, in review.

Hadgu, K.M., Kooistra, L., Rossing, W.A.H., Van Bruggen, A.H.C. 2008. Spatial and temporal changes in biodiversity and agricultural sustainability in Tigray, Ethiopia. Food Security: The Science, Sociology and Economics of Food Production and Access to Food, in review.

Conference contributions:

Hadgu, K.M., Kooistra, L., Rossing, W.A.H., Van Bruggen, A.H.C. 2006. Biophysical and human induced land use/land cover dynamics with an implication to biodiversity and environmental degradation in Tigray, Ethiopia. Presented at the Highland 2006: Environmental change, geomorphologic processes, land degradation and rehabilitation in tropical and subtropical highlands, 21-25 September, Mekelle, Ethiopia.

Hadgu, K.M., Kooistra, L., Rossing, W.A.H., Van Bruggen, A.H.C. 2008. Remote sensing based land use/ land cover changes and drivers of change for the period 1964-2005 in Tigray, Ethiopia. Presented at the Remote Sensing and Photogrammetry Society Conference: Measuring change in the Earth System, 15-17 September 2008, Falmouth, UK.

Hadgu, K.M., Kooistra, L., Rossing, W.A.H., Van Bruggen, A.H.C. 2008. Temporal and spatial changes in land use patterns and biodiversity in relation to farm productivity at multiple scales in Tigray, Ethiopia. Research School for Socio-Economic and Natural Science of the Environment (SENSE)/EPCEM Symposium Emerging Issues and Future Challenges in Environmental Sciences, 10 October 2008, Wageningen, the Netherlands.

PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

The C.T. De Wit Graduate School PE&RC
PRODUCTION ECOLOGY & RESOURCE CONSERVATION

Review of Literature (5.6 ECTS)

- Conserving and managing biodiversity to optimize small-holder farming in Arid climates: GIS, remote sensing and field survey approach (2004)

Writing of Project Proposal (7 ECTS)

- Biodiversity and productivity in smallholder farming systems in dryland areas: a multi-scale case study in Tigray, Ethiopia (2004)

Post-Graduate Courses (2.9 ECTS)

- Capacity building in research; Mekelle University, Ethiopia (2005)
- Erosion and sedimentation transport; Leuven Catholic University, Belgium and Mekelle University, Ethiopia (2006)
- Use of Geo-information and remote sensing for the study of competing claims on land; International Institute for Geo-information science and earth observation, Enschede, the Netherlands (2007)
- Multivariate Analysis, The C.T. de Wit Graduate School Production Ecology & Resource Conservation (PE & RC), Wageningen University (2008)

Competence Strengthening / Skills Courses (4.4 ECTS)

- Oral presentation; Mekelle University (2005)
- Time planning; Mekelle University (2005)
- Techniques for writing and presenting a scientific paper; Wageningen Graduate Schools, Wageningen University, the Netherlands (2007)

Discussion Groups / Local Seminars and Other Scientific Meetings (7 ECTS)

- Agricultural production systems (2003, 2004, 2006 & 2007)
- Research presentation series in Mekelle University (2005)
- Statistics, Maths and Modelling in production ecology and resource conservation (2007/2008)

PE&RC Annual Meetings, Seminars and the PE&RC Weekend (1.8 ECTS)

- PE&RC day: biological disasters (2004)
- PE&RC day: COLLAPSE: is our civilization able to stand the test of time? (2007)
- Scale and scaling issue (2007)
- Introduction weekend (2008)

International Symposia, Workshops and Conferences (6 ECTS)

- International conference on the highLAND2006: environmental change, geeomorphological processes, land degradation and rehabilitation in tropical and subtropical highlands; Mekelle, Ethiopia (2006)
- International Association for Landscape Ecology (IALE): World Congress (2007)
- Remote Sensing and Photogrammetry Society Annual Conference: measuring change in the Earth System; Falmouth, UK (2008)

Courses in Which the PhD Candidate Has Worked as a Teacher

- GIS for post graduate programme in rural development; Joint programme between Cork University College, Ireland and Mekelle University, Ethiopia (4 weeks)
- GIS and crop growth modelling for post graduate programme in Crop and Horticultural Sciences; Department of Crop Science, Mekelle University (16 weeks)
- GIS and remote sensing for post graduate programme in Tropical Land Resources; Department of Land Resources Management and Environmental Protection (4 weeks)

Funding

This PhD research was funded by the IITA-Lukas Brader Fellowship Programme for four years and by the Netherlands Fellowship Programme (NUFFIC) for the last 10 months. Additional financial support for printing was provided by the Dr. Judith Zwartz Foundation and the Fonds Landbouw Export-Bureau (LEB) Foundation. The author is very grateful to these institutions for their generous support.

