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Soil acidity-induced land use/cover change and management systems on soil quality parameters in the central highlands of Ethiopia

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Soil acidity-induced land use/cover change and management systems on soil quality parameters in the central highlands of Ethiopia

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Thesis
Submitted in fulfillment of the requirements for the degree of doctor
at the University of Valladolid

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Dedicated to:

My late mother, Tenfe Arbas, who passed away at the final stage of this dissertation. It is disappointing that she could not see her efforts bearing fruit. HOW Ironic!

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Doing PhD was a long-term commitment and made me to pass through significant turbulences socially as well as academically. The academic aspect was quietly managed by me and my supervisors. The social aspect was held by many people who were behind the scene who perfectly shouldered my family responsibilities and gave me great relief to focus on my studies. Firstly and foremost, my brother and friend, Aleka Argachew, who was always a consipicuous figure in this regard. Thank you bro., for your help, all your encouragement and love you offered me. I feel very fortunate to stand where I am today with the opportunities that you have afforded me. However, it was practically impossible to think of doing PhD out of home without prior consent and agreement of my beloved wife, Senait Dereje, who handled family matters in the absence of me. She deserves special thanks and grand appreciation; she tried to give her best in looking after our kids by sacrificing her comforts. I am really falling short of words to thank her for the determination she has shown to bear extra household responsibilities during many years of this study. A sense of apology is due from my sweet and loving kids, Sidisie, Situnaf, Oliyad and Rabira who missed many precious moments of their childhood from fatherly love and care. I would like to thank them for their patience and understanding which motivated me to remain focused towards achieving various milestones of my journey. I know you missed me so much at the time you needed me more. I promise you to compensate the years I spent on my study, and will never let you be alone again.

Finally, I humbly dedicate this thesis to my late mother, Tenfe Arbas, who did not go to school herself, but single handedly paid many sacrifice to send me to modern school. Without her, I would not have become the man I am today. You have always inspired me to do my best and have supported me in every decision I have made. I love you to pieces!

Above all, all praise goes to the **almighty God**, for giving me the stamina and strength to complete this work in time. This all happened according to His perfect plan. Praise YOU LORD! Thank you!

Table of contents

NOTE TO READERS

This thesis is based on five original works, which are referred in the text as chapters by their corresponding Roman numerals (**I**, **II**, **III**, **IV and V**), published or under revision in different international journals. Each manuscript constitutes one of the chapters of the thesis. Authors, co-authors, and the stage of the publication are described below. Before presentation of each study, the reader will find the outline of the thesis and an abstract of the thesis written in English and Spanish. Then, a summary of the whole thesis which includes an introduction with the general and specific objectives, the main methodologies and analyses employed, the main results and a general discussion will be briefly narrated. Finally, the reader will find the five chapters/studies with its own introduction, materials and methods, results and discussion followed by conclusions.

LIST OF ORIGINAL WORKS/CHAPTERS

Chapter-I Temesgen D., Cruz, F., Kindu, M., Turrión, M.B., Gonzalo, J. 2014. Land use/cover (LULC) change and socio-economic conditions of local community in the central highlands of Ethiopia. **Published in International Journal of Sustainable Development and World Ecology.** DOI: 10.1080/13504509.2014.961181

Chapter-II Temesgen D., Gonzalo, J., Pando, V., Turrión' M.B., 2014. Comparison of soil quality parameters under different land uses and management systems in the central highlands of Ethiopia. Submitted to **Land Degradation and Development**, and is under review.

Chapter-III Temesgen D., C. Herrero, Turrión, M.B., 2014. Soil carbon mineralization kinetics as influenced by changes in land use and management systems in the central highlands of Ethiopia. Submitted to **Soil Biology and Biochemistry**, and is under review.

Chapter-IV Temesgen D., J. Gonzalo, J., Turrión, M.B., 2014. Effects of short-rotation *Eucalyptus* plantations on soil quality attributes in highly acidic soils of the central highlands of Ethiopia. Submitted to **Soil use and Management**, and is under review.

Chapter-V Temesgen D., Getachew, A., Ayalew, A., Tolessa, D., Gonzalo, J., 2014. Effect of lime and phosphorus fertilizer on acid soils and barley (*Hordeum vulgare* L.) performance in the central highlands of Ethiopia. Accepted to be published in **Experimental Agriculture** with minor revisions.

Outline of the Thesis

This thesis focuses on exploring the impact of soil acidity-induced land use/cover change and management systems on soil quality parameters in the central highlands of Ethiopia. The study site was Wetabecha Minjaro commonly known as Bedi, one of the hot-spot areas in soil acidity and associated problems in Ethiopia. To accomplish this general objective five studies have been executed and referred as **chapter I-V** later in the text. The first chapter of the thesis presents an extended summary of the whole study. **Chapter I** describes Land use/cover (LULC) change and socio-economic conditions of local community in the central highlands of Ethiopia as determined by analyzing time series satellite imagery and social survey. **Chapter II** looks at comparison of soil quality parameters under different land use/cover and management practices in the central highlands of Ethiopia. **Chapter III** presents soil carbon mineralization kinetics as influenced by changes in land use and soil management in the central highlands of Ethiopia. **Chapter IV** deals with the effects of short-rotation *Eucalyptus* plantations on soil quality attributes in highly acidic soils in the central highlands of Ethiopia. **Chapter V** deals with the effect of lime and phosphorus fertilizer on acid soils and barley (*Hordeum vulgare* L.) performance in the central highlands of Ethiopia. Fig. A shows the conceptual model of the thesis topics and studies carried out. My sincere gratitude goes to all co-authors of different papers compiled in this thesis. I have learned a lot from these distinguished scholars, which will be an asset in my further career. This thesis is an output of institutional collaboration between Ethiopian Institute of Agricultural Research (**EIAR**) and University of Valladolid (**UVa**).

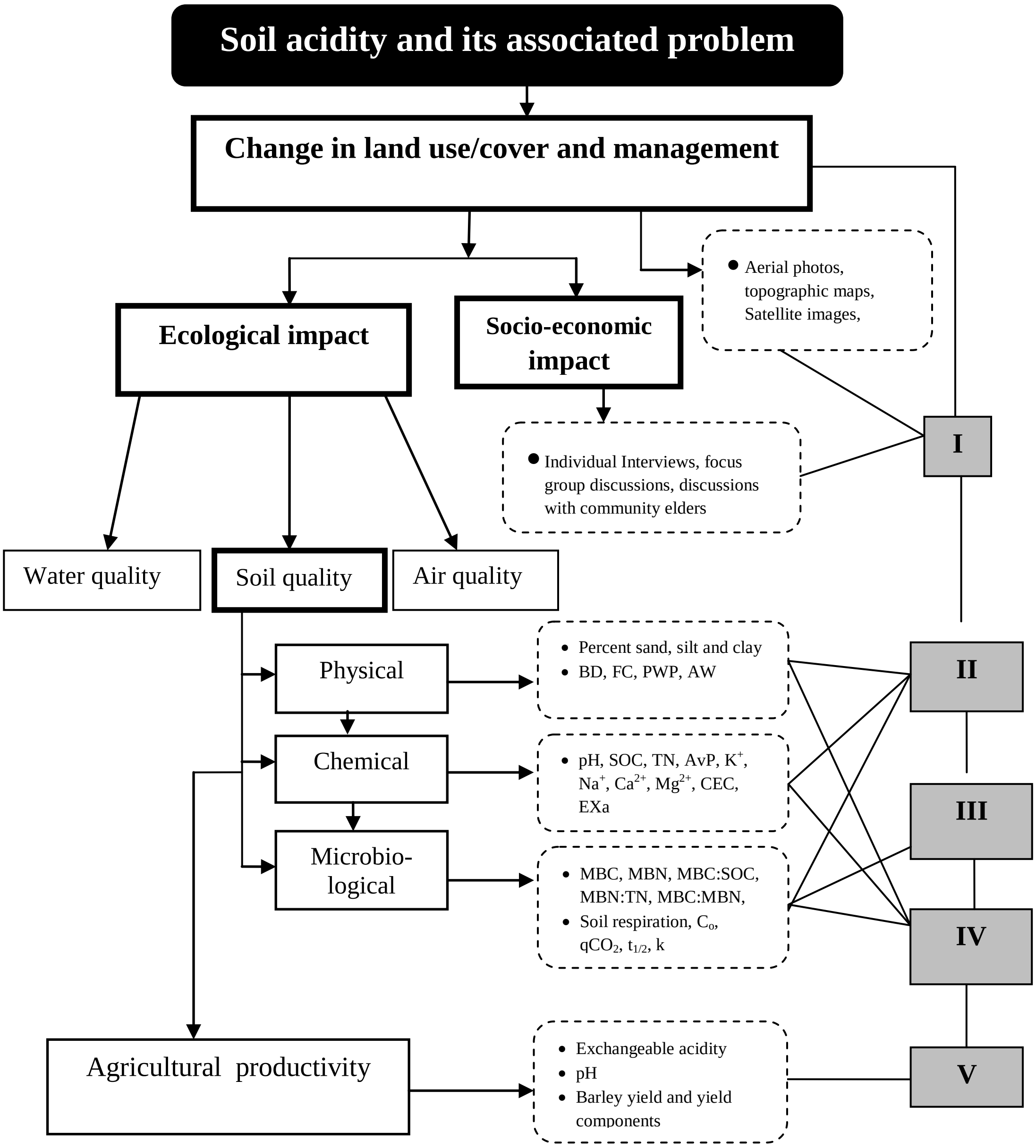

Fig. A: Conceptual model of land use change and management on soil quality parameters. Key factors are indicated in solid rectangles; measured variables/data used are indicated by discontinues lines; studies/chapters are indicated in Roman numbers, and links between them are shown.

ABSTRACT

ABSTRACT

Effects of land use/cover (LULC) changes and associated soil management practices on soil quality have recently received greater attention, due to its ecological and socioeconomic impact. Therefore, timely detection of land use change and its potential effect on soil quality parameters is an essential prerequisite to take any restorative measures, efficient land use planning and resource management. The study site for this PhD study was in Wetabecha Minjaro peasant association, in the central highlands of Ethiopia. The objectives of this thesis were: a) to show historic land use/land cover dynamics from 1975- 2014, and assess its relation to the socio-economic conditions of the local community; b) to determine soil quality parameters in response to change in land use and soil management practices; c) to assess the C-mineralization potentials of soils in response to change in land use and soil management practices, and to compare the effectiveness of some commonly used decay models for describing rates and amounts of C mineralization; d) to study the effects of grassland conversion to short-rotation *Eucalyptus* plantations on soil quality attributes; e) to evaluate the effects of different rates of lime and phosphorus fertilizer on soil and barley productivity.

Analysis of satellite images showed that four main types of land use/cover classes, which were identified as: natural forest, *Eucalyptus* plantations, cropland/settlements and grasslands. Between 1975 and 2014, cropland/settlements and *Eucalyptus* plantations considerably increased, whereas area under grassland decreased drastically. Deterioration of soil fertility and lack of financial capacity to restore, and availability of many religious holidays directly or indirectly contributed to the seasonal food shortages of the community in the study area. Studying soil physical, chemical and biological properties under grassland, cropland, *Eucalyptus*, limed land, and fallow land all existing adjacent to each other showed that the above parameters were higher under grassland as compared to the other four land uses. However, the three land uses (cropland, *Eucalyptus* and limed lands) were statistically comparable for most of the soil chemical properties. Depth of sampling only affected available phosphorus, Mg^{2+}, exchangeable acidity, ratios of microbial biomass carbon to soil organic carbon and microbial biomass nitrogen to total nitrogen. Soil organic carbon, microbial biomass carbon, ratio of microbial biomass carbon to soil organic carbon and microbial biomass nitrogen could be important parameters to assess functional capacities of soils under soil acidity conditions in the highlands of Ethiopia. Laboratory incubation experiment on cumulative CO_2 release followed the order: grassland >cropland > *Eucalyptus* >fallow land >limed land. Among six kinetic models tested, a first-order model $[C_t = C_o (1-e^{-kt})]$ was best fitted to describe C mineralization of the experimental data. Comparing soil quality attributes under 5- and 10-year-old *Eucalyptus* plantations with adjacent grassland soils showed that the mean values of pH, soil organic carbon, total nitrogen, calcium and cation exchange capacity, micriobial biomass carbon and nitrogen in grassland were significantly higher in both 0-10 cm and 10- 20 cm soil depths. Similarly, kinetics parameters calculated using first-order equation ($C_t = C_o (1-e^{-kt})$) showed that potentially mineralizable carbon (C_o) was also significantly higher ($p< 0.001$) under grassland. Converting of grassland to 5-year-old and 10-year-old *Eucalyptus* reduced the values of C_o by 21% and 43% respectively. However, available phosphorus, exchangeable potassium and magnesium were not significantly affected in the three land use systems. Microbial biomass carbon and nitrogen in 5- and 10-year-old *Eucalyptus* plantations were not significantly different from each other. However, results clearly showed that deterioration in soil quality parameters were more pronounced in 10-year-old *Eucalyptus* than in 5-year-old *Eucalyptus* planatations. The ameliorative effects of factorial combinations of five lime rates (0, 0.55, 1.1, 1.65 and 2.2 Mg ha^{-1}) in the of form $CaCO_3$ and four P rates (0, 10, 20 and 30 kg ha^{-1}) in the form of triple super phosphate on soil pH, exchangeable acidity and barley productivity were compared for two years. Results of soil analysis after two years of liming showed that liming significantly ($p<0.05$) increased soil pH, and markedly reduced exchangeable acidity. Grain yield of barley obtained at lime rate of 1.65 and 2.2 Mg ha^{-1} were comparable, and significantly ($p<0.05$) superior to the other lime rates. Similarly, additions of 10, 20 and 30 kg P ha^{-1}, increased grain yield of barley by about 29, 55 and 66 % as compared to control (without P addition). However, the combined applications 1.65 Mg ha^{-1} lime in the form of $CaCO_3$ and 30 kg P ha^{-1} in the form of triple super phosphate gave 133 % more grain yields of barley relative to control (without P and lime addition). Therefore, sustainable barley production on acid soils in the central highlands of Ethiopia should entail combined applications of both lime and P fertilizer.

Keywords: Ethiopian highlands, land use/cover, Satellite images, soil quality, exchangeable acidity, *Eucalyptus*, Carbon mineralization, Grassland

RESUMEN

El estudio del efecto de los cambios en el uso y en la cubierta del suelo así como los asociados a las prácticas de manejo sobre la calidad de los suelos, han recibido recientemente una gran atención, debido a su impacto ecológico y socioeconómico. La oportuna detección de las consecuencias de los cambios de uso en los parámetros de calidad de los suelos es un prerrequisito esencial para llevar a cabo medidas de recuperación y la planificación de los usos, así como el manejo eficiente de los recursos. La zona de estudio de la presente Tesis Doctoral se localiza en la asociación campesina de Wetabecha Minjaro, en tierras altas del centro de Etiopía. Los objetivos de esta Tesis fueron: a) mostrar la dinámica del cambio de uso del territorio y su relación con las condiciones socio-económicas de la comunidad local en la zona; b) determinar los parámetros de calidad del suelo que responden a los cambios de uso y a las prácticas de manejo en la zona; c) evaluar la capacidad de la mineralización de C de los suelos en respuesta a los cambios de usos y a las prácticas de manejo, y comparar la efectividad de algunos modelos para describir velocidades y cantidades de C mineralizados; d) estudiar el efecto de la conversión de pastos a plantaciones de eucalipto de rotación corta en distintos atributos de la calidad edáfica; e) evaluar los efectos de diferentes dosis de encalado y la adición de fósforo al suelo en la producción de cebada y en distintas propiedades edáficas.

El análisis de las imágenes de satélite de la zona mostró cuatro tipos principales de uso o cubierta que fueron identificados como: bosque natural, plantaciones de eucalipto, tierras de cultivo y pastos. Entre 1975 y 2014, la superficie ocupada por tierras de cultivo y por las plantaciones de eucalipto aumentó considerablemente, mientras que la superficie de pastos decreció drásticamente. El deterioro de la fertilidad edáfica y la ausencia de capacidad financiera para su recuperación, así como la disponibilidad de muchos días defectivos religiosos contribuyeron directa o indirectamente a la escasez estacional de alimentos en la comunidad.

El estudio de las propiedades físicas, químicas y biológicas de los suelos bajo pastos, cultivos, eucalipto, tierras encaladas y tierras en barbecho situadas adyacentemente han mostrado valores en los suelos bajo pastos indicativos de una mayor calidad edáfica que bajo los otros usos y sistemas de manejo considerados. Sin embargo, los cultivos, los suelos bajo eucaliptos y los terrenos encalados presentaron valores similares en la mayoría de las

propiedades edáficas estudiadas. La profundidad de muestreo afectó significativamente a las concentraciones de P disponible, de Mg^{+2} intercambiable, a la acidez intercambiable y a las ratios de carbono de la biomasa microbiana a carbono total del suelo (MBC/SOC) y de nitrógeno de la biomasa microbiana a nitrógeno total del suelo (MBN/TN). El SOC, el MBC y el MBN y la ratio MBC/SOC resultaron ser indicadores adecuados para evaluar las capacidades de funcionamiento de los suelos ácidos de las tierras altas de Etiopía estudiadas. La cantidad de carbono acumulado liberado como CO_2 en el ensayo de incubación siguió el siguiente orden: pasto> cultivo > eucalipto > terreno en barbecho > terreno encalado. Entre los seis modelos cinéticos comparados tras los resultados del experimento de incubación, el modelo cinético de primer orden [$C_t = C_o (1-e^{-kt})$] fue el que presentó el mejor ajuste para el C mineralizado. Por otro lado la comparación de los atributos de calidad de los suelos bajo plantaciones de eucalipto de 5 y 10 años de edad con suelos de pastos adyacentes mostraron valores medios de pH, SOC, TN, Ca^{+2}, capacidad de intercambio catiónico, MBC y MBN significativamente más altos en pastos que en los suelos bajo eucalipto tanto para la profundidad de 0 - 10 cm como para la de 10 - 20 cm. De manera similar, los parámetros cinéticos calculados usando la ecuación de primer orden [$C_t = C_o (1-e^{-kt})$] mostraron que el carbono potencialmente mineralizable (C_o) fue significativamente más alto bajo pasto que bajo eucalipto ($p<0{,}001$). La conversión de pasto a eucalipto tanto después de 5 años como de 10 años redujo los valores de Co en un 21% y en un 43%, respectivamente. Sin embargo, el P disponible, el K^+ y el Mg^{+2} intercambiables no mostraron diferencias significativas entre los tres usos. Igualmente, el MBC y MBN no mostraron diferencias significativas entre los suelos bajo las plantaciones de eucalipto de 5 y de 10 años. Los resultados mostraron que el deterioro en los parámetros que determinan la calidad edáfica fue mayor en los suelos bajo las plantaciones de eucalipto de 10 años que en las de 5 años.

Se compararon durante dos estaciones consecutivas el efecto de combinaciones factoriales de cinco dosis de encalado (0; 0,55; 1,1; 1,65 y 2,2 Mg de $CaCO_3$ ha^{-1}) y cuatro dosis de superfosfato triple, SPT (0, 10, 20 and 30 kg P ha^{-1}) sobre el pH del suelo, la acidez intercambiable y la producción de cebada. Los resultados de los análisis de suelo después de dos años de encalado mostraron que el pH edáfico se incrementó significativamente ($p<0{,}05$) y se redujo el acidez intercambiable. El rendimiento de grano de cebada obtenido tras las dosis de 1,65 y 2,2 Mg de $CaCO_3$ ha^{-1} fueron similares, y significativamente más

altos que el de las otras dosis de encalado ($p<0,05$). De manera similar las adiciones de 10, 20 y 30 kg de P ha^{-1} como SPT incrementaron la producción de grano de cebada en 29, 55 y 66% respectivamente comparada con el control sin adición de P. Sin embargo, la aplicación combinada de 1,65 Mg de $CaCO_3$ ha^{-1} y 30 kg P ha^{-1} como SPT dio como resultado un 133 % más producción de grano de cebada en comparación con el control (sin adición de P y sin encalar). Por lo tanto, la producción sostenible de cebada en los suelos ácidos de las tierras altas del centro de Etiopía debería implicar la aplicación combinada de fertilizantes fosfatados y el encalado del suelo.

Palabras clave: Tierras altas del centro de Etiopía, uso/cubierta del suelo, imágines por satélite, calidad del suelo, acidez intercambiable, eucalipto, mineralización de carbono, pasto.

GENERAL INTRODUCTION

1 Introduction

1.1 Overview of Ethiopia- The Country of Study

Ethiopia is located in the Northeastern corner of Africa lying between 2°54′ to 15°18′ N latitude, and between 32°42′ to 48°18′ E longitude (Fig. 1). The country is large with an area of 1.12 million km^2 occupying a significant portion of the Horn of Africa. It has a population of 94.1 million, and is the second most populous country in Africa just behind Nigeria (United Nations, 2012).

Figure 1 Location of the study area: (a) Location of Ethiopia in Africa (b) National Regional States of Ethiopia (Study region in grey color) (c) Study zone in Oromiya (West Shewa zone) (d) Study site and surrounding kebeles.

The general terrain of Ethiopia has high plateau with central mountain range divided by the Great Rift Valley that creates three major relief regions: the Western Highlands, the Eastern Highlands, and the low-lying Rift Valley and Western Lowlands. With regard to altitude, the country ranges from 126 m below sea level at Kobar Sink in Afar to 4620 m above sea level at the highest peak of Ras Dashen (Zerihun, 1999). It is a developing country with a largely agrarian economy, where over 85 per cent of the human population relies heavily on agriculture for its livelihood needs. Agriculture accounts nearly half of the Gross domestic Product and 90% of the foreign exchange earnings (CSA, 2007). However, it is virtually small-scale, subsistence-oriented and mainly dependent on rainfall. Consequently, about 90 percent of the country's agricultural output is generated by smallholder subsistence farmers who use traditional tools and farming practices (Omiti et al., 2000). The highlands are, areas lying >1500 m above sea level, cover close to 45% of Ethiopia's land mass but account for about 95% of all cultivated land. It caters 88% of the human population, 70% of the total livestock population, and where 90% of the country's economic activity takes place (Ayele, 1999) (Fig. 2). However, changing environmental factors have led to soil quality degradation which poses a critical risk for agricultural productivity and food security (Bekele and Holden, 1999; Krowntree and Fox, 2008).