Printing:
Ponsen & Looijen B.V., Wageningen

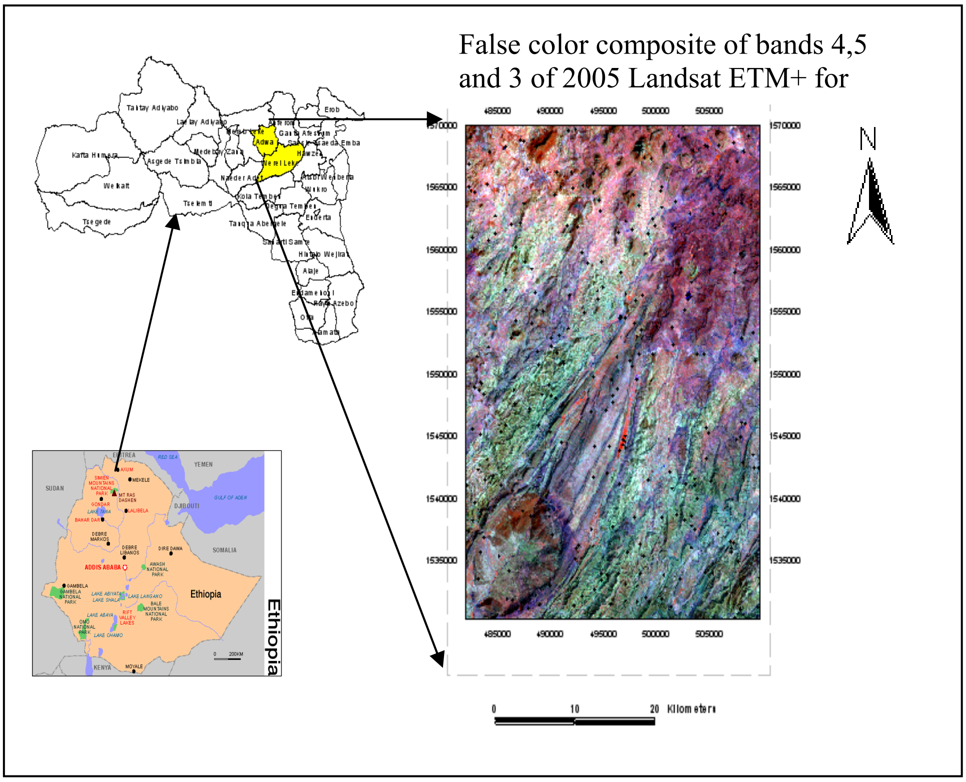


Figure 1 (Chapter 1 and 2). Location map of the study area, Tigray in northern Ethiopia.