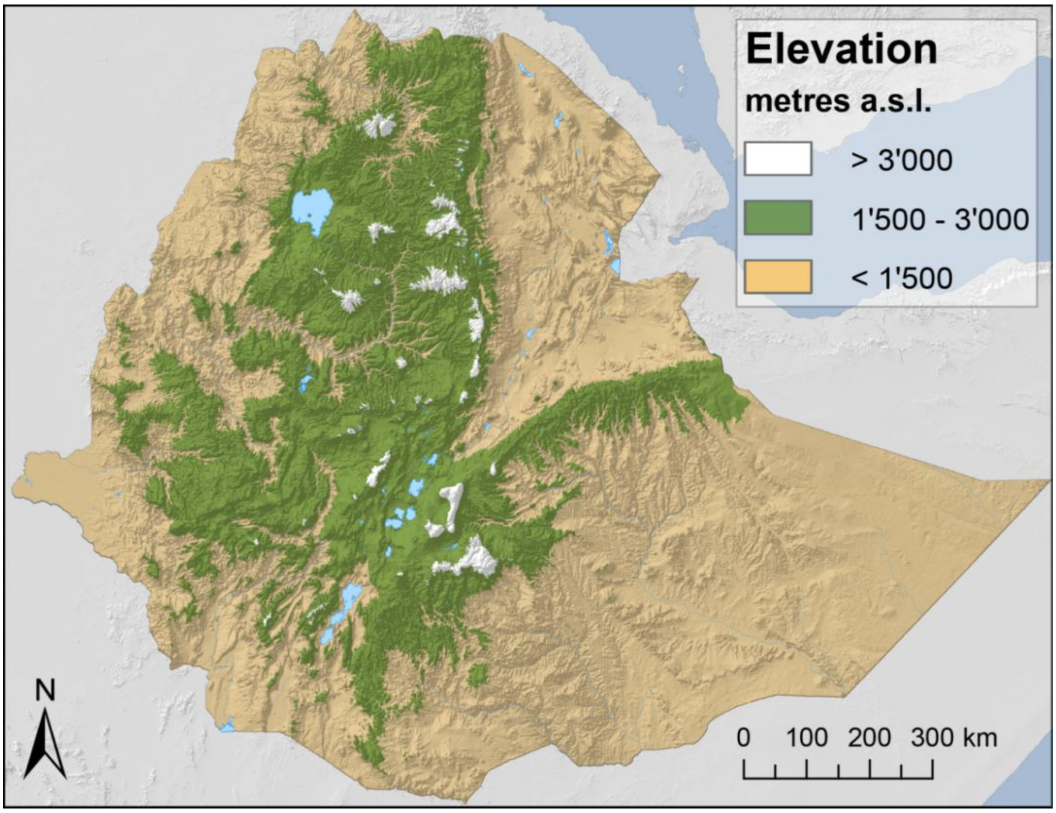

Figure 2 Map showing the highlands of Ethiopia (1500-3000 m.a.s.l). Source: FAO, 1986

1.2 Weather conditions, soils and vegetation

Ethiopia has diverse rainfall and temperature patterns as a result of predominantly tropical climate and mountainous topography. The highlands are with plateaus and mountain landforms with adequate rainfall for crop production, and moderate to cool temperature. The lowlands have scare vegetation, low rainfall for crop production, high temperature and less populated. The annual rainfall ranges between 100 mm in the northeast lowlands of Afar to 2400 mm in the southwest highlands. The coefficient of variation (CV) in the national inter-annual rainfall distribution is 8%, although the CV can be as high as 28% in some parts of the country such as Tigray (Mersha, 2000). Generally, the western and southwestern parts of the country receive relatively higher annual rainfall brought by the wind system from the Indian Ocean. The rainfall regime is mainly influenced by topographical variation in the country, seasonal cycles and opposing responses to regional and global weather systems, consequently, three rainfall regimes are commonly identified (Fig. 3). Unimodal rainfall regime is characterized by one distinct rainy season and one peak, and the areas with this regime are found in the north and west. Areas with two distinct rainy seasons are found in the south and in northeastern parts of the country. The main rain season is from February through May, and short rains from October to November, and the dry periods are June to September and December to February. Bimodal rainfall regime has one continuous season of rain, but with two peaks, the long rainy season (June-September) and short rains (March-May) locally referred as Kiremt and Belg rains respectively. The rest of the months (October to February) are dry period. Areas with bimodal rainfall regime are found in a transitional band between the two systems.

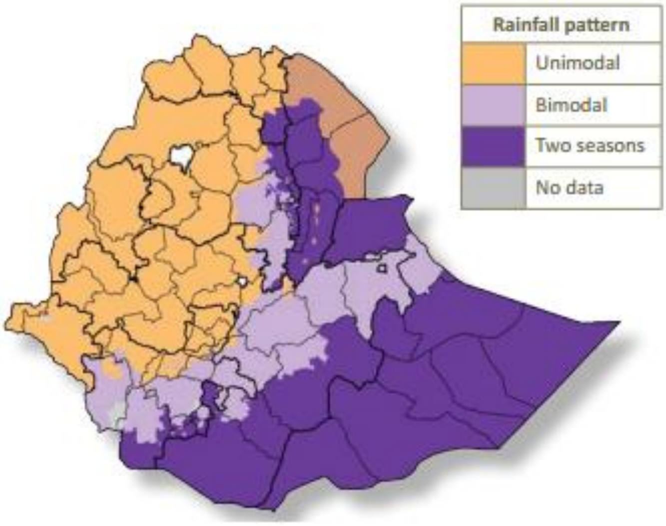

Figure 3 Main rainfall patterns in Ethiopia (Source: Atlas of Ethiopian livelihoods, 2010)

The variations in topography and climatic factors coupled with diversity in parent material and vegetation have resulted in a wide range of soil types. Among the soil types identified and mapped in Ethiopia, the major ones include: Leptosols (30.2%), Nitisols (13.9%), Calcisols (11.8%), Vertisols (10.4%), Gypsisols (8.9%), Cambisols (8.4%), Luvisols (7.4%) and Fluvisols (3.8%) (Marcel, 2012). Because of the strong interaction between different soil-forming factors, the resulting soil variability is extremely high, which makes the study of soil attributes a challenging task. The few studies undertaken in the highlands of Ethiopia indicate that the soils are deficient in terms of N, K, P, and low in cation exchange capacity (CEC), and soil organic matter by international standards (Alemneh, 2003).

Similar to soils, the type and distribution of vegetation is also a result of the interaction of several factors. Important among these are soil type, topography, and climate. Differences in these factors are the cause of a diverse vegetation cover in Ethiopia. For example, Ethiopia's natural vegetation comprises four biomes: savanna, mountain vegetation, tropical thickets and wooded steppe, and desert steppe vegetation. Wet savanna consists of montane, tropical vegetation with dense, luxuriant forests and rich undergrowth, and occurs predominantly in the western Highlands. The drier savannas comprise tropical dry forests mixed with grassland, and are found at lower elevations.

1.3 Land degradation in Ethiopian highlands

Generally, the weather conditions in the Highlands of Ethiopia are favorable for agriculture and human settlement. The volcanic parent material supplies a rich diversity of nutrients that makes soils more suitable for agriculture than in most other parts of Africa (Voortman et al., 2000). Today, however, this part of the country is severely degraded due to intensive land use and high population pressure leading to low agricultural productivity and food insecurity. Several causes of land degradation in Ethiopia were reported (Hawando, 1997; Demel, 2001; Berry, 2003; Hurni et al., 2007; World Bank, 2008). However, the five major causes of land degradation in Ethiopia synthesized by Mae (2013) include: (1) The heavy reliance of the rural population on subsistence oriented agriculture, (2) Ethiopia's rugged geomorphic features, steep slopes, highly erosive rainfall and scarce land cover, (3) Poor farming practices (continuous cropping with no/little addition of external inputs, use of crop residue as livestock feed, and dung as energy source, monoculture, slope cultivation, overgrazing), (4) Land tenure insecurity discourages land improvement measures, and (5) Inadequate agricultural knowledge and poor soil extension service, weak network in coordination and mobilization of human and financial resources.

Manifestations of soil degradation include decline of soil fertility, development of soil acidity, salinization, alkalization, deterioration of soil structure, accelerated wind and water erosion, loss of organic matter and biodiversity (FAO, 1999). Soil degradation occurs extensively in arable land as manifested in soil erosion, biological degradation (i.e., loss of organic matter), chemical degradation (i.e., loss of nutrients) and physical degradation (i.e., poor water infiltration and restricted aeration in rooting system). It is the consequence of different natural processes, but is usually accelerated by human activities. Consequently, soil degradation greatly contributed to the decline in agricultural productivity, persistent food insecurity, and rural poverty (World Bank, 2008). Particularly, the soil resources in the highlands are eroding at an alarming rate that might lead to irreversible damage. Hence, attempts to alleviate land degradation in Ethiopian highlands are critically dependent on efforts to deal with the three main underlying causes of land degradation: population growth, low agricultural productivity and high dependence on fuel wood, dung and crop residues as sources of household energy (Selamyihun, 2004).

1.4 Soil acidity scenario in Ethiopia

Acid soil is defined as a soil with a pH value < 7.0 (Soil Science Society of America, 1997). These include strongly acid soils with pH value < 5.0, and moderately acid soils with pH between 5.0 and 6.5 (Brady and Weil, 1996). Acid soils (soils with pH < 5.5 in the surface layer) constitute 3,950 million ha or 30% of the world's total ice-free land (von Uexküll and Mutert, 1995). In Africa, 22% or 659 million ha of the total 3.01 billion ha land has acid soils (Malcolm and Andrew, 2003). In Ethiopia nearly 41 % of the total land area is acidic (Schelede, 1989), and the area coverage presented in Fig. 4.

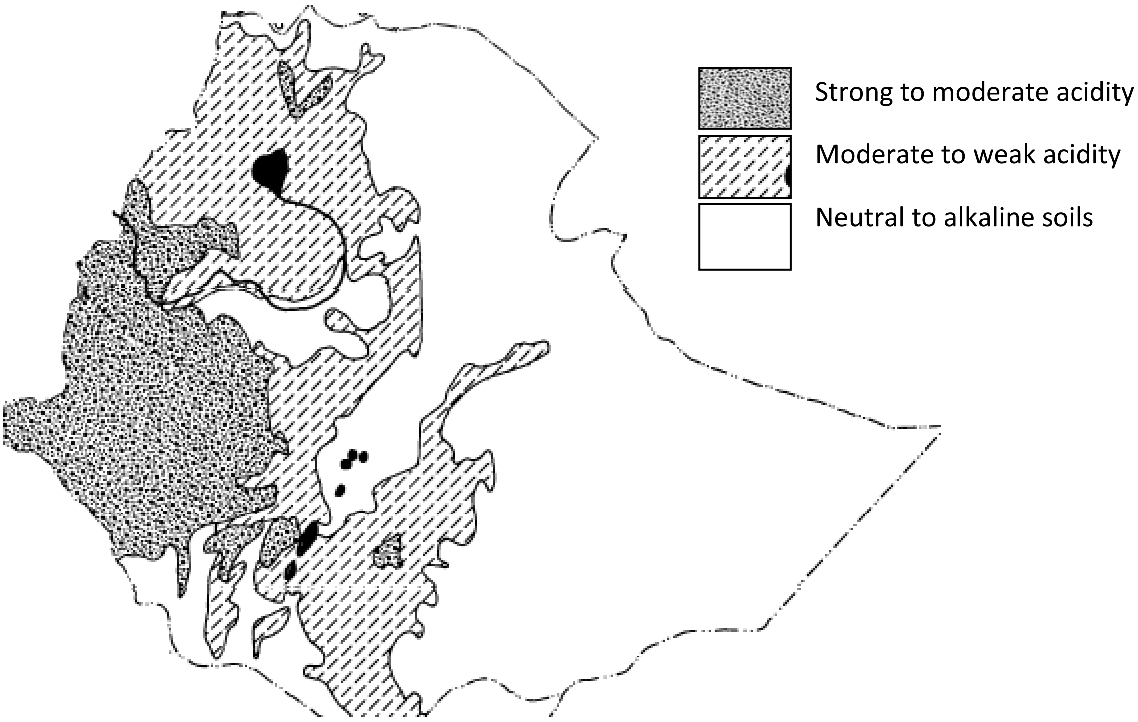

Figure 4 Soil acidity map of Ethiopia. Source: Schlede (1989)

Given that the data provided in the map is outdated, there is potential that this situation has worsened over the course of time. However, there are ongoing interventions to mitigate the negative impact, which is expected to minimize the problem going forward (ATA, 2013). The majority of acid soils in the highlands of Ethiopia are highly weathered mainly due to nature of the soils and anthropgenic activities that consequently leave the soil vulnerable to soil erosion. Hence, one of the major factors limiting agricultural production in the highlands of Ethiopia is mainly related to the presence of exchangeable acidity (EXa) in highly weathered acid soils (Paulos, 2001; IFPRI, 2010). Particularly, in areas where annual precipitation exceeds evapotranspiration, the problem of soil acidity is severe, and is one of the major factors that contributed to low agricultural productivity.

Acidity produces complex interactions of plant growth-limiting factors involving physical, chemical, biological and microbiological properties of soils. Deficiencies of N, P, and K are common in acidic soils due to low organic matter content, depletion of nutrient-bearing minerals, and fixation of phosphate by Fe and Al oxides (Baligar and Ahlrichs, 1998). Soil pH levels and associated conditions are presented in Table 1.

Table 1. Soil pH levels and associated conditions.

Soil pH	Indications	Associated conditions
< 5.5	Soil is deficient in Ca and/or Mg, and should be limed	Poor crop growth due to low CEC and possible Al toxicity. P deficiency is expected
5.5 - 6.5	Soil is lime free, should be closely monitored	Satisfactory for most crops
6.5 - 7.5	Ideal range for crop growth	Soil CEC is near 100% base saturation
7.5 - 8.4	Free lime ($CaCO_3$) exists in soil	Usually infiltration and percolation of water due high Ca content of clays. Both P and micronutrients are less available

Source: Hach Company (1992).

Numerous authors (Bolan et al., 2003; Fageria and Baligar, 2008) showed that plant growth in acidic soils is limited by a set of conditions, including the excess of protons (H^+), aluminum (Al^{3+}) and manganese (Mn) phytotoxicities, and deficiencies of essential nutrients, such as phosphorus (P), calcium (Ca), magnesium (Mg) and molybdenum (Mo). Other authors (Robert, 1995; Fageria and Baligar, 2003; Dahlgren et al., 2004; Hirth et al., 2009) experimentally demonstrated the limited agricultural productivity of acidic soils is due to diminished microbial activity as a consequence of the presence of high concentrations of Al around the root zone.

Soil acidification is a natural process which can be enhanced by human activity or can be controlled by appropriate soil management practices. These soils have various constraints for crop production and are readily degraded when subjected to erosion, leaching, or contamination. Therefore, proper management of acid soils is of both socio-economic and ecological importance for tropical and subtropical regions (He et al., 2003). Several agricultural practices have been recommended to overcome the problem of tropical acid soil infertility worldwide. One of the immediate solutions to this chronic problem is amelioration through application of ground calcium and/or magnesium carbonates, hydroxides, and oxides aiming at raising the soil pH, modifying its physical, chemical and biological properties (Edmeades and Ridley, 2003). However, in the past, this practice had not been in use among Ethiopian smallholder farmers owing to technological, institutional and socio-economic related constraints. Instead, among few strategies that were in practice and still in use to mitigate the negative effects of soil acidity includes: fallowing croplands, conversion of grassland/cropland to short rotation *Eucalyptus* plantations and expansion of farming to communal grazing lands. The so called ‘fallowing’, the resting state of agricultural field (Szott et al., 1999) is common in some high-spot soil acidity areas, and areas with low soil fertility. This is intended to allow the soil to rest and regain some of its fertility by growing vegetation, usually consisting of naturally growing weeds and grasses. However, due shorter fallow period (usually < 2 years) and free grazing of animals in the fallow field, most often the intended objectives are not met.

The growing demand for construction and fuel wood and the wide adaptation of *Eucalyptus* to the different agro-ecological zones of the country are resulting in increased plantation of *Eucalyptus* by smallholders. As a result the area of *Eucalyptus* is doubling every decade and more and more smallholder farmers are growing primarily on grassland or cropland. Even though the policy environment in Ethiopia discourages farmers from planting this exotic tree on productive land, many farm households still continued planting of *Eucalyptus*. Consequently, *Eucalyptus* is voraciously integrated into farming systems in spite of a perception that this practice adversely affects soil quality and crop productivity. In response to this, more recently, there is a great desire from government to improve the productivity of acid soils rather than converting it to other land use types. Consequently, the use of lime has widely begun in some soil acidity prone areas of the country. Hence, grassland, cropland, *Eucalyptus* plantations, fallow land and limed land are common types of land use in some high-spot soil acidity areas such as Wetabecha minjaro in the central highlands of Ethiopia.

1.5 Land use/cover (LULC) change in the highlands of Ethiopia

Land use and land cover change profoundly affect human well-being and, therefore, have become a major topic for society (Claudia et al., 2013). Land cover refers to all the natural, physical and man-made features that cover the earth's immediate surface such as vegetation, urbanization, water, ice, bare rock or sand surfaces. Conversely, land use refers to the human activity that is associated with a specific land-unit, in terms of utilization, impacts, or management practices (Thompson, 1996; Jansen and Di Gregorio, 2002). Land use is, therefore, based upon function, where a specific use can be “defined in terms of a series of activities undertaken to produce one or more goods or services” (Jansen and Di Gregorio, 2002). Land is a crucial physical asset that economic, social, infrastructure and other human activities are undertaken on. Thus, several land use/cover changes have occurred at all times in the past, are presently ongoing, and are likely continue in the future (Bossio et al., 2005; Nyssen et al., 2009; Yimer and Abdelkadir, 2011; Angassa et al., 2012), majorly related to population increase and their demand for diverse products. These changes have beneficial or detrimental impacts, the latter being the principal causes of global concern as they impact on human well-being and safety. Land use/cover changes are driven by both anthropogenic activities and natural phenomena (Meshesha et al., 2012); threaten food security, livelihood systems, and global sustainability (Stern, 2006; Turner et al., 2007). Therefore, when soils come under increasing pressure to maintain a range of ecosystem services, there is interest in how soils change over time in response to factors such as change in land use/cover (Tye et al., 2013).

It is widely known that Ethiopia faces serious LULC change problems, mainly as a result of population growth and the need for new agricultural lands, which have contributed to the clearing of forests and other natural land covers (Argaw et al., 1999; Kebrom 1999; FAO, 2007; Garedew et al., 2009; Meshesha et al., 2012). Since 85% of the population relies on subsistence agriculture, population growth affects agricultural land use. The need for increased food production results, amongst others, in the conversion of forest and grassland to cropland. As a consequence, there is a rapid decline in natural vegetation areas, dwindling of per capita land available for cropping, expansion of farming to marginal lands and steep slopes leading to land degradation. With limited regulation of farmland expansion into unsuitable areas, increased soil erosion from farm and sloppy lands has become a significant environmental concern in Ethiopia (Figure 5). Particularly, soil erosion by water is the highest land degradation problem in the highlands of Ethiopia (Hurni, 1993).

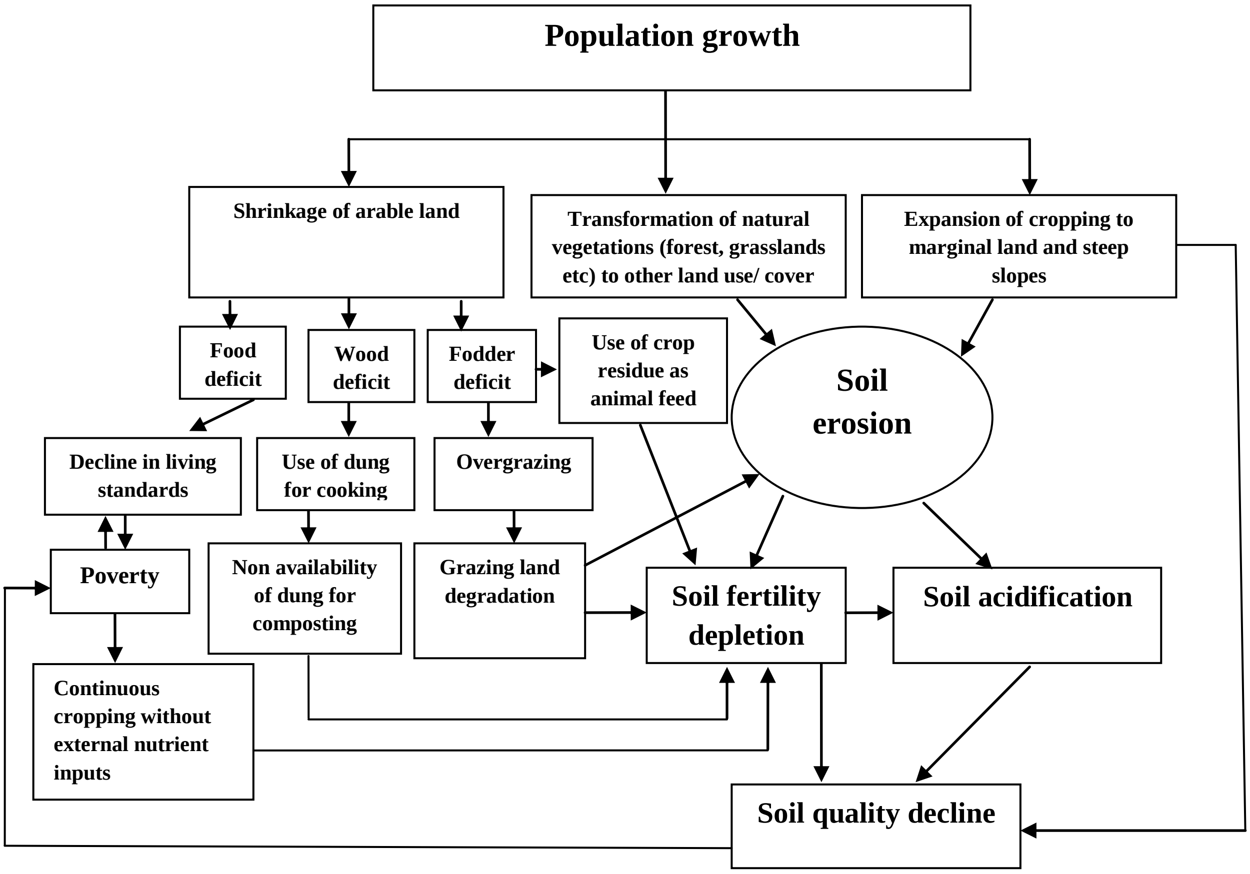

Figure 5 Effects of population growth on soil quality decline in the highlands of Ethiopia (Own illustrations).

For example, a report prepared for the national conservation strategy states: ‘unless major changes in the current management of soil resources occur, the land unable to support agriculture because of soil erosion will increase to some 10 million hectares by 2010 (FAO, 1986). Without recognizing consequences on soil conservation and environmental quality, significant decline in agricultural soil quality has occurred worldwide (Imeson et al., 2006). Therefore, any change in land cover or land use has direct impact on livelihoods of rural economy at large. To be able to guide future developments toward such undesirable outcomes, a thorough understanding of past and present land use/cover is essential. Understanding the dynamics and driving forces behind LULC changes on soil degradation at the local level is fundamental to development planning and the analysis of land-related policies (Tekle and Hedlund 2000). Land degradation is often associated with interactions among land use, soil management and local knowledge regarding agricultural production with inherent soil forming and erosion factors (Karlen et al., 2001). Therefore, it is necessary to go beyond disciplinary trend studies and examine methods for integrating LULC and socio-economic data and the experiences of different stakeholders.

The recent developments of a large number of sensors with increased spatial resolutions made tremendous advances in the use of remote sensing and geographic information system (GIS) thereby helping in the precise assessment and analysis of land use/land cover changes at local, regional and global levels. It is believed that, at a global scale, land use changes are cumulatively transforming land cover at an accelerating pace, mainly in the tropics (Houghton, 1994). However, quantitative data on where, when, and why such changes take place globally are still lacking (Turner et al., 1993).The recent advances in technologies such as global positioning systems (GPS), and GIS are considered to be the forefront techniques that allow us integrate the information generated from various sources on a single platform and analyze them efficiently in a spatial or temporal domain.