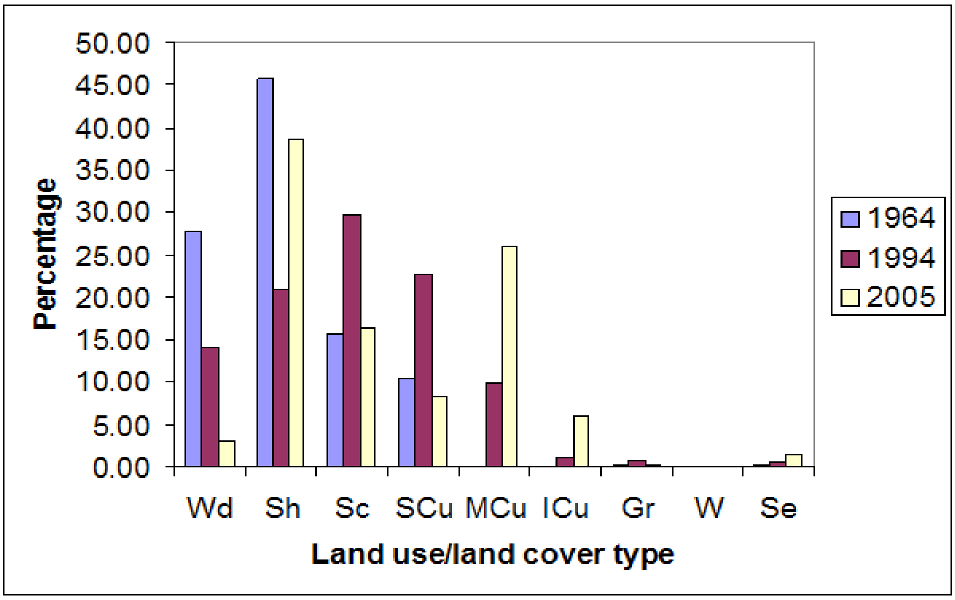


Figure 3 (Chapter 2). Percentages LULC over time (1964, 1994 and 2005) in Tigray, Ethiopia. Note: Class acronyms are presented in Table 2.

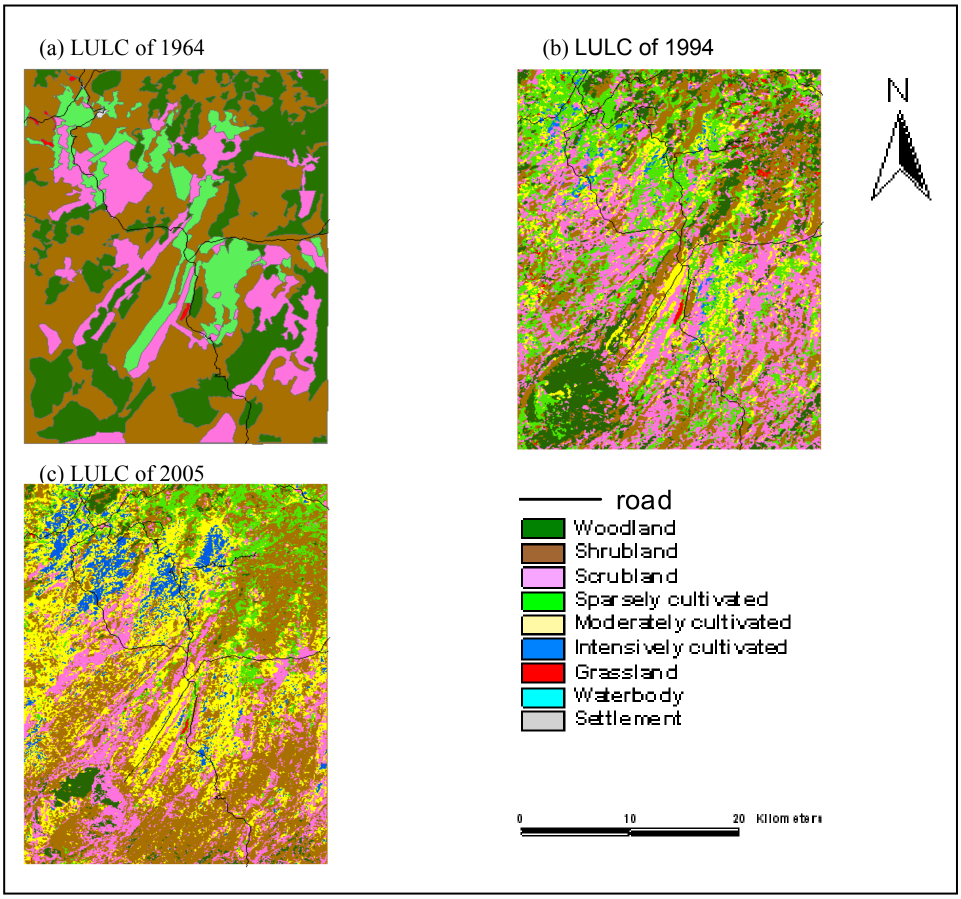


Figure 4 (Chapter 2). LULC maps of 1964, 1994 and 2005 combined with road maps of the study area in Tigray, northern Ethiopia.