Most LULC change studies use aerial photographs, satellite imagery or a combination of both. Especially if satellite imagery is used, ancillary data are needed for establishing training areas and performing accuracy assessment. For recent periods, ancillary data can be easily collected through field observations. However, for satellite imagery up to four decades old, these data are often not readily available. As an alternative, aerial photographs (Mertens and Lambin, 2000; Petit and Lambin, 2001), vegetation maps (Muñoz-Villers and Lopez-Blanco, 2008) or interview methods (Atwell et al., 2009) have been used. However, old aerial photographs often require ground truthing themselves (Rembold et al., 2000) and are therefore not an optimal data source. The limited scope and often questionable reliability are major drawbacks of interview methods (Tra and Egashira, 2004; Aynekulu et al., 2006).

1.6 Assessment of soil quality

Precise soil quality assessment is critical for designing sustainable agriculture policies, restoring degraded soils, carbon modeling, and improving environmental quality (Obade and Lal, 2013). Hence, the need to understand and assess soil quality has been identified as one of the most important goals for modern soil science (Wang and Gong, 1998), because of growing public interest in sustainability and the desire to determine effects of land use and management practices on soil resources (Claudia et al., 2013). Soil quality is defined as: "capacity of the soil to function, within the ecosystem and land use boundaries, to sustain biological productivity, maintain environmental quality, and promote plant and animal health (Karlen et al., 1997)"; and therefore, it is one of the most important factors in developing sustainable land management and sustaining the global biosphere (Nael et al., 2004). It is a concept that integrates soil biological, chemical and physical factors into a framework for soil resource evaluation (Khormali et al., 2009). The concept of soil quality (Doran and Jones, 1996; Karlen et al., 1997) is useful to assess the condition and sustainability of soil and to guide soil research, planning, and conservation policy. The rate of soil quality degradation depends, however, on land use systems, soil types, topography, and climatic conditions. Land uses have significant influences on soil quality indicators, particularly at the surface horizon (Wakene and Heluf, 2006). The increase in atmospheric concentration of greenhouse gasses such as CO_2, CH_4 and N_2O associated with climate change is also partially attributed to the decline in soil quality (Lal, 2009; Wielopolski et al., 2011).

Assessing soil quality relies on a combination of physical, chemical, biological, biochemical, and microbiological properties of the soil, and the selected properties should be those most sensitive to changes in the ecosystem (Jimenez et al., 2002). Accordingly, a wide range of soil physical, chemical and biological properties have been proposed for evaluation of soil quality worldwide. Quality soils have attributes that promote root growth, accept, hold, and supply water, hold, supply, and cycle mineral nutrients, promote optimum gas exchange, promote biological activity, and accept, hold, and release carbon (Burger and Kelting, 1999). All of these attributes are, in part, a function of soil physical properties and processes. Soil texture is another most fundamental qualitative soil physical property controlling water, nutrient, and oxygen exchange, retention, and uptake. However, soil texture and depth are soil properties that would change little through time for a given soil, and so they would not be very useful for assessing management effects. Soil bulk density varies among soils of different textures, structures, and organic matter content, but within a given soil type, it can be used to monitor degree of soil compaction. Changes in soil bulk density affect a host of other properties and processes that influence water and oxygen supply. Therefore, bulk density is one of the soil parameters needed in a minimum data set (MDS) for soil physical quality evaluation (Reynolds et al., 2009).

The soil's chemical condition affects soil-plant relations, water quality, buffering capacities, availability of nutrients and water to plants and other organisms, mobility of contaminants, and some physical conditions, such as the tendency for crust formation. Chemical indicators include measurements of soil pH, salinity, organic matter, CEC, concentrations of elements that are needed for plant growth and development (N, P, K, Ca, Mg etc). Soil pH appears in nearly every type of soil quality assessment in agricultural soils as a constituent of the MDS to be used further in pedotransfer functions (Larson and Pierce, 1994). Many chemical reactions that influence nutrient availability (e.g. chemical form, adsorption, precipitation) are influenced by the soil chemical environment and soil pH in particular. Thus, it is logical that pH should be included as a key chemical indicator. Soil organic carbon (SOC) is included in the MDS of soil quality assessment proposed by Larson and Pierce (1994) for agricultural soils, where it is used in pedotransfer functions (Bouma, 1989) to calculate bulk density, water retention capacity, leaching potential, cation exchange capacity (CEC), rooting depth, and soil productivity. One example of practical and user-friendly assessment of the role of soil organic matter (SOM) in soil quality is the Wisconsin Soil Health Scorecard, where SOM is one of the qualitative measures of soil health in a farmer based scoring system, using specific thresholds to indicate healthy (SOM between 4-6%), unhealthy (SOM<2 or >8%), or impaired (SOM 2-4 or 6-8%) soil conditions (Romig et al., 1996).

Even though, various physical and chemical soil properties can be used to characterize soil quality, soil biological properties are more sensitive to changes than other indicators and could describe the soil quality in a broader picture (Bastida, 2008). The diversity of microorganisms and the related biochemical processes are also the most important components of soil quality, especially for the highly weathered acid soils, in which plant productivity is closely related to biological cycling (He et al., 2003). Hence, whenever, the total sustainability of soil natural functions and its different uses has to be evaluated, key indicators must include biological, biochemical and microbiological parameters (Nsabimana et al., 2004; Gil-Sotres et al., 2005; Bastida, 2008). Several microbiological and biochemical parameters have been suggested as indicators of soil quality in different land use systems (Anderson, 2003). They include: microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), and microbial biomass phosphorus (MBP) and their turnover rates; the microbial quotient defined as MBC to SOC ratio, Soil respiration, metabolic quotient (qCO_2); the ratio of MBN over TN. In addition, microbial diversity parameters such as community level physiological profile (Bending et al., 2000), phospholipid fatty acids (Kanazawa and Berthelin, 1999), the ratio of Gram-negative/Gram-positive bacteria, and the ratio of fungal/bacterial microorganisms (Waldrop et al., 2000), have also been identified as important indicators of soil quality.

Amongst the general parameters, 41% of the previous authors considered microbial biomass carbon (MBC) to be the most reliable parameter (Gil-Sotres et al., 2005). It represents the living component of SOM, excluding animals and plant roots. Although microbial biomass usually makes up to less than 5% of soil organic matter (Dalal, 1998), it is eye of the needle through which all organic material that enters the soil must pass (Jenkinson, 1977). It carries out many critical functions in soil ecosystem, among which the following could be pointed out: it is both a sink and source for nutrients, it participates in the C, N, P and S transformations, it plays an active role in the degradation of xenobiotic organic compounds and in the immobilization of heavy metals, it participates in the formation of soil structure, etc (Nannipieri et al., 2002). However, MBC depends on soil organic matter as a substrate; therefore, the decrease of SOC will cause a reduction of MBC (Chen et al., 2005). Hence, MBC/SOC ratio or microbial quotient has been widely used as indicator of the changes in organic matter status due to alterations of soil conditions (Sparling, 1992). Similar to MBC, microbial biomass nitrogen (MBN) constitutes a significant part of the potentially mineralizable N and serves both as the transformation agent and source-sink of nitrogen (Bonde et al., 1998). Consequently, the MBN may have significant impacts on nitrogen availability and overall soil nitrogen cycling (Singh et al., 2009).

Soil respiration, which involves the emission of CO_2 during the decomposition of organic matter carried out by the metabolic activity of the plant roots and soil microorganisms, is a fundamental process in the carbon cycle and represents the main pathway whereby carbon fixed by the soil is returned to the atmosphere (Fernandez et al., 2006). In this process, soil microorganisms play an important role in the formation and turnover of SOM by decomposition of plant residues and mineralization of nutrients. Therefore, measurements of soil CO_2 flux have a great potential as an indicator of ecosystem processes including metabolic activity in soil, persistence and decomposition of plant residue in soil and conversion of soil organic carbon to atmospheric CO_2 (Ryan and Law, 2005). The words of Louis Pasteur, *'the role of the infinitely small is infinitely great,'* can be used to describe the impact of soil microbes on the quality and health of a soil. A healthy soil, full of active microorganisms in correct balance, is essential to productive agriculture. Their size and activity can therefore be used to investigate decomposition and deduce SOM turnover in soil. Hence, a good understanding of soil respiration favors the variation occurring in the organic carbon pool due to LULC change (Sanhueza and Santana, 1993).

In general, the high contents of MBC and soil respiration generally indicate better soil quality. However, soil respiration and MBC did not always show the same change tendency. Thus, qCO_2 is used to evaluate the efficiency of soil microbial biomass in utilizing the organic carbon compounds (Anderson and Domsch, 1990). It represents the quantity of substrate that is mineralized per unit of microbial biomass carbon and per unit of time (Anderson and Domsch, 1985). Generally, higher qCO_2 values indicate greater stress of the microbial community compared to soils with more stable ecosystem (Dalal, 1998). Major components of soil quality in relation to fertility and environment in tropical and subtropical regions are presented in Table 2.

Table 2. Major components of soil quality in relation to fertility and environment in tropical and subtropical regions.

Soil quality components	Relationship to soil functions and conditions
	Physical
Texture	Retention and transport of water, nutrients, and chemicals; modeling use, soil erosion and variability estimate
Depth of soil	Estimate of productivity potential and erosion
Top soil and rooting	Plant and animal production potential, nutrient use efficiency, and groundwater contamination
Soil bulk density and Infiltration	Potential for leaching, productivity, and erosivity, depth and volume of root
Water retention characteristics	Available water storage, water conductivity, water use efficiency, and surface runoff; aeration
	Chemical
Total organic C	Related to soil fertility, health, and environmental capacity such as nutrient availability, biological activity, and contaminant degradation/inactivation; aggregation
pH	Growth and health of plant and soil

	organisms; nutrient availability and toxicity; essential to process modeling
CEC	Related to nutrient availability and leaching potential
Electrical conductivity	Defines plant and microbial activity thresholds
Extractable N, P, and K	Plant-available nutrients and potential for loss from soil; productivity and environmental quality indicators
	Biological
Microbial biomass	Microbial catalytic potential and cycling and availability of C, N, P, and S; modeling, indicator of organic matter quality, soil fertility, and heavy metal contamination
Macrofauna/arthropods/ earthworm	Indicators of ecological stress or restoration, organic matter breakdown, humification, redistribution of soil organic matter
Enzyme activity	Nutrient cycling, mineralization/immobilization, heavy metal toxicity, soil degradation
Soil respiration	Measure of microbial activity (in some case, plants); process modeling, estimate of microbial biomass activity
Potentially mineralizable C	Soil productivity and C-supplying potential; indicator of microbial biomass carbon

Adopted from Elliott et al. (1996) and Doran et al. (1999), as cited by He et al. (2003)

The most proximate implication and negative consequences of LULC are directly or indirectly related to the issues of land degradation (Shan et al., 2007), decreases in biodiversity (Duadze, 2004), the size and number of water bodies (Mundia and Aniya 2006), accelerated soil erosion (Solomon et al., 2000), and decreased food security (Kebrom, 1999). Land use changes may create changes in nutrient availability and reduce SOC, which plays a crucial role in sustaining soil quality. In addition, it may induce substantial changes in both quantity and quality of SOM (Ashagrie et al., 2005). Such changes directly affect soil physical, chemical and biological properties such as soil water retention and availability, nutrient cycling, gas influx, plant root growth and soil conservation (Emadi et al., 2008). Therefore, the issue of soil quality degradation poses a critical risk for agricultural productivity and food security (Bekele and Holden, 1999; Krowntree and Fox, 2008), particularly in developing countries like Ethiopia. Therefore, timely detection of land use/cover change and its potential effect on soil quality parameters should be a prerequisite to take any restorative measures. However, information on land use change and management effects on soil quality parameters in barley-fallow based farming systems under soil acidity conditions of the central highlands of Ethiopia is few and far between.

1.7 General objective

The general objective of this PhD thesis was to explore changes in land use/cover and management systems, and contribute to the understanding of its potential impact on soil quality parameters in barley-fallow based farming systems in the central highlands of Ethiopia.

1.8 Specific objectives

Chapter-I Land use change has become an area of particular concern in the highlands of Ethiopia due to the rapid land conversion practices triggered by rapid population growth. The objective of this study was to show trends of land use/land cover changes from 1975-2014, and to understand the socio-economic conditions of the rural community in barley-fallow based farming systems in the central highland of Ethiopia.

Chapter-II Change in land use and management has potential effect on soil quality parameters. To our knowledge, however, there is no or insufficient scientific information on soil acidity-induced land use change and management effects on soil quality parameters in the study area. Therefore, the objective of this study was to assess changes that would occur in soil biological, chemical and physical properties in response to change in land use and soil management practices in barley-fallow based farming systems in Wetabecha Minjaro.

Chapter-III The native soil organic carbon dynamics in different land uses and its concomitant contribution to CO_2 fluxes have so far rarely been investigated and virtually nothing is known about CO_2 emissions from different land uses and management practices in barley-fallow based farming systems in the highlands of Ethiopia. Therefore, the objective of this study was to assess the C-mineralization potentials of soils from different land use and management by laboratory incubation studies, and to compare the effectiveness of some commonly used decay models for describing rates and amounts of C mineralization.

Chapter-IV Plantations of *Eucalyptus*, mainly *Eucalyptus globulus* Labill were being established on land that has previously been used for conventional agriculture. Consequently, huge areas of grasslands are being converted to short-harvest rotation (5-10 years) *Eucalyptus* annually. Previous attempts to study the effect of short-rotation *Eucalyptus* on soil resources were primarily focused on some selected physical and chemical properties of soils. However, biological indicators are more sensitive to changes than other indicators and could describe soil quality in a broader picture. Therefore, the objective of this study was to assess the effects of grassland conversion to short-rotation *Eucalyptus* on soil physical, chemical and biological properties, and to assess the C-mineralization potentials of the soils.

Chapter-V Aluminum toxicity and Phosphorus deficiency are the two major factors limiting barley production on acid soils in the highlands of Ethiopia. Hence, liming and phosphorus fertilization appears to be among the most important operations required to boost barley productivity in these areas. However, there is no or few information available on the effect of lime and phosphorus fertilizer in barley-fallow based production systems in the study area. The objective of this experiment is, therefore, to assess changes that would occur on soil pH and exchangeable acidity as a consequence of applications of different rates of lime, and evaluate the effects of different rates of lime and phosphorus fertilizer on barley grain yield and yield components.

2 Materials and Methods

2.1 Background information of the study site

The research for this thesis was conducted in Wetabecha Minjaro peasant associations[1], commonly known as Bedi, located in western central highlands of Oromiya regional State, Ethiopia. It is situated at 9° 05′ 55″ N, 38° 36′ 21″ E, at an altitude of 2600 m.a.s.l. According to the local agro-climatic classifications, the study area belongs to moist highland agro-climatic zone with two rainy periods; the main rainy season which occurs from June to mid September, and the short rainy season extending from February to April. The area receives about 1100 mm of rainfall annually. The mean maximum and mean minimum temperatures are 23.3°C and 8.7°C, respectively. The soils are classified as Nitisols with deep, red, well-drained tropical soils (IUSS, 2006). Most of the soils have a pH range of 4.5 to 5.5, contain low organic matter (<20 g kg^{-1}) and low nutrient availability. Agriculture is the main source of livelihood for the community, and subsistence type mixed barley-fallow-livestock best characterizes the farming system. The study site is predominantly inhabited by people belonging to the "Oromo" ethnic group. Relative to the other parts of the central highlands of Ethiopia, it is one of the most neglected in terms of research and development, with little or no governmental and non-governmental institutional support for agriculture. Because of soil acidity related problems, barley is the only major crop cultivated in the region. Apart from croplands, the study landscape also comprises mosaic natural forests that belong to a tropical dry Afromontane forest. In the past several decades, tropical meadow type grassland and shrub lands were the dominant type of vegetation. Now, such types of vegetations are gradually replaced by croplands, settlements and *Eucalyptus* plantations (Temesgen et al., 2014). *Eucalyptus* plantations are widespread and 95% of the community grows *Eucalyptus* on private and communal land or around homesteads. The harvest rotations of these plantations vary between 5-10 years depending on the purpose utilization. Literally, there is no/very few indigenous tree species that has a similar rapid growth rate as *Eucalyptus* and thereby satisfy the high demand of biomass energy, poles for construction, and use for farm implements in the area. This is one of the main reasons why *Eucalyptus* is voraciously integrated into the farming systems of the area.

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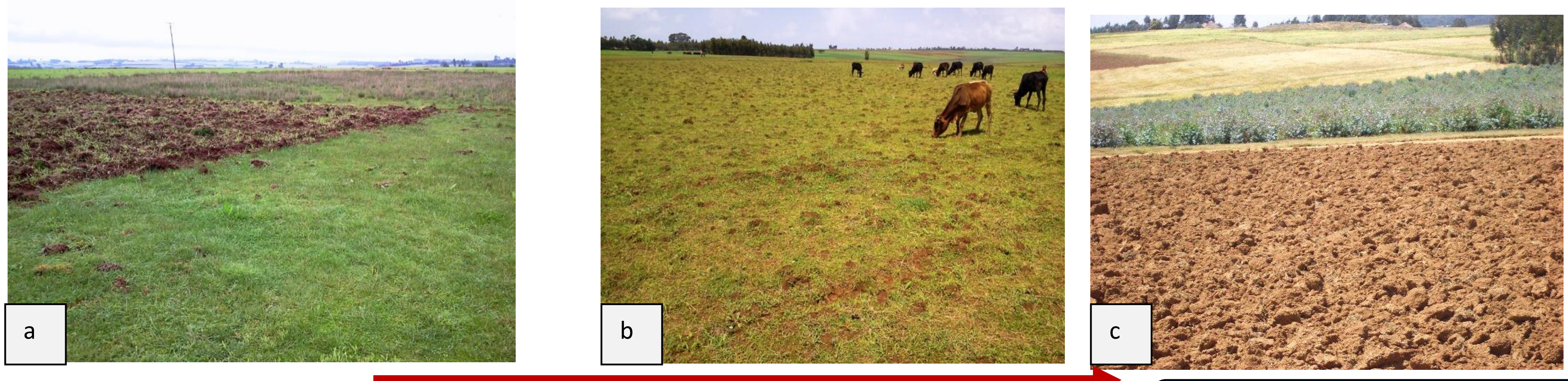
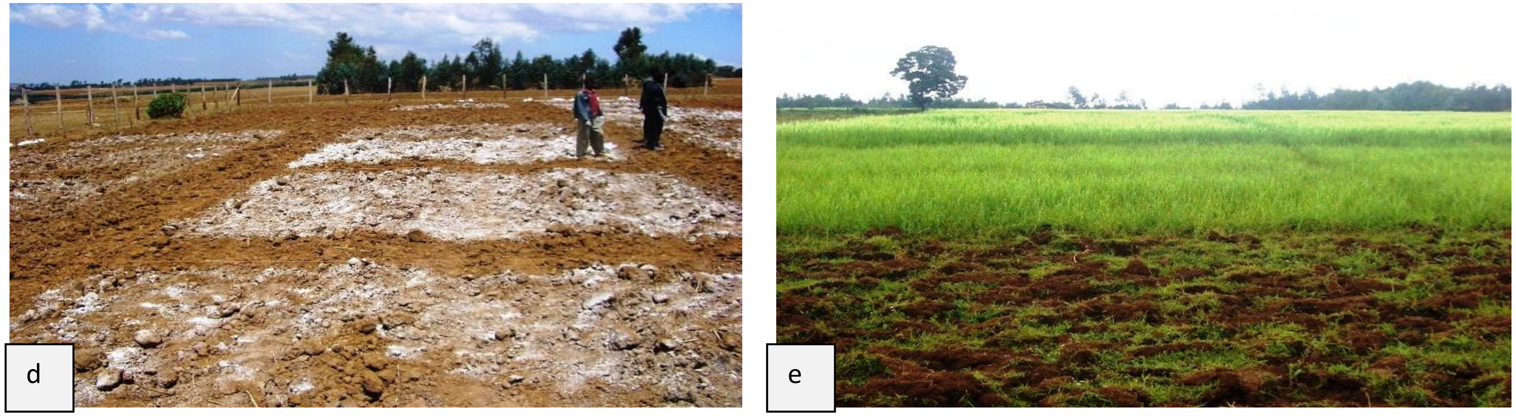
[1] Peasant association is the lowest administrative unit in government structure, and Wetabecha Minjaro is the union of two peasant associations (Wetabecha and Minjaro).



a) Grassland being converted to cropland

b) Fallowed cropland

c) Conversion of fallow/cropland to eucalyptus



(d) Testing of different lime and phosphorus rates at sub-station (e) Best treatment compared with fallow and conventional practice

Figure 6 Evolutions of different land uses and management systems at the study site, Wetabecha Minjaro

2.2 Land use/cover (LULC) change and household survey

The main data source for LULC classification and change analysis were a series of Landsat imagery data. These include Landsat MSS, Landsat Thematic Mapper (TM), Enhanced Thematic Mapper (ETM+) and Landsat OLI scenes of the year 1975, 1986 2000 and 2014, respectively. These datasets were obtained from the National Aeronautics and Space Administration (NASA) through their EOS Data Gateway Database. All the Landsat images were acquired in the same season (between October and January). All GIS data were projected to the Universal Transverse Mercator (UTM) projection system zone 37N and datum of World Geodetic System 84 (WGS84), ensuring consistency between datasets during analysis.

The household survey was carried out in July 2012, and adopted a purposive sampling method to select the study site, Wetabecha Minjaro peasant association (PA). The survey was conducted in two phases. In the first phase, field observations were made to obtain background information on farming systems followed by preparation and pre-testing of structured questionnaire. In the second phase, the information gathered was used to re-design the structured questionnaire for collection of qualitative and quantitative data. A semi-structured face-to-face individual interview, discussions with focus group and key informants were used to gather information pertaining to land use types, soil fertility status, current soil management practices and related challenges, and socio-economic conditions of the people living in the area. Fifty one households were randomly selected for the interviews. In addition, unstructured interviews were carried out with four knowledgeable key informants recommended by the local farmers' association, and several field visits were conducted for ground truth checking and confidence building.

2.3 Soil sampling and experimental design

In July, August and September, 2012, a plot size of 10 m x 10 m (100 m^2) was demarcated in different land uses for soil sample collection. From demarcated area, composite soil samples were randomly collected from eight locations where different land use and management systems (grassland, cropland, *Eucalyptus* plantation, limed land and fallow land) exist adjacent to each other (**Chapter II**), and another five locations where 5- and 10-year-old *Eucalyptus* plantations and grassland exist adjacent to each other (**Chapter IV**). The samples were collected using an auger from two depths (0-10 cm and 10-20 cm) for each land use and management in each location. In each study, besides using the locations as a replicates, samples were also replicated twice during laboratory analysis. In **Chapter II**, the samples for *Eucalyptus* plantations (*Eucalyptus globulus* Labill.) were collected from plantations that were 6-7 years old. Fallow land was referred to a resting period of 18 months without cropping. The samples from limed land were collected after three years of liming acid soils. About ten sub-samples that were randomly collected from each demarcated area constituted a composite sample for the analysis of physical, chemical, biological microbiological properties of soils. In **Chapter II**, a total of 80 soil samples (8 sites * 5 land uses * 2 depths). However, in **Chapter IV** a total of 30 soil samples (5 sites * 3 land uses * 2 depths) were collected in randomized complete block design for laboratory analysis. Samples were gently sieved through a 2 mm mesh to remove stones and roots, and were sealed in plastic bags before analysis. Soil chemical and biological parameters were analysed in duplicates.