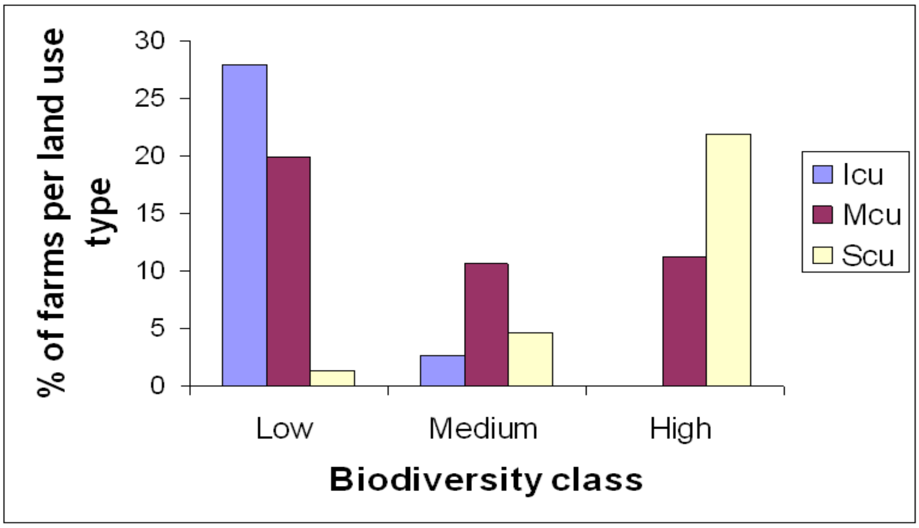


Figure 3 (Chapter 4). Relation between biodiversity classes and agricultural land use types for selected farms (n = 151) in the Tigray study area in northern Ethiopia. Land use types: Scu = Sparsely cultivated; Mcu = Moderately cultivated; Icu = Intensively cultivated.

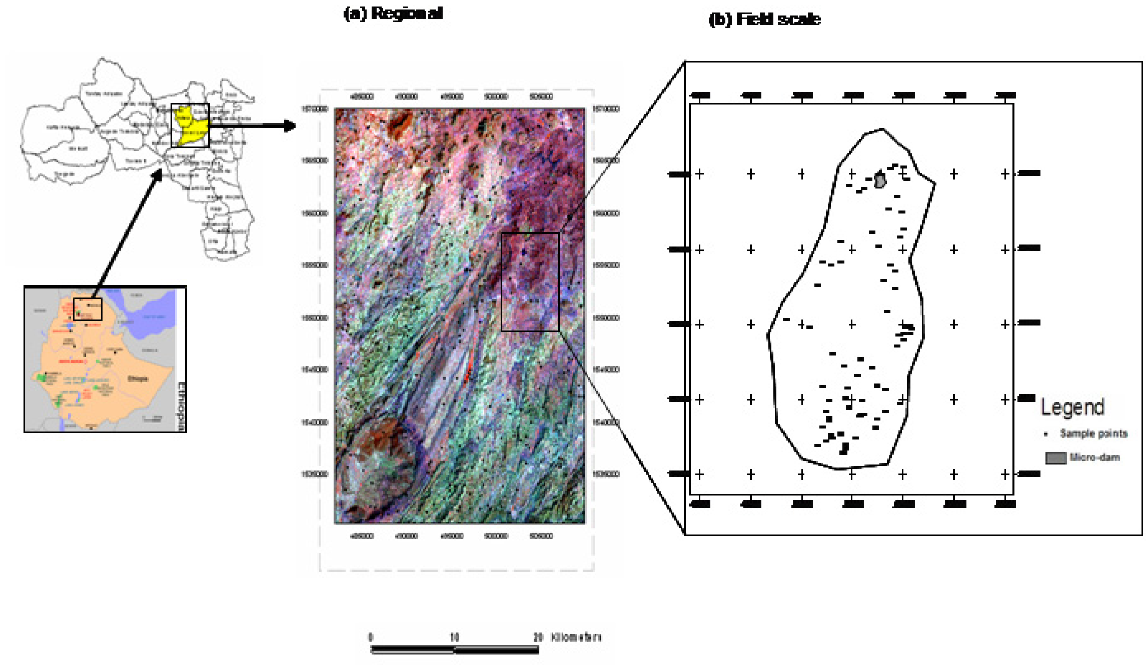


Figure 1 (Chapter 5). Location of study area: false color composite of bands 4, 5 and 3 of 2005 Landsat ETM+ at regional scale (a) and sub area with field scale sample points (b) in Tigray, northern Ethiopia.