Chapter V: The liming experiment consisted factorial combinations of five levels of lime (0.0x, 0.5x, 1.0x, 1.5x and 2.0x) Mg ha^{-1} in the form of $CaCO_3$ based on exchangeable acidity content of the soils, and four levels of phosphorous (0, 10, 20 and 30 kg P ha^{-1}) in the form of triple super phosphate in a randomized complete design. The amount of lime that was applied at each level was calculated on the basis of exchanageabl acidity concentration of the site (Kamprath, 1984) assuming that one equivalent of exchangeable acidity would be neutralized by an equivalent of $CaCO_3$. A high quality limestone (98 % $CaCO_3$, 99.5 % <250 µm in diameter) was applied uniformly to treatment plots one month ahead of planting. Phosphorus was broadcast applied in the form of TSP (triple superphosphate), and the recommended rate of nitrogen for barley i.e. 50 kg ha^{-1} was applied uniformly to all treatments including control plots. A high yielding barley variety named HB-1307 was used as a test crop at a seed rate of 125 kg ha^{-1}. The plot size used was 4.5 ×5.1 meters (22.95 m^2). Data were collected on barley grain yield and yield components. Soil samples were randomly collected prior to experimentation and after harvesting the crop for analysis of pH and exchangeable acidity.

2.4 Soil analysis

2.4.1 Physical and chemical parameters

Physical and chemical properties of soils were analyzed following standard procedures, and will be briefly elaborated as follows.

Chapter-II. Field capacity was determined by saturating soil samples with water and allowing them to drain for 24 hours. After oven drying at 105°C, moisture loss was expressed as percentages. Permanent wilting point was estimated from soil samples equilibrated at a pressure of 15 bars on a pressure plate (Cassel and Nielsen, 1986). Plant available water was determined by the difference between field capacity and permanent wilting point.

Chapeter II and IV. Bulk density (BD) was determined using a core sampler of a known volume following the procedures of Blake (1965). Soil particle size distribution was determined by hydrometric method (Bouyoucos, 1962). Soil pH was determined by using a pH meter in a 1:2.5 soil/water suspension, and soil organic carbon (SOC) by the Walkley and Black (1934) method. Total nitrogen (TN) was analyzed by wet oxidation procedure using the Kjeldhal digestion, distillation and titration method (Bremner and Mulvaney, 1982). The available phosphorus (AvP) content of the soil was determined using 0.5M sodium bicarbonate extraction solution method (Olsen and Sommers, 1982). Exchangeable bases (Na^+, K^+, Ca^{2+}, and Mg^{2+}) were measured by atomic absorption spectrophotometer after extraction by ammonium acetate (Black et al., 1965). The CEC was determined by extraction with ammonium acetate (Chapman, 1965). Exchangeable acidity was extracted by 1M KCl (Mclean, 1965).

2.4.2 Biological parameters: Chapter-II and IV.

Microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) were estimated by the classical chloroform fumigation extraction method (Brookes et al., 1985; Vance et al., 1987). The filtrates obtained after shaking were analyzed for organic C and total N by using SKALAR TOC/TN automatic analyzer. The difference in the C content of the extracts from fumigated and unfumigated samples was converted to biomass-C by dividing the value obtained by a factor (K_C) of 0.45 (Vance et al., 1987). The results are expressed as µg g^{-1} of oven-dried soil. The difference in the content of N of the extractants was also converted to biomass nitrogen by dividing the value obtained by a factor (K_N) of 0.54 (Brookes et al., 1985).

2.4.3 Soil respiration

Chapter III and IV: To measure soil respiration, moisture was adjusted to 60% of water holding capacity, and soil samples were incubated for 62 days (**Chapter-III**), and 60 days (**Chapter-IV**). Carbon mineralization was determined in closed jars under laboratory-controlled conditions at a temperature of 28°C (Isermayer (1952). The CO_2 evolved was trapped in plastic vials containing 10 ml of 0.5 M NaOH. The moisture content was kept constant by weighing at each sampling date. The amount of CO_2 evolved was measured after 8, 18, 26, 36, 45, 54 and 62 days of incubation (**Chapter-III**), and 4, 10, 17, 27, 42, 48 and 60 days of incubation **(Chapter-IV)** by titrating with 0.5 M HCl against a phenolphthalein indicator after precipitation with $BaCl_2$ (0.5 M). The metabolic quotient (qCO_2) calculated from respiration and MBC values with formula: $qCO_2 = [(\text{mg } CO_2\text{-C kg}^{-1}/\text{h})/ \text{ mg MBC kg}^{-1}]$ (Anderson and Domsch, 1985).

2.5 Data analysis

2.5.1 Satellite image analysis (Chapter-I)

The satellite images were analyzed by utilizing data image processing techniques in ERDAS Imagine© 10.0 and ArcGIS© 10.0 software. A supervised signature extraction with a maximum likelihood was used in the analysis. Change analysis was conducted using post image comparison technique (Singh, 1989). Ground truthing was complemented with topographical maps of the study area as well as several field visits, interviews with individuals and elderly people of the of the study site. As rural settlements are scattered and close to cultivated lands, croplands and settlements were classified together. The classified images were compared in three periods, i.e., 1975-1986, 1986- 2000, and 2000- 2014. The values were presented in terms of hectares and percentages.

2.5.2 Adjustment of SOC mineralization (Chapter-III and IV)

To describe the C mineralization patterns in the soil samples, different models were tested. The models were tested to know which model would be best to our data. The values of adjusted coefficient of determination ($R^2_{adj.}$), convergence, the squared sum error (SSE) and the mean squared error (MSE) were important criterions for choosing the best model. Model fittings were carried out with MODEL procedures of the SAS/STAT® (**Chapter-III**) and SPPS (**Chapter-IV**) statistical Software.

2.5.3 Statistical analysis

For the survey data, a statistical package for social sciences (SPSS) version 20 (SPSS Inc., 2008) was used to analyze the household data. Descriptive statistics such as cross tabulation, frequencies and percentages were employed to summarize the data (**Chapter-I**). For **Chapter-II and IV,** a PROC MIXED model analysis with depth as repeated measurement, considering two between-subjects factors (site and land use) in a main effects design, and one within-subjects factor (depth with two levels) was carried out in SAS. **For Chapter-III**, once the model was fitted, different parameters such as the potentially mineralizable carbon (C_o), the rate constant of carbon mineralization (k), the initial potential rate of C minerlization (C_o*k), the half-life time of carbon ($t_{1/2}$) were analysed by a PROC MIXED model in SAS in order to detect significant differences between different land uses and depths. For **Chapter-V**, a PROC GLM model was constructed using SAS statistical software to compare the measured agronomic parameters for both years separately as well as combined over years. Significance differences were set at $p<0.05$. When the effects were found significant, further analysis was made using Tukey multiple comparison test. Pearson correlation coefficients were also used to assess the significance of the relationships between different variables measured (**Chapter-IV and V**). In all the studies, the data was verified for its normal distribution with Kolmogorov-Smirnov test.

3 RESULTS

3.1 Land use/cover (LULC) change and socioeconomic conditions of local community in the central highlands of Ethiopia.

3.1.1 Remote Sensing and GIS

Analysis of remote sensing data clearly categorized four major land use/cover classes: natural forest, *Eucalyptus* plantations, cropland/settlements and grasslands (**Chapter-I Fig. 3**). In 1975, natural forest, *Eucalyptus* plantations, croplands/settlements and grasslands occupied 3.5, 7.5, 28.8 and 61.5 % of the total land area, respectively. Over a period of 39 years (1975 to 2014) of analysis, *Eucalyptus* plantations and cropland/settlements increased by 335 and 62.5 %, respectively (**Fig. 7 and Chapter-I Table 1**). The increase in the area of *Eucalyptus* and croplands/settlements was at the expense of grasslands, where a corresponding 74% decrease in the area of grassland was observed in the same period.

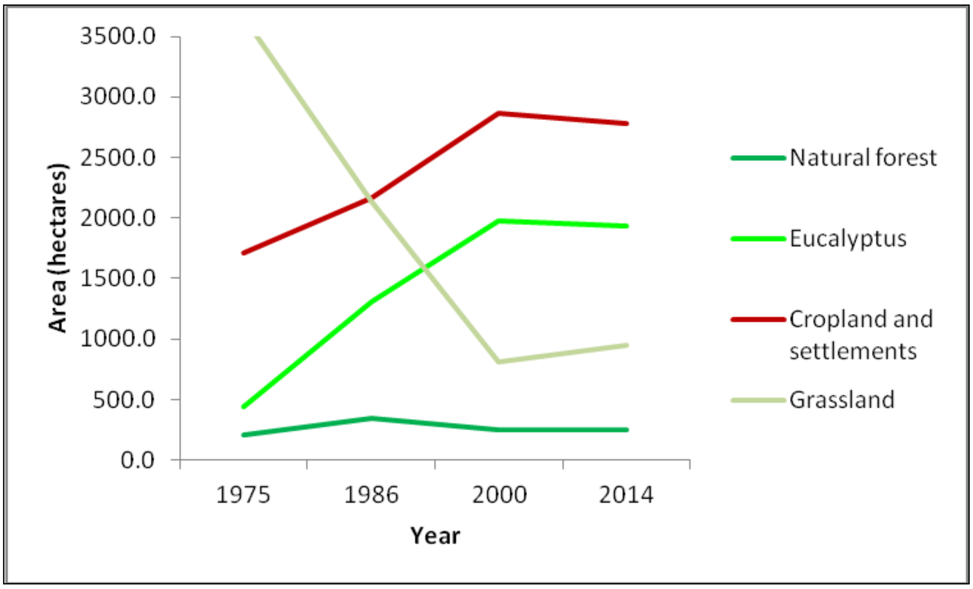


Figure 7 Summaries of land use and land cover changes between 1975 and 2014

3.1.2 Household survey

In prioritizing crop production constraints, poor farmers ranked deterioration of soil fertility (41.2%) followed by shortage of land (35.3%) as major impediment to crop production. Similarly, better-off farmers ranked deterioration of soil fertility (64.7%) and lack of credit (17.6%) as among the priority problems for crop production in the area

(Chapter-I, Table 3). The desire of farmers to buy commercial fertilizer and other agricultural inputs was hampered by lack of credit scheme in the area. Consequently, farmers adopt other options such as applications of manure/compost, fallowing, conversions of natural vegetations such as grassland to cropland, and infertile cropland to *Eucalyptus* plantations against soil fertility related problems in the area (Fig. 8)

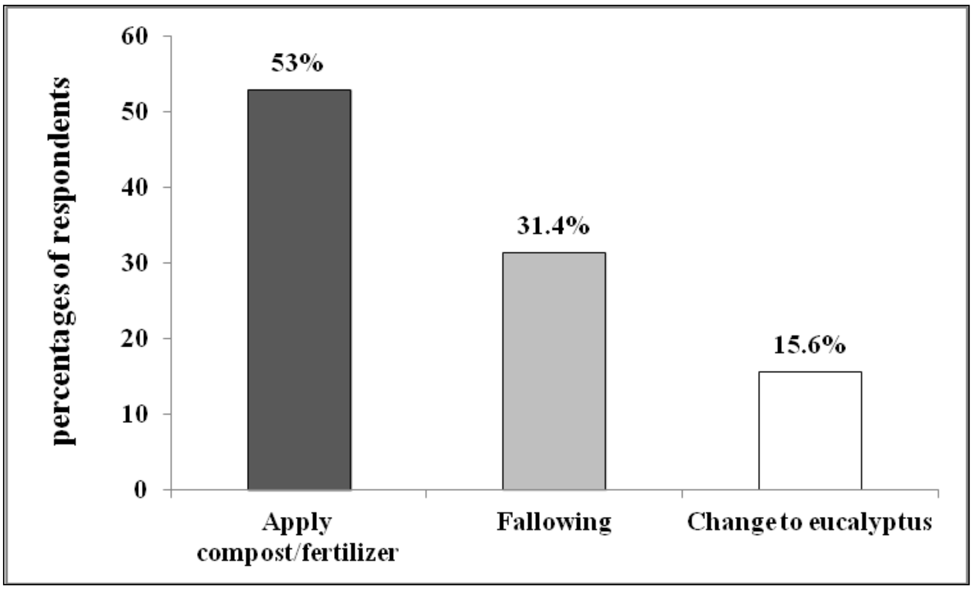


Figure 8 Measures taken by farmers when soil fertility declines drastically

The most frequently cited and serious problem to livestock production in the area was shortages of livestock feed (49%) and low productivity of local animals (27.5%). Shortage of livestock feed was pronounced on poor farmers (58.8%), whereas low productivity of local animals on better-off farmers (47.1%) (**Chapter-I Table 4**). A large proportion of the sample respondents reported that they did not have any other tree species other than *Eucalyptus* that can be used as source of wood for fuel, construction and farm implements. Figure 9 depicts the main reasons why the community in the study area converted part of their land to *Eucalyptus*.

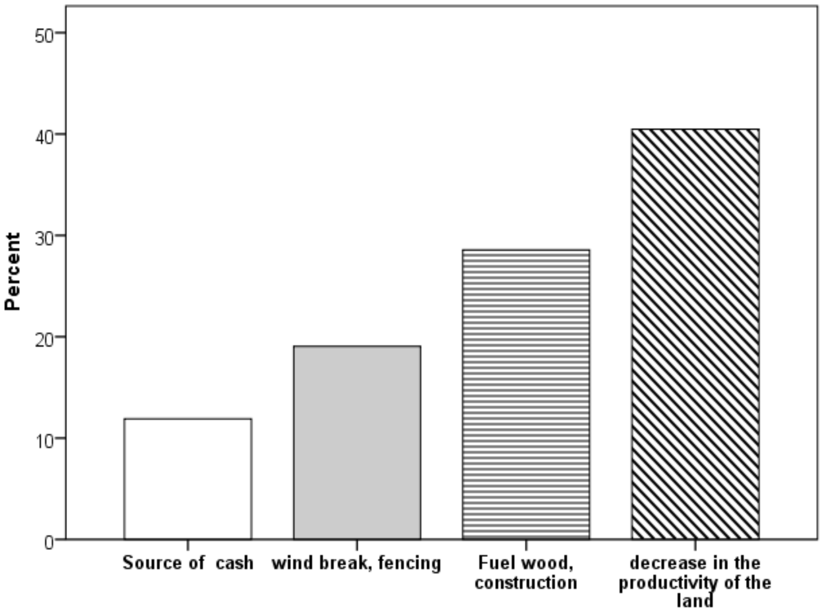


Figure 9 Main reasons of the respondents for changing cropland/grassland into *Eucalyptus*.

In the past, particularly women had to travel long distances to collect firewood for domestic uses. Nowadays, the presence of *Eucalyptus* woodlots at their farm relieved the burden of women by overcoming shortages of fuel wood to a larger extent. Since, majority of farmers in the study area are followers of the Coptic Orthodox church, they are obliged to observe a number of religious holidays on which they are customarily prohibited to undertake any farming activities except fencing and livestock husbandry. Hence, 68%, 28% and 4% of the sample respondents do strictly observe these holidays for 19, 16 and 14 days in a month, respectively (**Chapter-I, Fig. 4**).

3.2 Comparison of soil quality parameters under different land use/cover and management practices in the central highlands of Ethiopia.

Analysis of soil physical, chemical and biological characteristics under five adjacent land uses and management (grassland, cropland, *Eucalyptus*, limed land and fallow land) was carried out. Generally, results showed that soil quality was higher under grassland than under the other land uses and management systems. Bulk density recorded in grassland was significantly lower as compared to the other land uses and management. However, the mean values of FC and PWP recorded in grassland were significantly higher than the other land use/management. The other land use and management systems were not significantly different from each other in PWP (**Chapter- II, Fig.3**). The soils under cropland, *Eucalyptus*, limed land and fallow land contained 53, 45, 46 and 47% less SOC than grassland soils. On average a decrease of 54% soil nitrogen was observed by land conversions from grassland to other land use and management systems. Statistically, cropland, *Eucalyptus* and limed land did not differ from each other for most of the soil chemical properties analysed. However, exchangeable acidity was significantly higher under *Eucalyptus* plantations as compared to the other land use and management systems. Available phosphorus was considerably higher in surface soil (0- 10 cm). Contrary to this, exchangeable acidity and Mg^{2+} concentrations were found to be higher in 10 -20 cm soil profile (**Chapter-II, Table 3**). The highest values of MBC and MBN were recorded under grassland soils as compared to the other land use and management systems. Mean values of MBC/SOC was in the following order: grassland > limed land > *Eucalyptus* > cropland >fallow land. Whereas MBN/TN followed the order: Grassland > limed land >cropland > *Eucalyptus* > fallow land (**Chapter-II, Table 4).**

3.3 Carbon mineralization kinetics as influenced by changes in land use and management systems in the central highlands of Ethiopia.

During 62-days of laboratory incubation period, carbon mineralization rates followed similar general pattern across all land uses; an initial increase at the beginning of the incubation followed gradual decreases as the incubation time progresses (**Chapter-III, Fig. 1 and 2**). The CO_2 released in 0 -10 cm followed the order: grassland > cropland > fallow land > *Eucalyptus* > limed land (**Chapter-III, Fig. 1**). However, in 10- 20 cm the order was; grassland > fallow land > *Eucalyptus* > limed land > cropland. In grassland, the cumulative CO_2 released was higher in both 0-10 cm and 10-20 cm than the other land uses and management systems (**Chapter-III, Fig. 3**).

Among the six carbon mineralization kinetic models tested, the first-order model [$C_t = C_o (1-e^{-kt})$] best fitted the experimental data (**Chapter-III, Table 1**). This kinetic model provided a good fit to C mineralization with R^2 ranging from 0.90 to 0.99 for all land uses and management systems. In the surface layer (0-10 cm), significantly higher mean values of potentially mineralizable carbon (C_o) were observed in grassland. Potentally mineralizable values that were recorded in *Eucalyptus* and limed land were not statistically different from each other in both 0-10 and 10-20 cm soil depth (**Chapter-III, Table 3**). In 0-10 cm, the qCO_2 observed in fallow land was higher than the other land uses and management even though significant statistical differences did not exist with the other land uses except limed land. Limed land had significantly lower than fallow land and the other three land uses. Rate constant (k) for C mineralization in grassland was not significantly different from k values of *Eucalyptus* and limed land in similar depth. Cropland exhibited significantly higher values of $t_{1/2}$ as compared to the other land uses. However, significant changes in $t_{1/2}$ were not detected among grassland, *Eucalyptus*, limed land and fallow land in 0-10 cm soil depth. The half-life time observed in grassland was lower than the other land uses and management systems (**Chapter-III, Table 3**). In 0-10 cm depth, the mean value of qCO_2 recorded in limed land was the lowest as compared to the other land uses or management systems. Results also showed that soils that have mean values of MBC/SOC higher than 1.5 had efficient microorganisms in utilizing the available substrates than soil with MBC/SOC lower than 1.5 (**Chapter-III, Fig. 5**).

3.4 Effects of short-rotation *Eucalyptus* plantations on soil quality attributes in highly acidic soils of the central highlands of Ethiopia.

Analysis of soil chemical characteristics under three adjacent land uses (grassland and 5- and 10-year-old *Eucalyptus* plantations) showed that conversion of grassland to short harvest rotation of *Eucalyptus* plantations decreased mean values of pH, SOC, TN, Ca^{2+} and cation exchange capacity (**Chapter-IV, Table 3 and 4**). However, the two age groups of *Eucalyptus* did not differ from each other in the above parameters. Land use conversions from grassland to *Eucalyptus* plantations has also resulted in higher levels of soil acidity, and lower levels of SOC and TN. In general, soil pH, SOC and TN between 0-10 and 10-20 cm depths did not differ under the three land use systems. However, soils under grassland showed higher values of the above parameters, in both 0-10 cm and 10-20 cm soil depths. Mean values of MBC and MBN recorded in grassland were significantly higher than in both 5- and 10-year-old *Eucalyptus* plantations. In comparison with grassland MBC, MBC in 5- and 10-year-old plantations decreased by 45% and 58% respectively (**Chapter-IV, Table 5**). The values of C_o were significantly higher ($p<0.001$) under grassland as compared to 5- and 10-year-old *Eucalyptus* plantations. Conversion of grassland to 5-year-old and 10-year-old *Eucalyptus* reduced the values of C_o by 21% and 43% respectively (**Chapter-IV, Table 6**).

3.5 Effect of lime and phosphorus fertilizer on acid soils and barley (*Hordeum vulgare* L.) performance in the central highlands of Ethiopia.

Soil analysis results after two years of liming significantly ($p< 0.05$) increased soil pH, and markedly reduced exchangeable acidity to a negligible level. Liming at the rate of 0.55, 1.1, 1.65 and 2.2 Mg ha^{-1} increased soil pH by 0.5, 0.7, 0.8 and 1.1 units, and decreased exchangeable acidity by 0.88, 1.11, 1.20 and 1.19 $cmol_+$ kg^{-1}, respectively (**Chapter-V, Fig. 1 and 2**). Among the liming treatments, the highest rate (2.2 Mg ha^{-1}) of lime recorded the highest mean values of thousand seed weight (TSW), number of seeds per spike (NSPS), which was statistically comparable with lime rate of 1.65 Mg ha^{-1}. Similarly, successive applications of phosphorus fertilizer also resulted in increased yield and yield components of barley (**Chapter-V, Table 2**). During first year (2010 cropping season), interaction effects of lime and P were observed on grain yield of barley (**Chapter-V, Fig. 3**). Accordingly, the highest mean grain yield of barley was obtained by applications of 1.65 Mg ha^{-1} and 30 kg P ha^{-1}. In 2011, grain yield obtained by applications of 1.65 and 2.2 Mg ha^{-1} lime was statistically comparable, and significantly superior to the other lime rates. Similarly, grain yield obtained by application of 20 and 30 kg P ha^{-1} were also comparable, and significantly ($p< 0.05$) higher than the control (no P) and applications of 10 kg P ha^{-1}. As expected, the lowest grain yield was recorded in control plots, with no lime, no P addition. Combined over two years, the highest significant grain yield and biomass yield of barley were recorded by application of 1.65 and 2.2 Mg ha^{-1} lime (**Chapter-V, Table 4**). Statistically, these two lime rates were comparable, and significantly ($p< 0.05$) superior to the other lime rates. Similarly, significantly ($p< 0.05$) higher barley grain yield was obtained by application of 30 kg P ha^{-1}.