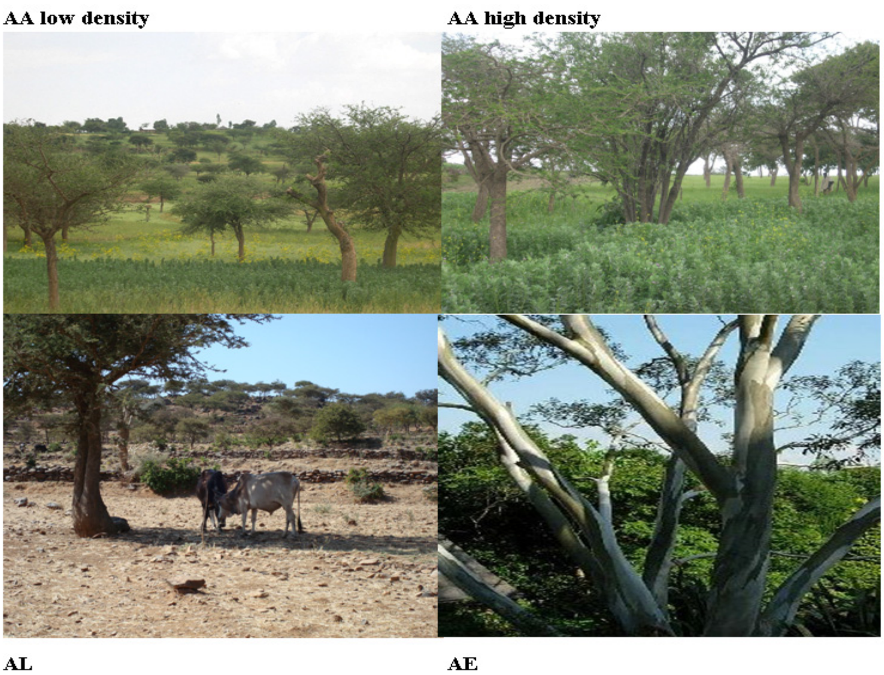


Figure 2 (Chapter 5). Different *Acacia albida* land use systems in the Tigray study area in northern Ethiopia with *Acacia albida* alone (AA), *Acacia albida* and livestock (AL) and *Acacia albida* and Eucalyptus (AE).

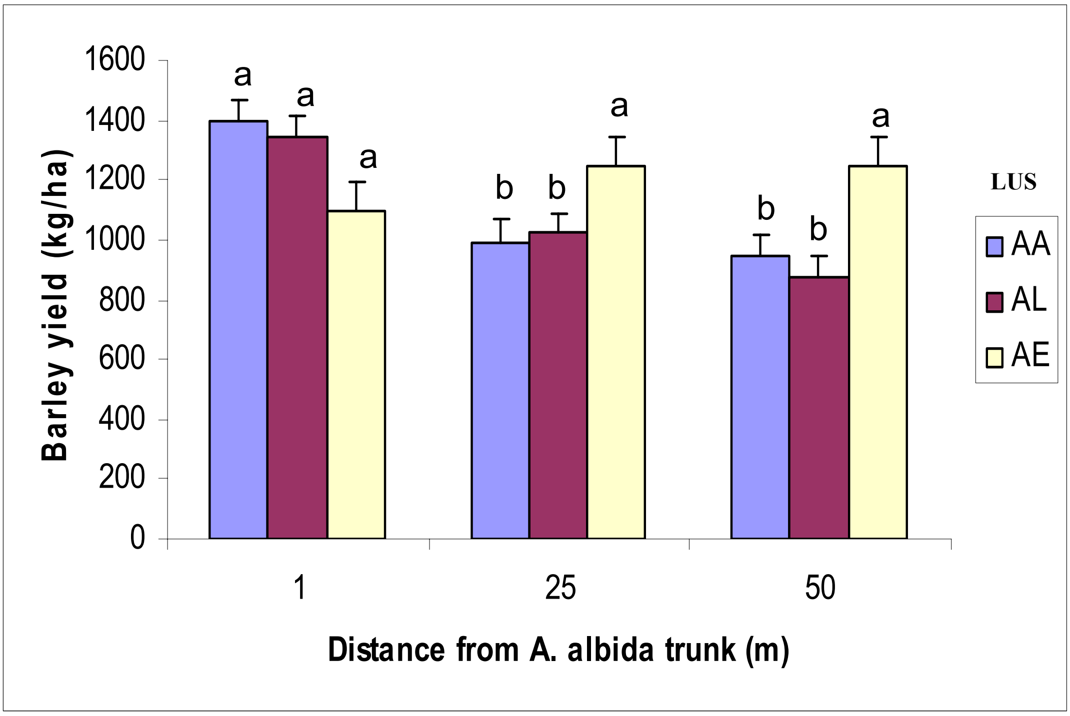


Figure 3 (Chapter 5). Mean (±SE) barley yield (kg ha^{-1}) at increasing distance from the centre of an *Acacia albida* trunk and for three land use system (*Acacia albida* only, *Acacia albida* and livestock, and *Acacia albida* & Eucalyptus) for 77 field locations sampled in 2005 in Tigray, northern Ethiopia.