4 DISCUSSION

4.1 Land use/cover (LULC) change and socioeconomic conditions of local community in the central highlands of Ethiopia.

4.1.1 Remote Sensing and GIS

Between 1975 and 1986, the increases in *Eucalyptus* plantation and cropland/settlements were due to rapid population increases in the study area, and their demand for diverse products (food, feed, fuel and farm implements). This situation forced farmers to convert natural vegetations such as grassland to cropland/settlements and *Eucalyptus*. The slight increase observed in the area of forest cover from 1975-1986 was attributed to the implementation of massive afforestation campaign by the then military government since it took power in 1974. Between 2000 and 2014, a minor increase (2.3%) in the area of grassland was observed due to rapacious removal of *Eucalyptus* plantations for construction purposes in the nearby cities and towns, where the area left open was covered by grasses. However, the reduction in the area of croplands was related to the enclosure of many farmlands to nearby town administrations. Similarly, the decrease in the area of *Eucalyptus* between 2000 and 2014 might be due to partial implementation of government policy that prevents further conversion of productive cropland/grassland to *Eucalyptus* and expansion of urbanization by clearing *Eucalyptus*. Mengistie et al. (2013) also reported the highest conversion of grasslands into other land uses in sub-humid highlands of Ethiopia. An increase in wood lots (*Eucalyptus* tree plantations) and cultivated land at the expense of grazing land have also been reported by Woldeamlak (2002) in both Sebat-bet Gurage in south-central Ethiopia, and in the Chemoga River watershed in north-western Ethiopia. Planting of trees especially *Eucalyptus* on farmlands is considered by many farmers of the North Western highlands of Ethiopia as a good source of income in a relatively shorter period of time (Eleni et al., 2013). In addition to source of income, the case of the central highlands of Ethiopia was also mainly related to soil fertility depletion and non availability of tree species having similar fast growth habit with that of *Eucalyptus*.

4.1.2 Household survey

Survey results also showed that the availability of *Eucalyptus* woodlots around homestead relieved the burden of women by overcoming shortages of fuel wood to a larger extent. Therefore, the main perceived causative factors of land use change from grassland/cropland to *Eucalyptus* are not only related to land degradation and lack of financial capacity on its restoration, but also the multiple benefits *Eucalyptus* provide for the community. Indeed, past socioeconomic evaluations of *Eucalyptus* in the country also confirmed that planting of the tree made a substantial contribution to the income of a household even more than agricultural crop did, especially where the indigenous woodland was degraded and the people were suffering from fuel shortages, water scarcity, erosion and land degradation (Tesfaye, 2009; FAO, 2011).

Even though livestock feed shortages are universal problem in the highlands of Ethiopia, the case of Wetabecha Minjaro is more pronounced due to rapid conversions of previous grasslands to either cropland or *Eucalyptus* plantations. The availability of many religious holidays (minimum of 14 to maximum of 19 days/month) directly or indirectly contributed to the current food insecurity problem in the study area.

4.2 Comparison of soil quality parameters under different land use/cover and management practices in the central highlands of Ethiopia

The lowest bulk density observed in grassland indicates increased pore space, allowing for increased aeration necessary for biological activity. However, higher bulk density in the other land uses might be due to occasional tillage, top soil removal by erosion and low organic matter content. The high amount of SOC (4.3%) observed in grassland relative to other cropland, land *Eucalyptus*, limed land and fallow was contributed to the high amount of CEC in grassland. Grassland in our study area includes tropical type grasses and herbaceous vegetations which resulted in a higher litter input compared to the other land uses and management systems. Therefore, greater return of plant litter to soils and high root biomass of grasses could be the reason for the higher SOC in grassland. Tripathi and Singh (2009) also showed cultivation of soil previously supporting natural vegetation could lead to considerable losses of soil organic matter and microbial biomass. The lower values of SOC in other land use and management systems could be due to less physical protection, because tillage periodically breaks up macro-aggregates and exposes previously protected organic matter. The lowest mean values of soil quality parameters under fallow land might be associated with the current fallow management practices in the study area. Fallow fields are considered as grazing grounds for different species of livestock even though the primary purpose of fallowing by individual farmers is to restore soil fertility. Such practice leaves the land bare and exposes it to surface run-off during rainy season. In addition, crop residues are removed for domestic use, either as a source of fuel or animal feed. Many studies (e.g. Cai and Qin, 2006; Hati et al., 2007; Lemke et al., 2010) have shown that increases in SOC levels is directly related to the amount of organic residues added to soils. Therefore, the lowest soil fertility status (low pH, SOC, available P, Mg^{2+}, Ca^{2+}, MBC and MBN) in fallow lands was due to removal of crop residues and the washing away of nutrients by intense rainfall during fallow period. This clearly demonstrates that highly weathered acid soils in the study area would not recover rapidly after short-term fallow periods of 18 months. Similar to this finding, short-term fallow (four years) in Senegal did not increase SOC or nutrient content (Masse et al., 2004). On the other hand, even though, it is generally believed that plantations of *Eucalyptus* bring about a decrease in soil fertility, the absence of significant variation between *Eucalyptus* and cropland/limed lands in most of the soil physical and chemical parameters is not clear, and needs further investigation. However, Danju et al. (2012) reported restoration of soil fertility following plantation of *Eucalyptus grandis* in south-western China. In their study, they found that soil organic matter content, SOC: TN ratio, and MBC and MBN concentrations showed an initial phase of decline and then increased significantly over time in the upper soil layers of *Eucalyptus grandis* plantations aged from 1 to 4 or 5 years. Similarly, Tilashwork (2009) also reported that soils under cropland and *Eucalyptus* did not vary significantly in texture, bulk density, organic matter, pH, exchangeable K and available water content in the highland of north western Ethiopia.

The most important biological soil properties such as MBC/SOC and MBN/TN showed lower values in fallow land and croplands relative to grasslands or limed land. Similar to this result, cultivation of soils in the central highlands of Mexico with maize reduced MBC, and Reyes-Reyes et al. (2007) reported that converting soil under natural vegetation to arable soil was not only detrimental for soil quality, but also unsustainable when organic matter input is limited. The ratio of MBC to SOC has been suggested as a sensitive indicator of soil organic matter changes (Anderson and Domsch, 1989; Sparling, 1992), partly because the ratio will normalize some of the variability caused by temporal fluctuations in microbial biomass (Rice et al., 1996). A low MBC/SOC indicates a reduced pool of available carbon in soil (Klose et al., 2004). Therefore, this work suggested that the MBC/SOC and MBN/TN could be useful tools to assess biological soil quality changes due to the conversion of grasslands to other land uses management systems in highly weathered acidic soils of the central highlands of Ethiopia.

4.3 Soil carbon mineralization kinetics as influenced by changes in land use and management systems in the central highlands of Ethiopia

The higher amount CO_2 evolved at initial stage indicate a rapid depletion of an easily mineralizable fraction (labile SOC) while the slow-steady phases in which mineralization declined to a fairly constant rate indicate that the most active fraction has exhausted and the resistant and stable fraction of soil SOC was being mineralized (Wander et al., 1994). The higher CO_2 release in grassland could be attributed to the higher organic matter content as compared to cropland, *Eucalyptus*, limed land and fallow land. Mukhopadhyay and Maiti (2014) reported higher CO_2 flux under grassland as compared to afforested land because of higher root density in grasslands, which conserves moisture and enhances root and microbial respiration. Similarly, Chen et al. (2010) also reported significantly higher microbial respiration in grasslands as compared to other land uses in North Eastern Tibetan plateau. High rates of soil respiration can occur as a result of large pool of labile C substrates or rapid oxidation of smaller pool (Islam and Weil, 2000). Thus, high basal respiration may indicate ecological stress and degradation or a high level of ecosystem productivity. According to Frank et al. (2006), higher SOC and MBC lead to higher soil respiration, while the lowest values of soil respiration corresponded to sites with lowest MBC. The relatively greater SOC to be mineralized in grasslands indicates that grasslands contained easily decomposable organic matter than the other land uses and management systems. This finding is in line with the results of Haiqing et al. (2009) where they reported higher mineralized carbon under grassland and reduced tillage due to less disturbance, promotion and stabilization of soil aggregates compared to plowed soils in Southern Germany. Nonetheless, the decrease in the C mineralization in 10-20 cm might be due to lower organic carbon content and relatively smaller number of microbes as soil depth increases. These results are in line with the findings of Taylor (2002), where, reduced activities of microbial and fungal were reported in deeper versus surface soil layers.

The first-order kinetic model used to describe the C mineralization process of soil organic matter assumes that the microbial biomass is constant and the rate of decomposition only depends on the available substrate. Many researchers have fitted C mineralization data with first-order model (Dossa et al, 2009; Aulen et al, 2012). Decreases in potentially mineralizable carbon (C_o) either suggest a lower activity of microbial community or residues more difficult to decompose, due to a different chemical composition. In general MBC is commonly described as a living or active pool in models that simulate SOC turnover in soils, and the size of this pool directly affects the model outputs (Probert et al., 1998). Therefore, differences in SOC and MBC could substantially contribute to the differences observed in the outputs of carbon kinetic models in this study. The half-life time observed in grassland was lower the other land uses. Half-life time is a more clearly interpretable parameter, where high levels are associated with ecosystem stresses (Anderson and Domsch, 2010). Therefore, the higher half-life time in fallow land and cropland indicates lower carbon mineralization rates.

Metabolic quotient (qCO_2) is used to evaluate the efficiency of soil microbial biomass in utilizing the organic carbon compounds (Anderson and Domsch, 1990). Higher values of qCO_2 imply a higher requirement of maintenance energy or lower metabolic efficiency in the utilization of both the native organic matter and the added plant material. In ecological terms, a high qCO_2 reflects a high maintenance carbon demand, and if the soil system cannot replenish the carbon which is lost through respiration, microbial biomass must decline (Anderson and Domsch, 2010). In this study, the beneficial effect of liming was conspicuously observed by significantly lowering the values of qCO_2 only in 0-10cm soil depth. Agricultural liming is generally used to overcome the problem of acidification, would result in higher abundance and diversity of detritivorous soil fauna such as some species of earthworms (Bishop, 2003); contribute to an improved organic matter decomposition and nutrient mineralization (Bradford et al., 2002). The qCO_2 also indicates the changes in microbial activity between natural and disturbed ecosystems more clearly (Islam and Weil 2000; Bastida et al., 2008). Hence, the relatively higher qCO_2 values observed in soils of fallow land in both depths and limed land in 10-20 cm indicate greater stress of the microbial community compared to soils with more stable ecosystems.

4.4 Effects of short-rotation *Eucalyptus* plantations on soil quality attributes in highly acidic soils of the central highlands of Ethiopia.

In this study, the major reason why the proportions of sand, silt and clay were not affected by change in land use might be due to the fact that the mineral particles of the studied soils are not readily subjected to change as a result of land use change. Similar non significant textural classes due to land use changes were previously reported by Behera and Sahani (2003) by comparing three land uses in Western Orissa. Prasad and Power (1997) also indicated that a soil textural class is a permanent characteristic of a soil that gives a general picture of soil's physical properties, i.e., density, porosity, consistency, water holding capacity, and suitability for plant growth. The observed BD in grassland was associated with higher organic carbon content in grassland. Similar low BD in grassland as compared to other land uses was reported by Celik (2005). Lower SOC and TN in *Eucalyptus* plantations agree with reports from Balagopalan and Jose (1995), Animon et al. (1999) and Behera and Sahani (2003). Generally, the observed low percentages of TN in the study area might be associated to low organic matter contents of the soils. Our results revealed a non-significant ($p>0.05$) observation in terms of AvP, K^+ and Mg^{+2} under the three land use systems. Contrary to this finding, afforestation of grasslands in the Argentine pampas with *Eucalyptus camaldulensis* was found to decrease mineral soil cations by redistribution from soil to biomass pools (Jobbagy and Jackson, 2003). The increased acidity under *Eucalyptus* plantations is probably associated with increased cation uptake by trees and consequent changes in the proportions of adsorbed cations to the soil exchange complex.

Soil microbial biomass greatly depends on soil organic matter as substrate; a decrease in SOM causes a reduction in soil microbial biomass (Chen et al., 2005). Hence, the higher MBC and MBN in grassland is mainly attributed to greater availability of organic matter. The lower microbial biomass under *Eucalyptus* plantations could possibly be due to the toxic effects of harmful allelochemical compounds released from *Eucalyptus* leaf litter (Rice, 1984). Harmful effects of *Eucalyptus* leaf litter on microbes were also reported by Dellacassa et al. (1989) and Sankaran (1993). In this study, MBC/SOC did not show remarkable differences among land uses. However, the lower MBC/SOC observed in 10-year-old *Eucalyptus* plantations could be considered as an indication of damage that has occurred to the soil ecosystem. Lower levels of MBN/TN in 10-year-old *Eucalyptus* indicate that the nitrogen supplying ability of *Eucalyptus* plantations is gradually decreasing as the age of the plantations progresses. Low ratios of microbial biomass and nitrogen in *Eucalyptus* plantations were also reported by Yu et al. (2008). Higher mean values of both MBC and MBN in 0-10 cm depth as compared to 10-20 cm might be attributed to a decline in carbon availability and more occurrence of microbial biomass in the surface of 10 cm soil profile. The study demonstrated that more C mineralization happens in the first 0-10 cm than in 10-20 cm, indicating rapid activities of microbes that mineralize C within the surface of the soil profile. The decrease in the C mineralization in 10- 20 cm might be due to lower SOC content at 10-20 cm depth and relatively smaller number of microbes. These results are in line with the findings of Taylor (2002), who found reduced microbial and fungal activities in deeper *versus* surface soil layers.

4.5 Effect of lime and phosphorus fertilizer on acid soils and barley (*Hordeum vulgare* L.) performance in the central highlands of Ethiopia.

In this study, soil pH generally increased in a linear fashion with increasing lime rate. When lime is added to acid soils that contain high aluminum and H^+ concentrations, it dissociates into Ca^{+2} and OH^- ions. The hydroxyl ions will react with hydrogen and aluminum ions forming aluminum hydroxide and water, thereby increase soil pH in the soil solution. Meanwhile, applications of the highest rate of lime appreciably reduced soil exchangeable acidity, which was 1.32 $cmol_+ kg^{-1}$ at the start of the experiment to a negligible level of 0.12 $cmol_+ kg^{-1}$ after two years of soil analysis. Many authors (e.g., Fageria and Stone, 2004; Fageria and Baligar, 2008; Álvarez and Fernández, 2009) have also reported that liming raises soil pH, base saturation, and Ca^{2+} and Mg^{2+} contents, and reduces Al^{3+} concentration.

Successive applications of P increased grain yield and yield components of barley, and counteracted Al toxicity by precipitating exchangeable aluminum as $AlPO_4$. This could be the reason why large applications of phosphate fertilizers to acid soils overcome the toxic effects of Al and thereby improve growth of plants. A major characteristic of Al toxicity is an inhibition of the uptake and translocation of P by plants (Foy and Fleming, 1978). Thus, liming acid soils often increases P uptake by plants by decreasing A1 toxicity rather than by an effect on soil P availability, per se (Haynes and Ludecke, 1981). After reviewing of liming on phosphate availability, Haynes (1982) concluded that large additions of phosphates to acid soils reduce the injurious effects of Al ions by precipitating it from the soil and supplying sufficient phosphate for plant metabolic activity. Liming induced favorable conditions for plant growth was the main reason for yield increment of barley in this study. Numerous authors (Farhoodi and Coventry, 2008; Álvarez and Fernández, 2009) also reported that application of lime at an appropriate rate brings several chemical and biological changes in the soil, which is beneficial or helpful in improving crop yields in acid soils. Studies elsewhere (e.g., Wang et al., 2011) reported that yield increase from liming is mainly associated with an increase in soil pH and a reduction in plant uptake of aluminum and manganese.

Several mechanisms are involved in increasing yield and yield components of barley when lime and P are used to ameliorate acid soils. Past laboratory and field studies conducted to determine how phosphorus availability responds to lime addition reported that liming enhances P uptake by alleviating Al toxicity and thereby improving root growth (Bolan, 2003; Haynes, 1982; Fageria and Santos, 2008). The improved root growth would allow a great volume of soils to be explored. This in turn favors improvement of barley grain yield and yield components. Many authors (e.g., Meng et al., 2004, Moir and Moot, 2010) also reported that liming increased soil pH and significantly reduced the concentrations of exchangeable acicity in the soil. The observed significant lime×P interaction is in the first year (2010) is typical of P deficient, highly-weathered, acid soils (Friesen et al., 1980).

GENERAL CONCLUSIONS

1. Analysis of land use/cover (LULC) study over a period of 39 years (1975 - 2014) at Wetabecha Minjaro showed that *Eucalyptus* plantations and cropland/settlements increased by 335 and 62.5 %, respectively. The increase was at the expense of grasslands, where a corresponding 74% decrease in the area of grassland was observed in the same period.
2. Drivers of LULC change were rapid population growth and their demand for diverse products and soil fertility deterioration over time which forced farming families to change part of their land to other forms of land use/cover.
3. Declining soil fertility due to soil erosion and lack of financial capacity for its restoration leave majority of the household food insecure in general, poor households in particular.
4. Due to the proximity of the study area to major market outlet i.e. Addis Ababa city, building public-private partnerships around market-oriented barley production can be an entry point for encouraging investment in use of external nutrient inputs to improve soil fertility and boost agricultural productivity.
5. The availability of many religious and related holidays in the study area greatly contributes directly or indirectly to seasonal food shortages of the community. Therefore government/local officials should intervene by discussing the issue with religious leaders and community elders to reduce the number of religious holidays. Besides this, enabling and capacity building of the local people with different agricultural technologies not only help them become food secure but also greatly contribute to environmental protection in the future.
6. Continued conversions of grasslands to either cropland or *Eucalyptus* plantations deteriorate the functional capacities of soils as evidenced from soil physical, chemical and biological properties. Grassland promoted soil organic carbon accumulation and decomposition both in surface and subsurface soil compared to cropland, *Eucalyptus* plantations, limed land and fallow land. Particularly, the lower values of biological attributes observed in fallow land could be an early indication of soil quality deterioration.

7. As evidenced from soil physical, chemical and biological analysis, the traditional way of restoring soil fertility by fallowing land after a cropping period of 18 months could not improve soil quality parameters. However, improving soils conditions under cropland and fallow land requires judicious application of lime along with phosphate fertilizers, which would be sustainable options for the current soil acidity problem that has resulted in land use change.
8. Grassland had higher C-CO_2 mineralized than adjacent cropland, *Eucalyptus* plantations, limed land and fallow lands, indicating high rates of biological activity and C cycling relative to the other land uses.
9. Soil organic carbon, the ratio of microbial biomass carbon to soil organic carbon, microbial biomass nitrogen to total nitrogen,, potentially mineralizable carbon and metabolic quotient could be considered as the five most important bio-chemical parameters to assess functional capacities of soils in soil acidity affected areas in the central highlands of Ethiopia. However, integration of these parameters with soil physical and chemical properties would be essential.
10. Deterioration in soil quality parameters was more pronounced in 10-year-old *Eucalyptus* plantations than in 5-year-old *Eucalyptus*. However, considering the current high demand of *Eucalyptus* for construction, fuel wood and farm implements, cautions should be taken in large scale conversion of grasslands to short-rotation *Eucalyptus* in the central highlands of Ethiopia.
11. Acid soils of the study area were greatly responsive to applications of both lime and phosphorus fertilizer. Successive applications of lime drastically decreased exchangeable aluminum to the minimum level, and raised soil pH close to the optimum pH requirement for barley.
12. Applications of 1.65 Mg ha^{-1} of lime in the form of $CaCO_3$ and 30 kg P ha^{-1} in the form of triple super phosphate gave the maximum grain yield of barley, which was five times the yield obtained by conventional way of barley production. Therefore, sustainable production of barley production in the highlands of Ethiopia should entail applications of 1.65 Mg ha^{-1}, 30 kg P ha^{-1}, and use of improved high yielding barley varieties.

CONCLUSIONES GENERALES

1. El análisis de la cubierta vegetal y del uso del territorio durante un periodo de 39 años (1975 a 2014) en Wetabecha Minjaro, mostró que las plantaciones de eucalipto y los cultivos incrementaron su superficie en 335 y 62,5% respectivamente. El incremento de estos dos tipos de uso fue principalmente a expensas de los pastos, que disminuyeron su superficie en un 74% en la zona durante ese mismo periodo.
2. Las razones de estos cambios de uso / cubierta de la tierra fueron el crecimiento rápido de la población con la consiguiente demanda de diversos productos y el deterioro de la fertilidad del suelo a través del tiempo lo que ha obligado a los agricultores a cambiar parte de sus tierras a otras formas de uso de la tierra / cubierta.
3. La disminución de la fertilidad del suelo debido a la erosión y a la ausencia de capacidad financiera para su recuperación ha llevado a una gran inseguridad alimentaria en los hogares en general y en los hogares más pobres en particular.
4. Debido a la proximidad del área de estudio a un importante Mercado como es la ciudad de Addis Abeba, la creación de asociaciones público-privadas alrededor de la producción de cebada orientada al mercado puede ser un punto de partida para el fomento de la inversión en el uso de insumos externos de nutrientes para mejorar la fertilidad del suelo y aumentar la productividad agrícola.
5. La existencia de muchos días festivos religiosos contribuye directa o indirectamente a la escasez estacional de alimentos para la comunidad. Por lo tanto, los funcionarios del gobierno o locales deberían intervenir mediante la discusión del tema con los líderes religiosos y los ancianos de la comunidad con el fin de reducir el número de fiestas religiosas. El aprendizaje y la aplicación de diferentes tecnologías o prácticas de manejo agrícolas por parte de la población local les ayudará no sólo a disponer de alimentos, sino también a proteger el medio ambiente en el futuro.
6. La transformación de pastos a tierras de cultivo o a plantaciones de eucalipto deteriora la capacidad de funcionamiento de los suelos como se evidencia a partir de sus propiedades físicas, químicas y biológicas. Los pastos favorecen la acumulación de carbono orgánico edáfico y su descomposición tanto en el suelo superficial como en el subsuperficial comparado con los suelos bajo cultivo agrícola, plantaciones de eucalipto, y terrenos encalados y en barbecho. Particularmente los bajos valores

observados en los parámetros biológicos en las tierras en barbecho podrían indicar un deterioro en la calidad del suelo.

7. Los análisis de las propiedades físicas, químicas y biológicas de los suelos ponen de manifiesto que la forma tradicional para la recuperación de la fertilidad edáfica mediante el barbecho de la tierra después de un período de cultivo de 18 meses no mejoran los parámetros de calidad de los suelos. Sin embargo, la mejora de los suelos de cultivo y barbecho requiere el encalado juicioso junto con la aplicación de fertilizantes con fosfatos. Además serían una opción adecuada para solucionar el problema de acidez edáfica que resulta del cambio de uso.
8. Los suelos bajo pastos mostraron valores más altos de $C\text{-}CO_2$ mineralizado que los adyacentes suelos bajo cultivo, plantaciones de eucalipto, terrenos encalados y en barbecho, indicando que sus tasa de actividad biológica y reciclaje de carbono fueron más altos que en los otros usos comparados.
9. El carbono orgánico edáfico, las ratios del carbono de la biomasa microbiana al carbono orgánico del suelo y del nitrógeno de la biomasa microbiana al nitrógeno total del suelo, el carbono potencialmente mineralizable, y el cociente metabólico podrían ser considerados como los más importantes parámetros bioquímicos para evaluar la capacidad de funcionamiento edáfico en áreas de suelos ácidos de las tierras altas del centro de Etiopía. Sin embargo, es esencial la integración de estos parámetros con parámetros físicos y químicos.
10. El deterioro de la calidad del suelo fue más pronunciado en las plantaciones de eucalipto de 10 años que en las de cinco años. Sin embargo, considerando la gran demanda de eucalipto para la construcción, para leña y para aperos de labranza se deberían tomar precauciones en la conversión a gran escala de los pastizales en plantaciones de eucalipto de rotación corta en las tierras altas del centro de Etiopía.
11. Los suelos ácidos del área de estudio respondieron de forma significativa a la aplicación tanto de encalado como de fertilizantes fosforados. La aplicación sucesiva de encalado disminuyó drásticamente los niveles de aluminio intercambiable y elevó el pH del suelo hasta valores cercanos al óptimo para el cultivo de cebada.

12. La adición de fertilizante fosfatado en dosis de 30 kg P ha^{-1} en forma de superfosfato triple (SPT) junto con el encalado con 1,65 Mg de $CaCO_3$ ha^{-1} dieron el rendimiento máximo de producción de cebada de los probados en el ensayo, y siendo cinco veces mayor que la producción habitual de cebada en la zona. Por ello, la producción sostenible de cebada en las tierras altas de Etiopía debería considerar la aplicación conjunta de fertilizantes fosforados en dosis de 30 kg P ha^{-1} en forma de SPT y el encalado 1.65 Mg $CaCO_3$ ha^{-1}.

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Chapters

Chapter I: Land use/cover (LULC) change and socio-economic conditions of local community in the central highlands of Ethiopia

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Chapter IV: Effects of short-rotation *Eucalyptus* plantations on soil quality attributes in highly acidic soils of the central highlands of Ethiopia

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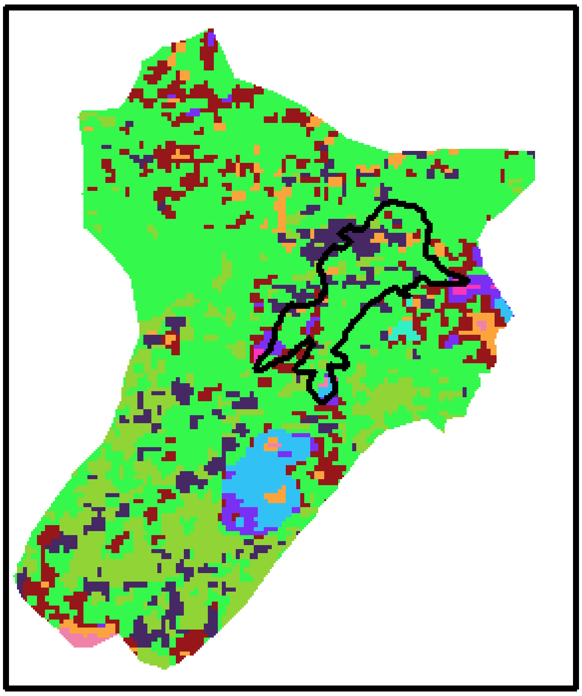
Chapter I

Land use/cover (LULC) change and socioeconomic conditions of local community in the central highlands of Ethiopia



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Land use/cover (LULC) change and socio-economic conditions of local community in the central highlands of Ethiopia.

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Abstract

This paper presents a case study of land use/cover changes from 1975-2014 in the central highlands of Ethiopia, and trace out its impact on socio-economic conditions of the local community in the study area. We used four time series Landsat satellite images i.e. Landsat MSS (1975), Landsat Thematic Mapper (1986), Enhanced Thematic Mapper (2000), and Landsat 8 OLI scenes (2014) to investigate the changes in LULC. In addition, individual interviews with 51 randomly selected households, discussions with focus group and key informants, and field observations were also incorporated for the study. The image classification indicated four categories of LULC classes: Natural forest, *Eucalyptus* plantations, cropland/settlements and grasslands. Between 1975 and 2014, cropland/settlements and *Eucalyptus* plantations considerably increased, whereas grassland cover drastically decreased. According to the results, the area under cropland/settlements and *Eucalyptus* plantations increased by 62 and 335% respectively, with 74% concomitant decrease in the area of grasslands in the same period. Survey results showed that deterioration of soil fertility (41.2%) followed by shortage of land (35.3%) are the major constraints for crop production for poor farmers in the study area. However, better-off farmers ranked deterioration of soil fertility (64.7%) followed by lack of credit (17.6%) as priority constraints for crop production. Interviews mainly focused on selected women group revealed that the expansion of *Eucalyptus* in the area greatly curbed the burdens of collecting fuel woods from long distances in the past. The availability of too many religious holidays (on average 16 days/month) directly or indirectly contributes to the current seasonal food shortages of the community. Generally, our results show that the community in the study area is beset with a host of social, economic and institutional challenges. As a result, majority of the farming households are destitute, unable to make a livelihood from their small plot of land and live in absolute poverty. Therefore, in light of these finding, it is imperative that timely interventions by government and other development stakeholders are needed to come to grips with problems of soil fertility, land use change and food insecurity in the study area.

Keywords: Land use/cover, Landsat, highlands, household survey, soil fertility

1. Introduction

The issues of land use/cover (LULC) change and soil fertility problem in the African farming systems have attracted the attentions of many researchers, and have raised to top policy makers in the recent years (Nico, 2005; Kassa et al., 2013). Population growth is commonly blamed for widespread land use change and environmental degradation (Cleaver and Schrieber 1994; Ramankutty et al., 2002) although several interacting factors are involved. In developing countries like Ethiopia, where a large proportion of the human population depends almost entirely on natural resources for their livelihoods, there are increasing competing demands for utilization, development and sustainable management of the land resources (e.g., natural vegetation), resulting in land-use and cover changes (Mwavu and Witkowski, 2008). Many land use changes (e.g., conversions of grasslands to croplands, fallowing croplands, replacement of infertile croplands by *Eucalyptus* plantations) are being practiced as mitigative measures against the negative impact of soil acidity in the highlands of Ethiopia. Even though, liming is recommended and practiced in many farms, the so called “fallowing”, the resting state of agricultural field (Szott et al., 1999) is a preferred by many farmers to restore soil fertility due to its cheaper practice. In high crop production potential areas, the expansion of *Eucalyptus* into productive croplands/grasslands is also rapid. At the moment, Ethiopia has the largest area of *Eucalyptus* plantations in the east Africa, and is one of the 10 pioneer countries that introduced eucalypt (FAO, 2011). Even though, the policy environment in Ethiopia discourages farmers from planting *Eucalyptus* on productive lands due to its likely negative impact on the environment (Mekonen et al., 2007), farmers have still continued expanding the area of *Eucalyptus* plantations at the expense of agricultural lands owing to its fast growth habit, and lack of alternative seedlings of other trees species with similar growth habit with that of *Eucalyptus* (Owen personal communication with farmers). This is because of a high demand of *Eucalyptus* poles in big cities and towns for construction purpose and biomass energy, wherein farmers get lump sum amount of money better than agricultural crops. Hierarchical evolution of *Eucalyptus* in the farming systems of the central highlands of Ethiopia illustrated in figure 1.

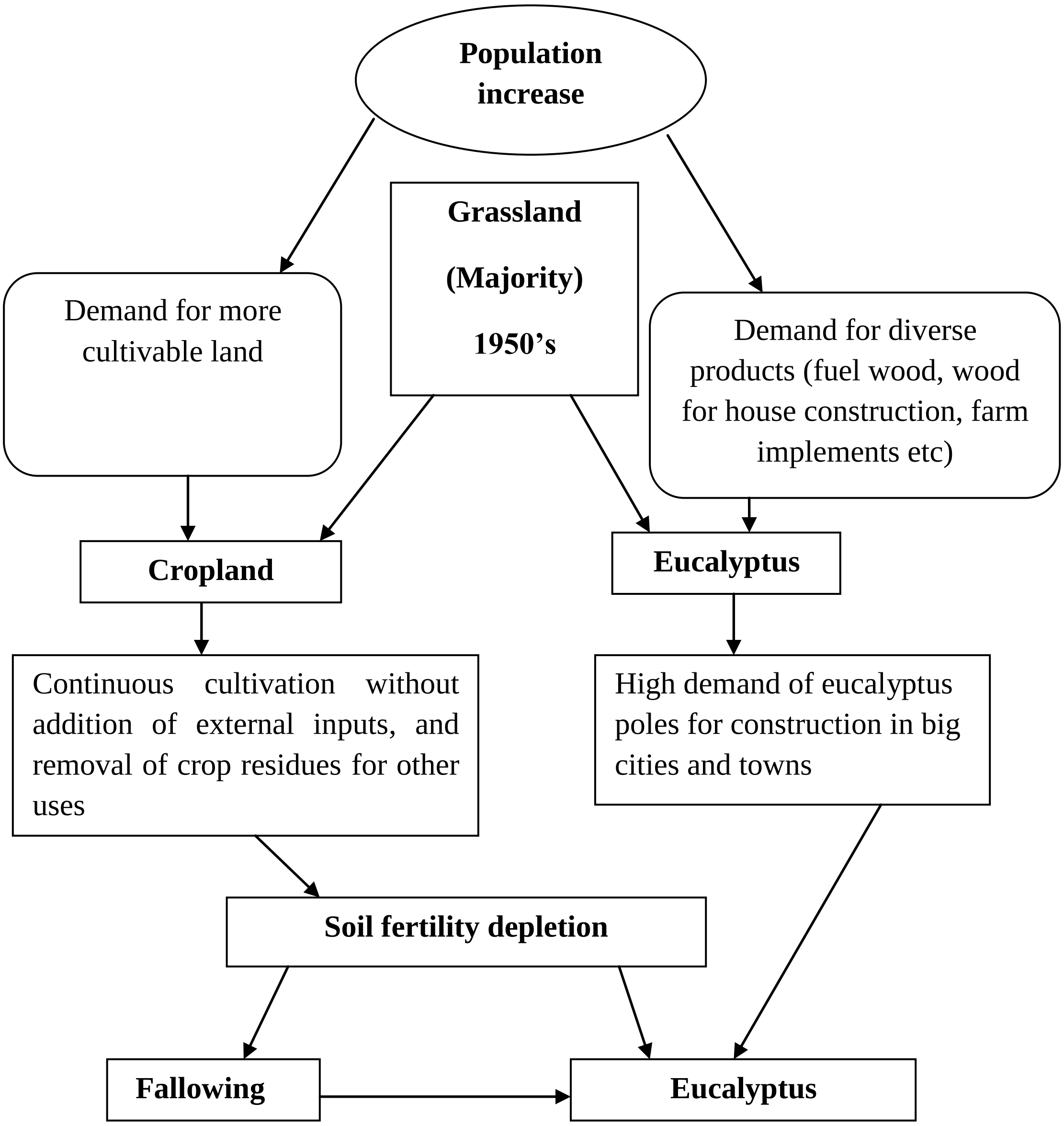

Fig.1 Hierarchical evolution of *Eucalyptus* in the farming systems of Wetabecha Minijaro, in the central highlands of Ethiopia (Own Survey result, 2012).

Consequently, land use change has become an area of particular concern due to rapid land conversion practices in the highlands of the country. In recent decades, Remote Sensing (RS) with multi-temporal high-resolution satellite data has been widely used to obtain land cover information such as degradation level of forests and wetlands, rate of urbanization, intensity of agricultural activities, and other human-induced changes (Yuksel et al., 2008). However, these bio-physical approaches do not give information about why changes occur. Understanding land use/cover study requires an understanding of people and their societal situation, their priorities, livelihood strategies, views on the land, and the wider implications of social, political, cultural, biophysical and institutional factors, among others (Maro, 2011). Incorporations of local experiences of key informants in the community provide information on past, present and expected future land use changes (Sandewall et al., 2001). Therefore, it is necessary to go beyond disciplinary trend studies and examine methods for integrating LULC and social research to get knowledge and the experiences of different stakeholders. Therefore, integration of the remote sensing and household survey are important tools to study changes in land cover patterns and dynamics in order to obtain rapid, economical, reliable, and accurate results (Sertel et al., 2008). As explicitly stated by Maro (2011), one of the merits of using qualitative research in social science and survey research methods to understand local perceptions of land use change is its obvious contribution to answer the questions ‘why is change occurring?’ and ‘so what?. Klintenberg et al. (2007) used individual semi-structured interviews with local farmers to understand whether national and local perceptions of environmental change in central Northern Namibia were related. These and other similar studies show that a combination of local and scientific knowledge can lead to more useful assessment of land use change and its implications for local land-users and managers (Klintenberg et al., 2007). Hence, the integration of information from household surveys and data on land cover changes derived from remote sensing improves our understanding of the causes and processes of LULC changes (Benoît et al., 2000).

Studies related to land use/cover changes in Ethiopia are rare, with most focusing on Northern highlands of Ethiopia (IFPRI et al., 2005). Apart from Northern Ethiopia, there are scarce literature on LULC change detections using remote sensing and GIS in different parts of the highlands of the country. Particularly, studies aimed in integrating land use change and socio-economic data in barley-fallow based farming systems in the central highlands of Ethiopia are few and far between. Hence, this study is the first of its kind to explore about farmer's socio-economic conditions and their perceptions about land use/cover change. The objectives of this study were, therefore, to show trends of LULC changes from 1975-2014, and to understand the socioeconomic conditions of the community and their perceptions about the expansion of *Eucalyptus* in barley-fallow based farming systems in the central highland of Ethiopia.

2. Materials and Methods

2.1 Study area

Wetabecha Minjaro (9° 05′ 55″ N, 38° 36′ 21″ E, altitude 2565 m a.s.l), is representative of a barley-fallow/livestock production system in the central highlands of Ethiopia (Fig. 2). It receives about 1100 mm of rainfall annually. The mean monthly maximum and mean monthly minimum temperatures are 23.3 °C and 8.7 °C, respectively. According to the local agro-climatic classifications, it belongs to moist highland agro-climatic zone with two rainy periods; the main rainy season which occurs from June to mid September, and the short rainy season extending from February to April. Nitisols or Alfisols form the dominant soil types in the study area (IUSS, 2006).

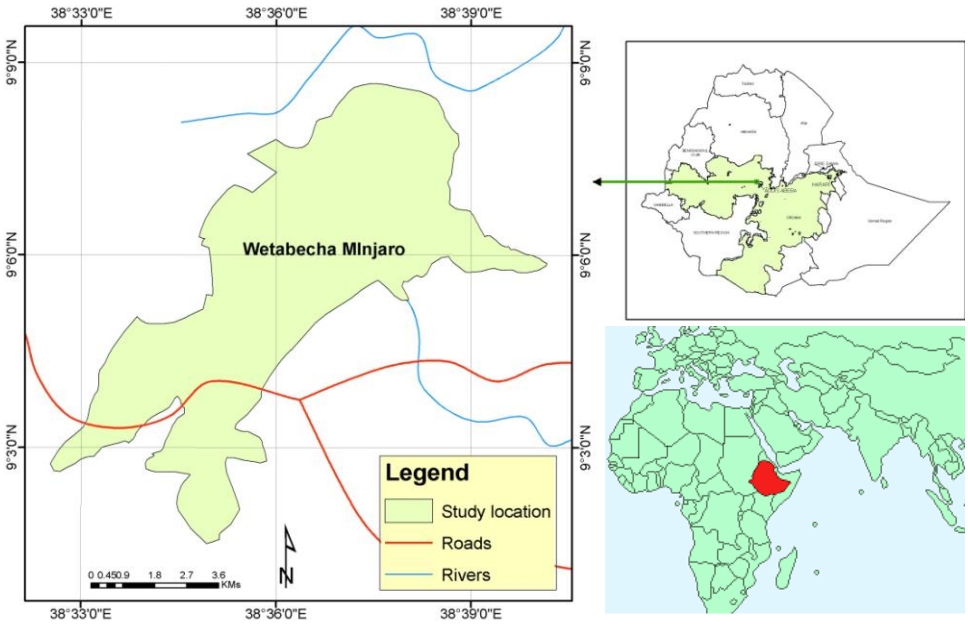

Fig. 2 Location map of the study area.

Most of the soils have a pH range of 4.5 to 5.5, contain low organic matter (<20 g kg^{-1}) and low nutrient availability. In the past several decades, tropical meadow type grassland vegetation and shrub lands were the dominant type of vegetation. Now, such types of vegetations have been gradually replaced by croplands/settlements and *Eucalyptus* plantations. The study site is predominantly inhabited by farmers belonging to the "Oromo"[2] ethnic group, and over 95% of the population relies on agriculture for their livelihood needs. The only major cereal crop grown in the region is barley (*Hordeum vulgare* L.). Other minor crops grown include oats (*Avena sativa* L.*)* and potato (*Solanum tuberosum* L.). However, the area is characterized by low input-output farming system, with barley grain yield rarely exceeding one ton per hectare. Relative to the other parts of the central highlands of Ethiopia, it is one of the most neglected regions in terms of agricultural innovations and infrastructural development, with little/no governmental and non-governmental institutional support for the improvement of the livelihoods of the community. Apart from croplands, the study landscape also comprises mosaic natural forests that belong to a tropical dry Afromontane forest.

2.2 Data collection

2.2.1 Land use/cover

The main data source for land use/cover classification and change analysis were a series of Landsat imagery data. These include Landsat MSS, Landsat Thematic Mapper (TM), Enhanced Thematic Mapper (ETM+) and Landsat OLI scenes of the year 1975, 1986 2000 and 2014, respectively. These datasets were obtained from the National Aeronautics and Space Administration (NASA) through their EOS Data Gateway Database. All the Landsat images were acquired in the same season (between October and January). Accuracy assessment was performed using forty randomly collected samples by stratified random sampling method following the procedures of Congalton and Green (2009). The reference data for 2014 map for each land use/cover was collected from field visits, historical black and white aerial photos, topographic maps, and raw images. However, the reference data for 1975, 1986 and 2000 was collected through visual interpretations of the raw data of the Landsat images of the respective years supplemented by field visits and discussions with elders in the study area.

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[2] The largest ethnic group occupying the largest proportion of Ethiopian landmass

2.3 Household survey

2.3.1 Sampling and survey approach

The survey was carried out in July 2012, and adopted a purposive sampling method to select the study site, Wetabecha Minjaro peasant association (PA)[3]. The main reason for selecting this site was due to its peculiar farming system, i.e. barley-fallow crop production systems in the central highlands of Ethiopia, where soil acidity-induced land use changes are among the major challenge to boost agricultural productivity. The survey was conducted in two phases. In the first phase, field observations were made to obtain background information on farming systems followed by preparation and pre-testing of structured questionnaire. In the second phase, the information gathered was used to re-design the structured questionnaire for collection of qualitative and quantitative data. A semi-structured face-to-face individual interview, discussions with focus group and key informants were used to gather information about land use types, soil fertility status, current soil management practices and related challenges, and socio-economic conditions of the people living in the area. We randomly selected 51 households from the peasant association. In all the interviews, heads of the selected household, who are implicit decision makers in the household and responsible for the whole farm management, were interviewed. The questionnaire covered wide range socio-economic conditions, and looked at issues pertaining to: (1) household size, (2) land size (3) land use types and changes that have occurred over time, and (4) perception about land use change particularly with regard to expansion of *Eucalyptus* in the area. In addition, unstructured interviews were carried out with four knowledgeable key informants recommended by the local farmer's association, and several field visits were conducted for ground truth checking and confidence building.

2.4 Data analyses

All GIS data were projected to the Universal Transverse Mercator (UTM) projection system zone 37N and datum of World Geodetic System 84 (WGS84), ensuring consistency between datasets during analysis. The images were analyzed by utilizing data

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[3] Peasant association is the lowest administrative unit in government structure in Ethiopia, and Wetabecha Minjaro is the union of two peasant associations (Wetabecha and Minjaro).

image processing techniques in ERDAS Imagine© 10.0 and ArcGIS© 10.0 software. Since the identity and location of some of the land use and land cover types such as, grassland, agricultural land, natural forest areas and *Eucalyptus* plantations of the area were known based on the *a priori* knowledge of the author and with ground truth data, a supervised signature extraction with a maximum likelihood was used in the analysis. The pixel oriented classification with the maximum likelihood method was used, because this method usually delivers better results than minimum distance method (Gomarasca, 2011). Change analysis was conducted using post image comparison technique (Singh, 1989). Ground truthing was complemented with topographical maps of the study area as well as several field visits, interviews with individuals and elderly people of the area. As rural settlements are scattered and close to cultivated lands, croplands and settlements were classified together. The classified images were compared in three periods, i.e., 1975-1986, 1986-2000, and 2000-2014. The values were presented in terms of hectares and percentages. The percentage LULC changes were calculated using the following equation:

$$Percentage\ LULC\ change = \frac{Area\ final\ year - Area\ intial\ year}{Area\ intial\ year}\ X\ 100$$

For the survey data, a statistical package for social sciences - (SPSS) version 20 (SPSS Inc., 2008) software was used to analyze the household data. Descriptive statistics such as cross tabulation, frequencies and percentages were employed to summarize the data.

3. Results and discussion

3.1 Land use/cover

As evidenced from remotely sensed data, the proportionate spatial coverage of each land use/cover is summarized and presented in Fig. 3, and Table 1. The major land use/cover types identified include: croplands/settlements, grasslands, *Eucalyptus* plantations and natural forest (Fig. 3). The maps indicated a drastic land use/cover changes over a period of 39 years of analysis. In the mid 1970s, grasslands were the dominant land use/cover type in the area. Starting from mid 1980s, grassland was gradually overtaken by arable land and settlements mainly owing to rapid population increase and their demand for diverse products, which forced farmers to convert part of their land to other land use types.

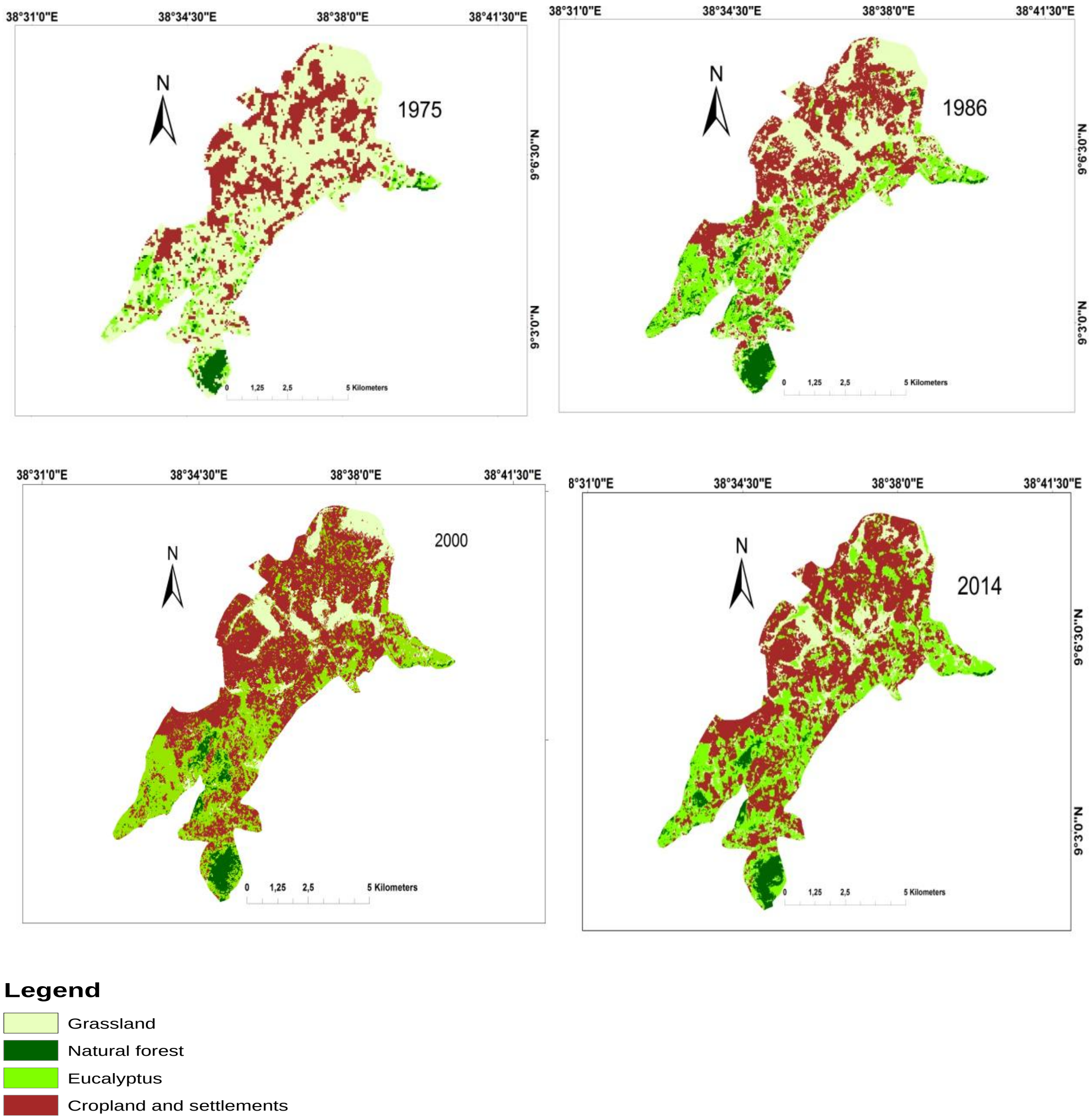

Fig. 3 Classified land use/cover Landsat MSS 1975, TM 1986, ETM$^+$ 2000 and Landsat 8 OLI 2014 imagery of Wetabecha Minjaro, central highlands of Ethiopia

In 1975, natural forest, *Eucalyptus* plantations, croplands/settlements and grasslands occupied 3.5, 7.5, 28.8 and 61.5 % of the total land area, respectively (Table 1). By the year 1986, land brought to *Eucalyptus* plantations and cropland/settlements increased by 194.6 and 26.5%, compared to 1975. The increases in *Eucalyptus* plantation and cultivated lands were, however, paralleled by rapid declines in land area under grasslands.