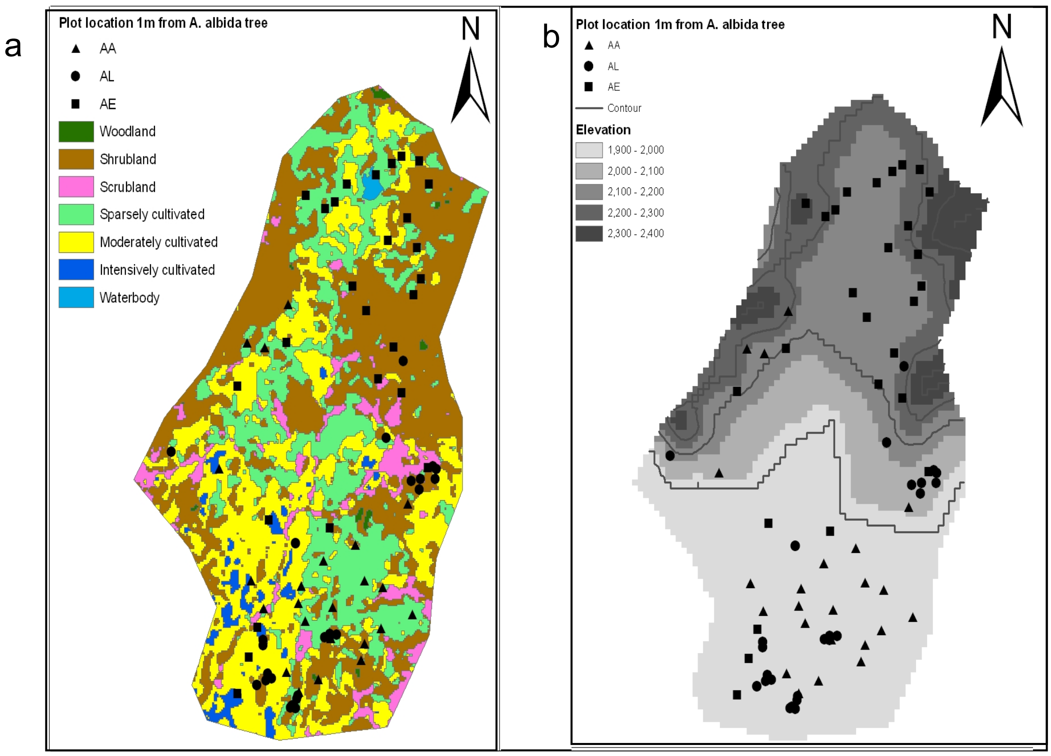


Figure 4 (Chapter 5). Overlay of field locations with *A. albida* trees with (a) 2005 LULC map and (b) elevation map for the study area in Tigray, northern Ethiopia.