In fact the area under natural forest showed a steady increase between these periods due to implementation of massive afforestation campaign by the then military government since it took power in 1974. In the period between 1986 and 2000, grasslands which were mainly open grazing lands continued to decline very rapidly with subsequent increases in *Eucalyptus* plantations and croplands/settlements. However, between 2000 and 2014, a minor increase (2.3%) in the area of grassland was observed due to rapacious removal of *Eucalyptus* plantations for construction purposes in the nearby cities and towns, whereby the area is left open and covered by grasses. In the same period, the reduction in the area of croplands/settlements was related to the enclosure of many farmlands to nearby town administrations. In the period between 2000 and 2014, the area under *Eucalyptus* decreased as compared to the previous periods partly due to the implementation of government policy that prevents conversion of productive cropland/grassland to *Eucalyptus* and expansion of urbanization by clearing *Eucalyptus*.

Overall, in the period between 1975- 2014 (39 years), *Eucalyptus* plantations and cropland/settlements increased by 335% and 62.5 %, respectively. The increase in the area of *Eucalyptus* and croplands/settlements was at the expense of grasslands, where a corresponding 74% decrease in the area of grassland was observed in the same period. These results are in agreement with that of Mengistie et al. (2013) who reported the highest conversion of grasslands into other land uses in Sub-humid highlands of Ethiopia. An increase in wood lots (*Eucalyptus* tree plantations) and cultivated land at the expense of grazing land have also been reported by Woldeamlak (2002) in both Sebat-bet Gurage in South-central Ethiopia, and in the Chemoga River watershed in North-western Ethiopia.

Table 1. Summaries of land use and land cover changes from 1975 to 1986, 1986 to 2000 and 2000 to 2014 time periods showing area changed in hectares (ha) percentage change in land use/cover.

	1975		1975 -1986		1986 -2000		2000 -2014	
Land use/cover types	area (ha)	%	area (ha)	% change	area (ha)	% change	area (ha)	% change
Natural forest	207	3.4	342.4	2.3	255.5	-1.5	253.5	-0.03
Eucalyptus plantations	444.6	7.4	1309.8	14.5	1980.3	11.3	1933.5	-0.8
Cropland and settlements	1713.6	28.4	2168.4	7.6	2869.9	11.8	2784.9	-1.4
Grassland	3659.7	60.7	2130.8	-25.7	808.0	-22.2	945.6	2.3

Eleni et al. (2013) reported that planting trees especially *Eucalyptus* on farmlands is considered by many farmers of the North Western highlands of Ethiopia as a good source of income in a relatively shorter period of time. Numerous studies in Ethiopia and elsewhere (Dessie and Kleman, 2007; Kamusoko, 2007; Ningal et al., 2008; Paré et al., 2008; Zhao et al., 2006) have also reported expansion of croplands and *Eucalyptus* plantations at the expense of grasslands. However, Tekle and Hedlund (2000) reported increases in the sizes of open areas and settlements at the expense of shrublands and forests.

3.2 *Household survey*

Table 2 presents summary statistics of some household characteristics of the sample respondents. The average family size of the sample respondents was 6.3 persons. The average age of the sample farmers interviewed was 43.6 years. Average farm size for poor and better-off farmers was 2.6 and 5.3 hectares respectively.

Table 2. Some household characteristics (mean and standard deviation).

Variable	Wealth class †		Total
	Poor	Better-off	
Family size	5.7 ±2.40	7.6 ±1.96	6.3 ±2.42
Age of interviewee	41.5 ±11.49	48.1 ±10.51	43.6 ±11.51
Farm size (ha)	2.6 ±1.32	5.3 ±2.03	3.7 ±2.33
Total area under crop (ha)	2.5 ±1.29	5.1 ±1.98	3.6 ±2.29
Area under *Eucalyptus* (ha)*	0.10 ±0.04	0.15 ±0.07	0.12 ±0.57

Note: Family size includes all household members resident at home during the interview, Farm size includes all land held in different parcels including cropland, grassland, fallow land and area devoted to *Eucalyptus*. * It excludes community owned *Eucalyptus* plantations. †Wealth class: poor=respondents who face seasonal food shortages and who have limited capacity to invest on farm land, better-off= respondents relatively at better positions, very rarely face seasonal food shortages and have capacity to purchase agricultural inputs (seed, fertilizers and herbicides).

The farm size owned by the respondents, of course, varies from a minimum of about 1.1 hectares to a maximum of 10.3 hectares. It is also important to note that 53% of the respondents owned less than 3.0 hectares of land. About 14% and 39% of the respondents were illiterate and people who are able to write and read respectively. Without considering community owned *Eucalyptus* plantations, average area of land devoted for *Eucalyptus* varies from 0.10 hectares for poor farmers to 0.15 hectares for better-off farmers.

Responses of sample respondents in prioritizing crop production constraints were presented in Table 3. Poor farmers ranked deterioration of soil fertility (41.2%) followed by shortage of land (35.3%) as the main constraints to crop production. Whereas, better-off farmers ranked deterioration of soil fertility (64.7%) and lack of credit (17.6%) as among the priority problems for crop production in the area. Overall, regardless of wealth class, 49% of the respondents declared deteriorations of soil fertility as the major obstacle for crop production in the region.

Table 3. Percentages of respondents prioritizing crop production constraints according to wealth class.

	Wealth class		
Constraints	Poor	Better-off	Total
Deterioration of soil fertility	41.2	64.7	49.0
Shortage of land	35.3	5.9	25.5
Lack of credit	11.8	17.6	13.7
Crop pests and diseases	8.8	5.9	7.8
Lack of drought oxen	2.9	5.9	3.9
Total (%)	100.0	100.0	100.0

This is due to the fact that farmers are poor and their desire to buy commercial fertilizer is hampered by lack of credit scheme. Accordingly, 14% of the total respondents mentioned unavailability of credit schemes for purchase of agricultural inputs as one of the major obstacles to crop production. Consequently, farmers adopt other options such as fallowing, conversions of grassland to cropland and infertile cropland to *Eucalyptus* plantations as an alternative measures against soil acidity related infertility problems in the region.

The main reasons for conversion of either cropland or grassland to *Eucalyptus* include, decrease in the productivity of land, demand for fuel wood, construction, as windbreak/fencing, and to generate cash by selling *Eucalyptus* poles. A large proportion of the sample respondents reported that they did not have any other tree species other than *Eucalyptus* that can be used as source of wood for fuel, construction and farm implements. As indicated by one key informant who had been living in the area since 1942 indicated that there were no/few tree species before the introduction of *Eucalyptus*, and fuel wood shortages had been severe problems for the community. Similar informal discussions with the community, women group in particular also revealed that they had to travel long distances to collect firewood for domestic uses in the past. Nowadays, the presence of *Eucalyptus* woodlots at their farm relieved the burden of women by overcoming shortages of fuel wood to a larger extent. Therefore, the main perceived causative factors of land use change from grassland/cropland to *Eucalyptus* are not only related to land degradation and lack of financial capacity on its restoration, but also the multiple benefits *Eucalyptus* provide for the community. Indeed, past socio-economic evaluations of *Eucalyptus* in the country also confirmed that planting of the tree made a substantial contribution to the income of a household even more than agricultural crop did, especially where the indigenous woodland was degraded and the people were suffering from fuel shortages, water scarcity, erosion and land degradation (Tesfaye, 2009; Holden et al., 2003; FAO, 2011).

Responses of farmers to priority constraints to livestock production are presented in Table 4. The most frequently cited and serious problem to livestock production in the area was shortages of livestock feed (49%) and low productivity of local animals (27.5%). Shortage of livestock feed was pronounced on poor farmers (58.8%), whereas low productivity of local animals on better-off farmers (47.1%).

Table 4. Percentages of respondents prioritizing livestock production constraints according to wealth class.

Main constraint	Wealth class		Total
	poor	Better- off	
Shortages of livestock feed	58.8	29.4	49.0
Poor productivity of the local breeds	17.6	47.1	27.5
Animal disease and parasite	8.8	17.6	11.8
Lack of credit	8.8	5.9	7.8
Shortages of labour	5.9	-	3.9
Total (%)	100.0	100.0	100.0

Even though livestock feed shortages are universal problem in the highlands of Ethiopia, the case of Wetabecha Minjaro is more pronounced due to rapid conversions of previous grasslands to either cropland or Eucalyptus plantations. Fig. 4 shows total number of religious and related holidays observed in a month during which farmers are not allowed to undertake any farm activities. This is precisely because of the great majorities of the farmers in the study area are followers of the Coptic Orthodox church and obliged to observe a number of religious holidays on which they are customarily prohibited to undertake any cropping activities. Hence, 68%, 28% and 4% of the sample respondents do strictly observe these holidays for 19, 16 and 14 days in a month, respectively.

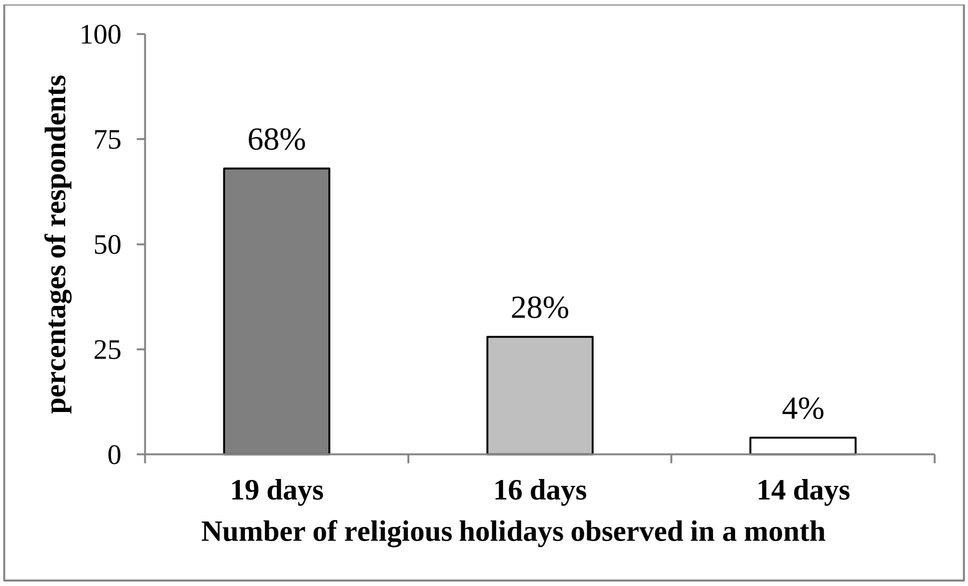

Fig. 4 Number of religious holidays in a month during which farmers does not undertake any farming activities.

Only fencing and livestock husbandry activities are permitted to be undertaken on these religious holidays. On the other hand, the very fascinating part of our study was that majority of the poor farmers interviewed reported to suffer from seasonal food shortages of 1-3 months in a year (mainly between crop planting and before harvesting). In general, it was observed that the religious holidays constrain labour available for cropping during the peak demand period, and therefore, directly or indirectly responsible for the current food insecurity problem in the study area.

4. Conclusions

Remote sensing and GIS analysis results showed a dramatic decrease in the area of grassland from 1975 to 2014, accompanied by an increase in the area of croplands and settlements in the same period. Rapid population growth and their demand for diverse products and soil fertility deterioration over time forced farming families to change part of their land to other forms of land use/cover. Declining soil fertility due to soil erosion and lack of financial capacity for its restoration leave majority of the household food insecure in general, poor households in particular. Therefore, future attempts in soil fertility management in the region should not only entail application of technologies that add nutrients to the soil, but also should be complemented by measures that reduce nutrient losses through runoff and soil erosion. Due to the proximity of the study area to major market i.e. Addis Ababa city, building public-private partnerships around market-oriented barley production can be an entry point for encouraging investment in use of external nutrient inputs to improve soil fertility and boost agricultural productivity. The availability of too many religious holidays in the study area also contributes directly or indirectly to the current seasonal food shortages of the community. The government/local officials should intervene by discussing the issue with religious leaders and community elders to reduce the number of religious holidays in the area. In general, the results of our study provide compelling evidence that the local community in the study area is beset with a host of social, economic and institutional challenges which need to be properly addressed to come to grips with problems of food insecurity. Therefore, we recommend the involvement of interdisciplinary stakeholders and policy framework to curb these dire situations, looking from both biophysical and social perspectives. Particularly, enabling and capacity building of the local people with different agricultural technologies not only help them become food secure but also greatly contribute to environmental protection in the future.

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Chapter II

Comparison of soil quality parameters under different land use/cover and management systems in the central highlands of Ethiopia

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Comparison of soil quality parameters under different land use/cover and management systems in the central highlands of Ethiopia

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Abstract

In response to the prevailing low soil pH and associated problems in the highlands of Ethiopia, conversions of natural vegetations and agricultural lands to other land use and management systems have been in practice since several decades. We compared several soil physical, chemical and biological properties under three land use (grassland, cropland, *Eucalyptus*) and two management systems (limed land and fallow land) all existing adjacent to each other. Results showed that soil quality was higher under grassland than under the other land uses and management systems considered. A reduction of 53, 45, 46 and 47% in soil organic carbon (SOC) was observed under cropland, *Eucalyptus*, limed and fallow lands, respectively. However, cropland, *Eucalyptus* and limed showed similar values for most of the soil chemical properties studied. Soil microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) were also significantly higher under grassland, and lower under fallow land. Depth of sampling only affected available phosphorus, Mg^{2+}, exchangeable acidity, ratios of MBC to SOC and MBN to total nitrogen (TN). Our results suggested that SOC, MBC: SOC and MBN: TN could be considered to assess functional capacities of soils under soil acidity conditions in the highlands of Ethiopia.

Keywords: Low pH, Land use, fallowing, *Eucalyptus*, Ethiopian highlands

1 Introduction

Land use change trends in many developing countries are both extremely rapid and the direction of changes and rates are in flux (Olson et al., 2012). In the Ethiopian highlands, the rapidly growing population with heavy reliance on subsistence type of agriculture has forced farmers to unwise use of land resources leading to subsequent deterioration of functional capacity of soils. When soils come under increasing pressure to maintain a range of ecosystem services, there is interest in how soils change over time in response to factors such as change in land use (Tye et al., 2013). Particularly the areas with altitudes >1800 m.a.s.l., here after referred to as the central highlands of Ethiopia, were once majorly covered with tropical type meadow vegetation. In the last fifty years, however, land use changes have been more rapid due to population growth and demand of the local people for diverse products with its negative consequence on soil resources. For example, due to the prevailing soil acidity problem, the highland ecology is known to have undergone a series of changes in land use/cover types. Acidity produces complex interactions of plant growth-limiting factors involving physical, chemical, and biological properties of soil. Land use change (e.g. grassland to cropland, infertile cropland to *Eucalyptus* plantations) and change in management (fallowing croplands and liming of croplands) are being practiced as alternative strategies to mitigate the negative effects soil acidity. The so called "fallowing", the resting state of agricultural field (Szott et al., 1999) is common due to its cheaper practice to restore soil fertility. However, due to population pressure in the highlands and their demand for diverse products, fallow periods have become as short as 18 months. Any change in land use/cover or management system has a direct impact on food production and alternative economic activities (Amare et al., 2011). Since 85% of the population relies on subsistence type of agriculture, population growth affects agricultural land use. As a consequence, there is a rapid decline in natural vegetation areas, dwindling of per capita land available for cropping, expansion of farming to marginal lands and steep slopes leading to soil quality degradation.

The need for understanding and assessing soil quality is getting increasingly important because of growing public interest in determining the effect of management practices on the sustainability of the soil resource base (Rongjiang et al., 2013). Soil quality assessment was envisioned as a tool to help balance challenges associated with (1) increasing world demand for food, feed, and fiber, (2) increasing public demand for environmental protection, and (3) decreasing supplies of nonrenewable energy and mineral resources (Pesek, 1994; Doran et al., 1996). The capacity of soil to function can be evaluated by measuring some selected physical, chemical and biological properties, also known as soil quality indicators. In this context, several soil quality assessment have been conducted in different regions under various cropping conditions including: organic and conventional farming (Fliessbach et al., 2007), tillage and residue management (Sharma et al., 2005; Imaz et al., 2010), crop rotation (Mubarak et al., 2005; Aziz et al., 2011), soil quality around mining areas (Shukla et al., 2004), manure application and burning (Lee et al., 2006). However, concepts of soil quality under tropical conditions are still insufficient and missing because these concepts were mainly developed for temperate climates and cannot be applied to tropical conditions (Sánchez et al. 2007). The most effective soil quality indicators will probably vary according to region, climate, and cropping systems (Parr et al., 1992). Therefore, there are many factors that affect soil quality indicators in tropical regions, including but not limited to, soil and vegetation type, socio-economic conditions of the users, current and past land use practices. Many studies (e.g. Lepsch et al., 1994; Shukla et al., 2006; Yimer et al., 2007, 2008) indicate that conversion of native vegetation into cultivation in tropical regions causes important changes in soil properties, including loss of organic matter, increase in soil bulk density and decreases in exchangeable cations, pH and base saturation. Yimer et al. (2008) reported that land use change mainly through converting the natural vegetation into cropland and grassland in the highlands of Ethiopia influenced many natural phenomena and ecological processes, leading to a remarkable change in the soil properties. Such changes directly affect soil physical, chemical and biological processes such as soil water retention and availability, nutrient cycling, gas influx, plant root growth and soil conservation (Ashagrie et al., 2005; Emadi et al., 2008). As a result, apart from many development bottlenecks currently facing the highlands of Ethiopia, soil degradation in the form of soil acidification, soil salinization and nutrient transport through erosion, deteriorate the functional capacity of soils. Teklu et al. (2006) reported that soil quality degradation and reduced productivity as the main causes of wide spread poverty in the highlands of Ethiopia.

In the Ethiopian highlands, land use change has become an area of particular concern due to the rapid land conversion practices and its environmental consequences. Therefore, timely detection of land use change and its potential effect on soil quality parameters is an essential prerequisite to take appropriate restorative measures, efficient land use planning and resource management. To our knowledge, however, there is no or insufficient knowledge on the effect of soil acidity-induced land use changes and management systems on soil quality in the highland agro-ecosystems of Ethiopia. The objectives of this study were: 1) to assess and compare the changes in soil biological, chemical and physical properties under different land uses (grassland, cropland and *Eucalyptus*) and management systems (limed land and fallow land); 2) appraise whether short-term fallowing would help improve important soil quality parameters such as SOC, MBC and MBN and; 3) investigate whether the soil quality parameters differ due to depths of soil sampling.

2 Materials and Methods

2.1 Description of the study site

The study was conducted in Wetabecha Minjaro peasant associations, commonly known as Bedi, located in western central highlands of Oromiya regional State, Ethiopia. It is situated at 9° 05′ 55″ N, 38° 36′ 21″ E, at an altitude of 2600 m.a.s.l (Fig. 1). According to the local agro-climatic classifications, the study area belongs to moist highland agro-climatic zone with two rainy periods; the main rainy season which occurs from June to mid September and the short rainy season extending from February to April. The area receives about 1100 mm of rainfall annually. The mean monthly maximum and mean monthly minimum temperatures are 23.3°C and 8.7°C, respectively (Fig. 2). The soils are classified as Nitisols with deep, red, well- drained tropical soils (IUSS, 2006). These soils are characterized by thick solum with high contents of weathered minerals. In terms of topography, all land uses of the study site are located within similar topography and altitude. Hence, there was no variation in terms of soil types and potential vegetation cover types of the area. However, in the past several decades, tropical meadow type grassland vegetation and shrub lands were the dominant type of vegetation. Now, such types of vegetations are gradually replaced by croplands and *Eucalyptus* plantations (Temesgen et al., 2014).

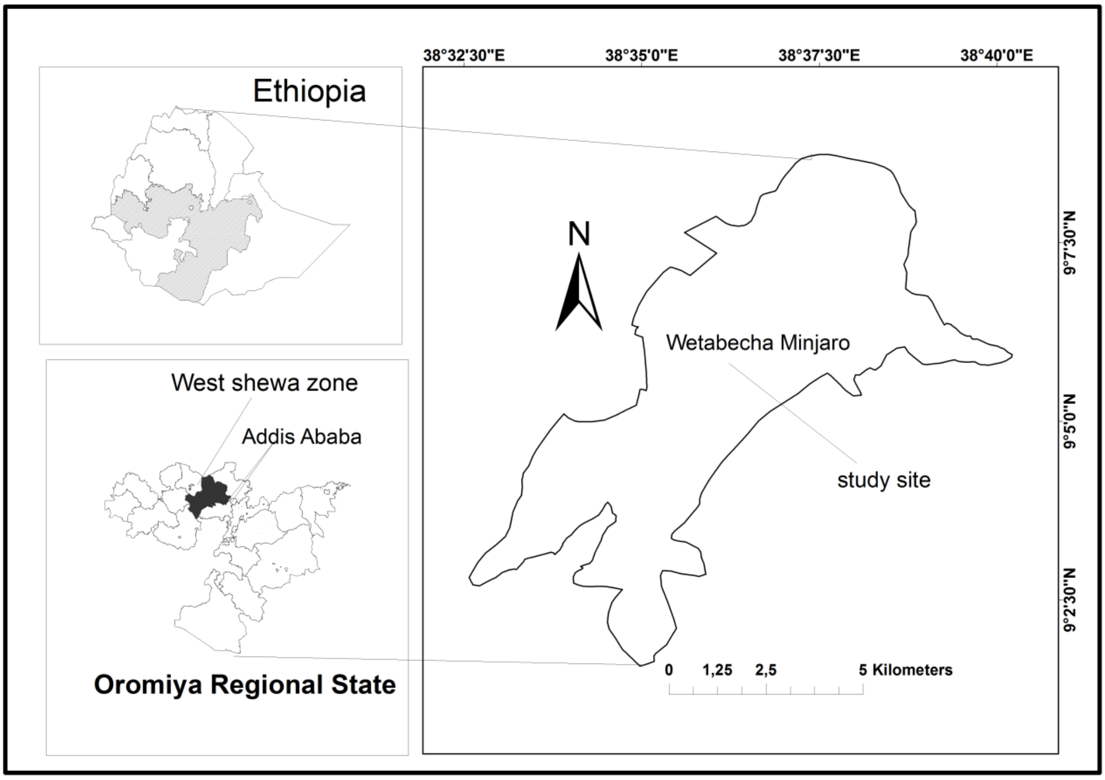

Fig. 1 Location map of the study area.