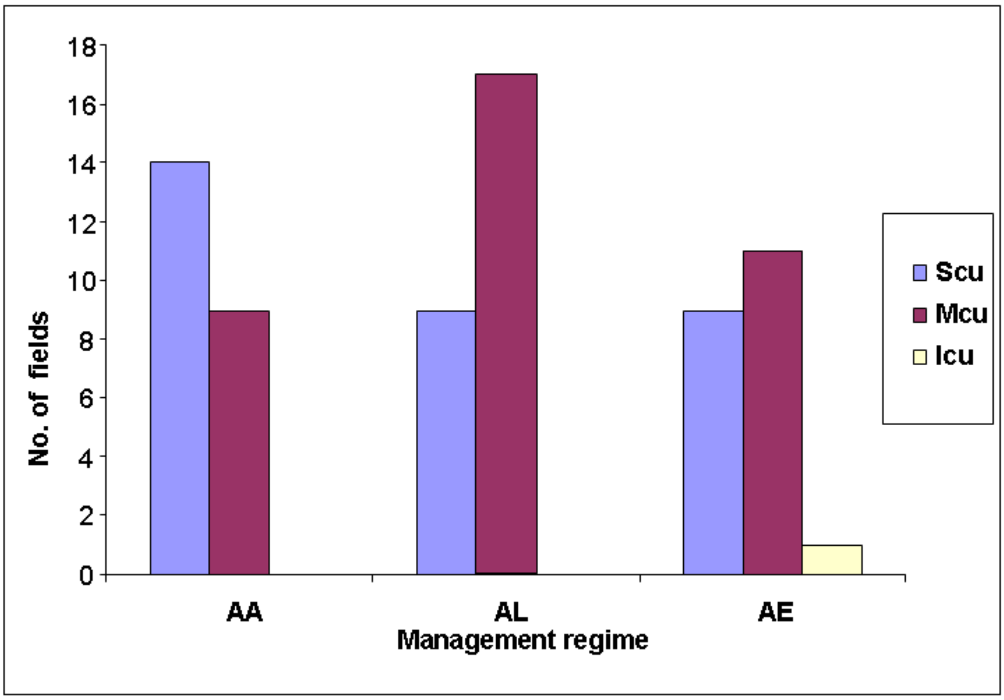


Figure 5 (Chapter 5). Relation between agricultural land use types and land use system derived from field scale observations for 2005 in Tigray, northern Ethiopia.

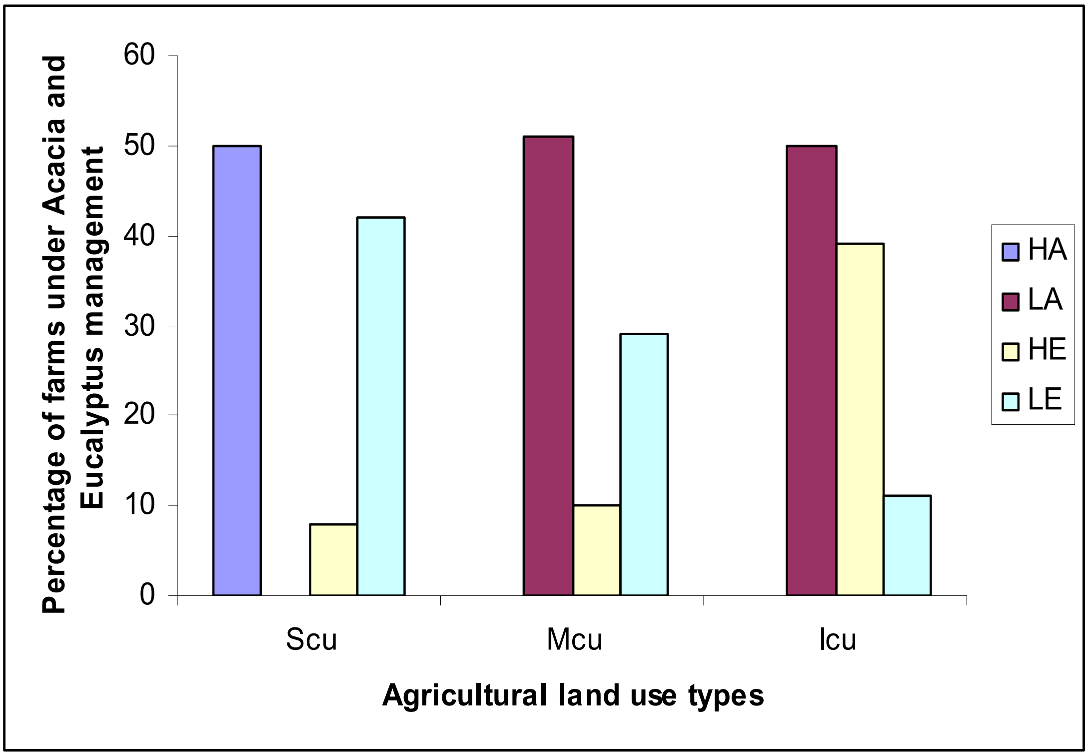


Figure 7 (Chapter 5). *Acacia albida* density and Eucalyptus tree farm characteristics in relation to agricultural land use types at regional scale in Tigray, northern Ethiopia.