The grassland mainly composed of grasses and very few legumes such as, *Schizachyrium* sp. *Paspalum notatum*, *Axonopus sp.*, *Desmodium* species.

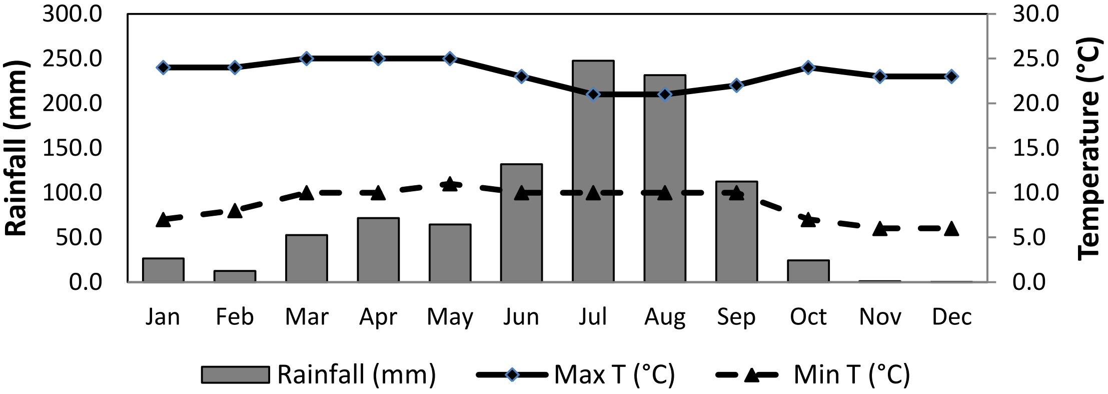

Fig. 2 Mean monthly maximum and minimum temperature and mean monthly precipitation for the study site, (mean of 10 years, 1998- 2007) taken from the nearest meteorology station, Holetta Agri. Research Center.

Agriculture is the main source of livelihood for the community and subsistence type mixed crop-livestock systems characterize the farming system. Barley is the only major cereal crop grown in the region.

Communal/private *Eucalyptus* plantations are widespread and literally native forest species is non-existent that satisfies the high demand for construction and biomass energy.

2.2 Experimental design and sampling

A land use/cover survey study carried out in 2012 in relation to this study identified three major land uses and two management practices, namely; grassland (open grazing lands dominated by natural tropical grasses), cropland (barley monoculture without liming), *Eucalyptus* plantations (6-7 years old); fallow land (18 months of resting period) and limed land (lands reclaimed by liming to counteract the negative effect of soil acidity). Descriptions of land uses and management systems are given in Table 1. Identifications and classifications of the three land uses were supported by interpretation of aerial photographs and satellite images of the study area (Temesgen et al., 2014). However, the two management practices were identified by collecting information from land owners and government development agents. The sites had similar altitudes, slopes and soil types.

Table 1. Descriptions of land use/management systems in the study area.

Land use/management	Brief descriptions
Cropland	Areas that were under barley cultivation at the time of soil sampling; no history of liming
Grassland	Huge areas of land with no cropping practice, trees or settlements; totally dominated by natural grasses and used for grazing
Fallow land	Abandoned previously croplands from cultivation for a period of 18 months to restore soil fertility
Limed land	Lime applied fields to counteract soil acidity and its associated problems
Eucalyptus plantations	Areas occupied by *Eucalyptus globulus* plantations (6 -7 years of age)

In July, August and September, 2012, eight sites where selected with the following criteria: 1) grassland, cropland, *Eucalyptus* plantation, fallow land, and limed land that were located in adjacent areas; 2) previous land use must grassland based on the individual interviews and by comparing satellite images between 1986 and 2014; 3) for soil sample collection, the area of each land use and management practice should be greater or equal to half a hectare. Soil samples from limed lands were collected after 3 years of liming based on exchangeable acidity (EXa) of the area (Kamprath, 1984). The exchangeable acidity of the area was 1.32 $cmol_+ kg^{-1}$ of soil, and the corresponding lime applied was 1.65 Mg ha^{-1}. Samples were collected from two depths; 0-10 cm and 10-20 cm for all land use types. Each of the soil samples consisted of ten sub-samples in a composite, which were collected from a 10 x 10 m demarcated plots. A total of 80 soil samples (8 sites * 5 land use/manegement * 2 depths) were collected in randomized complete block design for laboratory analysis. Samples was gently sieved through a 2 mm mesh to remove stones, roots, and were sealed in plastic bags before analysis. Soil chemical and biological parameters were analysed in duplicates. Soil biological analyses were done by wetting and keeping for one week of acclimatization period at room temperature.

2.3 Soil physical and chemical analysis

Soil bulk density (BD) of the top layer soil was determined using a 5 cm diameter and 5cm height metal cylinder. Field capacity (FC) was determined by saturating soil samples with water and allowing them to drain for 24 hours. After oven drying at 105°C, moisture loss was expressed as percentages. Permanent wilting point (PWP) was estimated from soil samples equilibrated at a pressure of 15 bars on a pressure plate (Cassel and Nielsen, 1986). Hence, plant available water (PAW) was determined by the difference between field capacity and permanent wilting point in percentage. Soil texture analysis was performed using hydrometric method (Bouyoucos, 1962). The USDA particle size classes viz. sand (2.0-0.05 mm), silt (0.05-0.002 mm) and clay (<0.002 mm), were used when classifying textural classes. Soil pH was determined by potentiometric methods at a 1:2.5 soil to water ratio. Soil organic carbon was determined by the Walkley-Black oxidation method (Walkley and Black, 1934). Total nitrogen (TN) by Kjeldahl digestion method (Bremner and Mulvaney, 1982), and Available phosphorous (AvP) was determined using Olsen's extraction method (Olsen and Sommers, 1982). Exchangeable bases (Na^+, K^+, Ca^{2+}, and Mg^{2+}) were measured by atomic absorption spectrophotometer after extraction by ammonium acetate (Black et al., 1965). The cation exchange capacity (CEC) was determined by extraction with ammonium acetate (Chapman, 1965). Exchangeable-titratable acidity was determined in 1 M KCl extracts titrated with 0.01 M NaOH.

2.4 Biological properties

Microbial biomass carbon and microbial biomass nitrogen (MBN) were estimated by the classical chloroform fumigation extraction method (Brookes et al., 1985; Vance et al., 1987). Twenty five grams of dry weight-equivalent soil samples were fumigated with $CHCl_3$ for 24 hours in a dark in vacuum desiccators in two duplicates. After removal of chloroform by three repeated evacuations, the soil samples were extracted by 0.5 M K_2SO_4 (using a soil: extractant ratio of 1:4). Similarly, the unfumigated controls were also subjected to 0.5 M K_2SO_4 extraction. After shaking for 30 minutes in automatic shaker, the extracts were filtered through Whatman filter paper (N^o.42). The filtrates were analysed for organic C and total N by using SKALAR TOC/TN automatic analyzer. The difference in the C content of the extracts from fumigated and unfumigated samples was converted to biomass-C by dividing the value obtained by a factor (K_C) of 0.45 (Vance et al., 1987). The results were expressed as µg g^{-1} of oven-dried soil. The difference in the content of N of the extractants was also converted to biomass nitrogen by dividing the value obtained by a factor (K_N) of 0.54 (Brookes et al., 1985).

2.5 Statistical analysis

Analysis of variance (ANOVA) was performed to evaluate the main effects of land use/management, depth, and their interactions using SAS (version 9.1). A linear mixed model analysis with repeated measurements, considering two between-subjects factors (site with eight levels and land use with five levels) in a main effects design, and one within-subjects factor (depth with two levels). The mathematical formulation of the model was given by:

$$Y_{ij;k} = \mu + \alpha_i + \beta_j + \gamma_k + \beta\gamma_{jk} + \varepsilon_{ij;k}$$

with i=1,…,8 for the sites, j=1,…,5 for the land use/management and k=1,2 for the two depths, and being:

$Y_{ij;k} =$ observed value of the dependent variable for the land use j at depth k in site i.

$\mu =$ general mean effect; $\alpha_i =$ main effect of the site I; $\beta_j =$ main effect of the land use/management j; $\gamma_k =$ main effect of the depth k; $\beta\gamma_{jk} =$ interaction effect of the land use j with the depth k; $\varepsilon_{ij;k} =$ random error in the dependent variable for the land use j at depth k in the site i.

The assumptions for the model were:

- $\varepsilon_{ij;k} \rightsquigarrow N(0, \sigma_k^2)$, with σ_k^2= random variance for errors at depth k.
- $Cov(\varepsilon_{ij;k}, \varepsilon_{i'j';k'}) = \begin{cases} \omega & \text{if } i = i', j = j' \; and \;\; k \neq k' \\ 0 & \text{if } i \neq i' \; or \;\; j \neq j' \end{cases}$, with ω=covariance between

errors at different depths. Therefore, the model included three variance parameters, which were estimated using the restricted maximum likelihood method (REML). Finally, Tukey´s HSD procedure was used for multiple comparisons of mean physical, chemical and biological properties of the soil under different land use systems.

3. Results

3.1 Soil physical properties

Mean values of percent sand, silt and clay for each of the five land use and management under two sampling depths are summarized in Table 2. Results revealed that the soil was majorly composed of silt and clay, clay being the most representative fraction. It represents about 46% in the top 0-10 cm and 48% in the 10-20 cm soil profile. Relative to the other four land uses, soils under fallow land had lower sand content. Percent sand under the other four land uses (grassland, cropland, *Eucalyptus* and limed lands) did not differ from each other. Grassland had lower clay content relative to fallow lands, *Eucalyptus*, limed lands and croplands. Analysis of variance showed that depth of sampling had significant effect on soil texture. Soil samples from 0-10 cm had higher silt content as compared 0-10 cm. However, clay content was significantly higher ($p<0.05$) in 10-20 cm soil profile. Sand content was not significantly affected by depth of soil sampling.

Table 2. Mean values of sand, silt and clay content (%) for land use and management systems at two depths.

	Soil texture (%)			
LUM	Sand	Silt	Clay	n
Grassland	14.69a	43.75a	41.56b	16
Cropland	13.59a	39.22a	47.19a	16
Eucalyptus	10.94a	38.13b	50.94a	16
Limed land	13.91a	39.38a	46.72a	16
Fallow land	8.59b	41.41a	50.00a	16
S.e	0.94	1.18	1.16	
Depth (D)				
0 -10 cm	11.81ns	41.75a ± 0.62	46.44b ± 0.51	40
10 -20 cm	12.88ns	39.00b ± 0.69	48.13a ± 0.76	40
ANOVA				
LUM	***	*	***	
Depth	ns	**	*	
LUM*D	ns	ns	ns	

†LUM= land use/management, different letters within a column represent significant differences between different land use and management systems (Tukey's HSD procedure). The analysis of variance for each factor and their interaction is reported, p <0.001***, p <0.01** and p <0.05, n= number of samples, S.e= standard error, ns= not significant

Mean values of BD ranged from 0.99 to 1.17 g cm^{-3} (Fig. 3). Bulk density recorded in grassland was significantly lower as compared to the other land uses and management. Similarly, grassland recorded significantly higher values of FC and PWP. Permanent wilting point recorded in 0-20 cm soil profile ranged from 14.7-19.5%; the highest being in grassland. The other land use and management systems were not significantly different from each other.

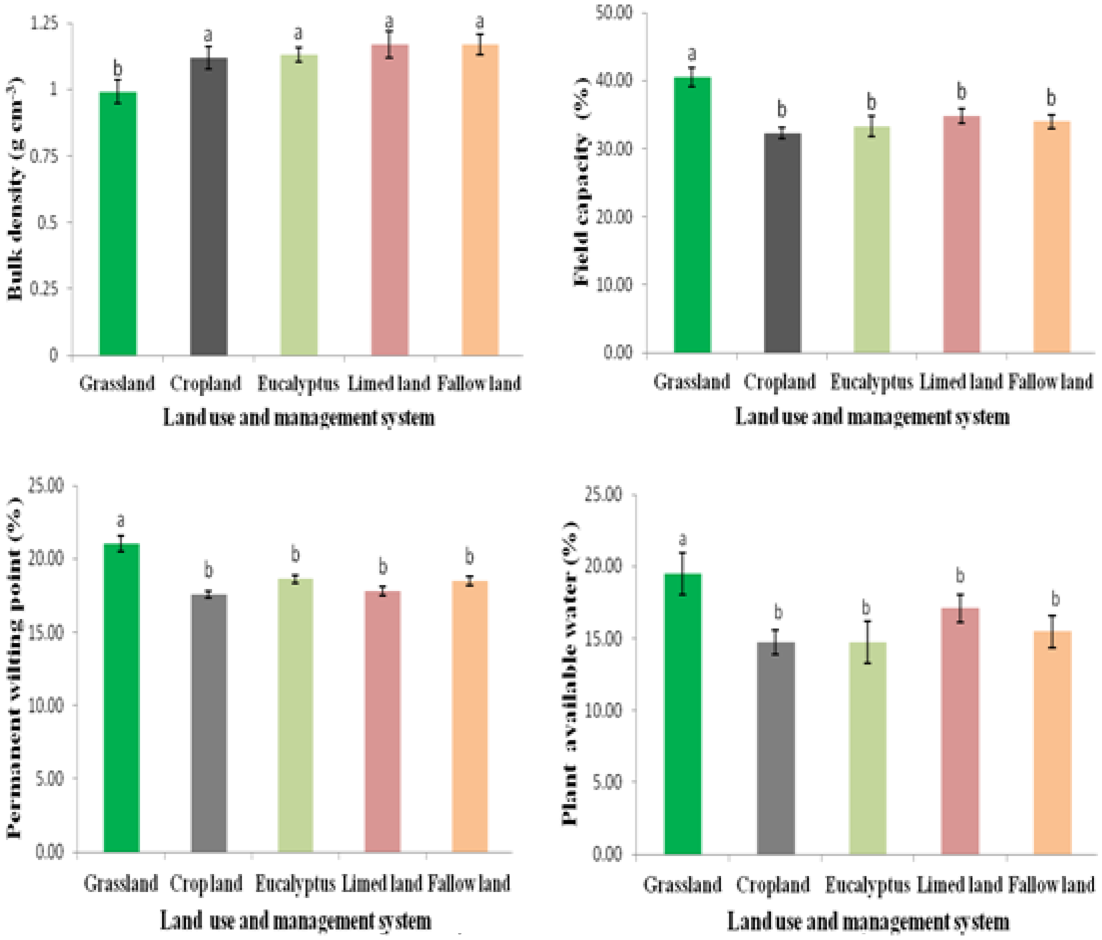

Fig. 3 Effects of land use and management systems on soil bulk density, field capacity, permanent wilting point and plant available water (n=8). Different letters represent significant differences between different land use and management systems (Tukey's HSD procedure).

3.2 Soil chemical properties

Mean values of soil chemical properties as affected by different land uses and management systems at two sampling depths are presented in Table 3. Soil pH ranged from 4.3 to 4.9 indicating strongly acidic nature of the soils. The soils under cropland, *Eucalyptus*, limed and fallow lands contained 53, 45, 46 and 47% less SOC than grassland soils. On average a decrease of 54% in TN concentration was also observed by land conversions from grassland to other land use types. However, land use change did not affect C/N ratio and Na^+ concentrations in the soil. Statistically, cropland, *Eucalyptus* and limed lands were similar for most of the soil chemical properties.

However, EXa was significantly higher under *Eucalyptus* plantations as compared to the other land uses and management systems. Similarly, concentrations of Ca^{2+} and Mg^{2+} were higher in grassland as compared to cropland, *Eucalyptus*, limed land and fallow land. The mean values of Ca^{2+} concentration in limed land, cropland, *Eucalyptus* plantation and fallow land were comparable, though slightly higher values of Ca^{2+} were observed in limed land. Mean values of K^{+} from fallow land were higher than the other land uses and management systems. Among soil chemical properties, depth of sampling only affected AvP, Ea and Mg^{2+} Available phosphorus was considerably higher in the surface soil (0- 10cm). Contrary to this, EXa and Mg^{2+} concentrations were found to be higher in 10-20 cm soil profile. Analysis of variance revealed no significant interaction between land use and depth of sampling for soil chemical properties.

Table 3. Mean values of soil chemical properties affected by different land uses and management systems (n=16) at two sampling depths (n=40).

		SOC	TN	AvP	K^+	Na^+	Ca^{2+}	Mg^{2+}	CEC	EXa
LUM†	pH (H_2O)	-----------%---------		---- mg kg^{-1}----	----------------------------------($cmol_+$ kg^{-1})--------------------------------------					
Grassland	4.9a	4.4a	0.4a	5.1	0.8b	0.2ns	12.6a	2.6a	23.2	1.2b
Crop land	4.6b	2.3b	0.2b	5.6	0.9ab	0.2	8.9b	2.0b	17.5	1.2b
Eucalyptus	4.5b	2.5b	0.2b	6.0	0.8b	0.2	8.6b	2.3b	18.0	2.3a
Limed land	4.7ab	2.4b	0.2b	4.9	0.7b	0.3	9.6ab	1.9b	18.6	0.9b
Fallow land	4.3c	2.3b	0.2b	4.4	1.0a	0.1	0.18c	1.2c	18.9	1.5b
S.e	0.06	0.13	0.01	0.73	0.05	0.03	0.96	0.23	0.82	0.26
Depth(D)										
0 -10 cm	4.6 ± 0.02ns	2.8ns	0.26ns	5.6a ± 0.33	0.9ns	0.22ns	8.0ns	1.9b ± 0.11	19.1 ± 0.41	1.3b ± 0.11
10 -20 cm	4.6 ± 0.35ns	2.7ns	0.25ns	4.8b ± 0.35	0.8ns	0.19ns	7.9ns	2.1a ± 0.11	19.4 ± 0.42	1.5.a ± 0.13
ANOVA										
LUM	***	***	***	ns	**	ns	***	**	***	*
Depth	ns	ns	ns	***	ns	ns	ns	*	ns	*
LUM*D	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

†LUM= land use/ management, SOC= soil organic carbon, TN= total nitrogen, AvP= available phosphorus, CEC= cation exchange capacity, EXa= exchangeable acidity. Mean values with different letters within the same column indicate significant differences (Tukey's HSD procedure). The analysis of variance for each land use is reported, p <0.001***, p <0.01** and p <0.05, S.e= standard error, ns= not significant

3.3 Soil biological properties

Microbial biomass carbon, MBN, MBC/MBN, MBC/SOC and MBN/TN were also affected by land use and management systems (Table 4). The highest values of MBC (763.7 µg g^{-1}) and MBN (87.8 µg g^{-1}) were recorded under grassland soils as compared to cropland, *Eucalyptus*, limed land and fallow land. Soils under fallows had the lowest MBC (190.8 µg g^{-1}) and MBN (23.1 µg g^{-1}). However, mean values of MBC and MBN recorded under cropland, *Eucalyptus* plantations and limed land did not show significant differences. Depth wise, MBC and MBN values were significantly higher in 0 -10 cm relative to 10 -20 cm. In this study, changes in the ratios of MBC/SOC and MBN/TN due to land use changes were quite considerable. Accordingly, the values of MBC/SOC were in the following order: grassland >limed land >*Eucalyptus* > cropland >fallow land. Whereas, MBN/TN followed the order: grassland >limed land >cropland >*Eucalyptus* >fallow land. As expected, the mean values of MBC/SOC and MBN/ TN were significantly higher in 0-10 cm as compared to 10-20 cm soil profile.

Table 4. Mean values of microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), MBC/MBN, MBC/SOC and MBN/TN as affected by different land uses and management systems (n=16) at two sampling depths (n=40).

	MBC	MBN		MBC/SOC	MBN/TN
LUM	------------µg g^{-1} soil	---------------	MBC/MBN	------------%	-------------
Grassland	763.7a†	87.8a	9.0ab	2.56a	2.89a
Cropland	342.6b	71.28a	5.7c	1.03cd	2.30b
Eucalyptus	345.0b	37.9bc	10.2a	1.44bc	1.69c
Limed land	335.7b	47.2b	7.4b	1.54b	2.31b
Fallow land	190.8c	23.1c	8.8ab	0.80d	1.06d
S.e	35.25	4.16	0.40	0.14	0.16
Depth (D)					
0 -10 cm	485.4a ± 21.48	67.2a ± 2.99	8.00ns	1.62a±0.09	2.31a ±0.10
10 -20 cm	305.8b ± 15.45	39.7b ± 2.40	8.42ns	1.32b ±0.09	1.78b ±0.10
ANOVA					
LUM	***	***	***	***	***
Depth	***	***	ns	*	**
LUM*D	ns	ns	ns	ns	ns

†LUM= land use/ management

Means within a column with different letters between different land uses and management systems indicate significant differences ((Tukey's HSD procedure). The analysis of variance for each land use and management is reported, p <0.001***, S.e= standard error, ns= not significant

4 Discussion

A basic assumption in this comparative study was that initially the soils were similar in each ecosystem. Change in land use and management markedly affected several soil physical, chemical and biological properties. Soil textural class is a permanent characteristic of a soil that gives a general picture of soil's physical properties. However, in this study the change in particle size distribution due to land use change might be related to frequent tiling of cropland, fallow land and limed lands, where there is a chance of soil profile mixing as compared to grassland. In Transmexican Volcanic Belt, Covaleda et al. (2011) also reported that land use changes affect the particle size distribution. The lower bulk density in grassland indicates increased pore space, allowing for increased aeration necessary for biological activity. Generally, soil quality was higher in grassland than the other land uses and management. The high amount of SOC (4.3%) observed relative to other land uses or management systems contributed to the higher CEC in grassland. In the highlands of Ethiopia, deforestation and subsequent unsustainable agricultural management, as well as use of dung and crop residues for energy, have resulted in soil organic matter and nutrient depletion, hydrological instability, reduced primary productivity, and low biological diversity (Solomon et al., 2002; Mulugeta et al., 2005).

Grassland in our study area includes tropical type grasses and herbaceous vegetations which resulted in a higher litter input compared to the other land uses and management systems. In grassland soils, much of the litter input is from root biomass (Tate et al., 2000). Therefore, greater return of plant litter to soils and high root biomass of grasses could be the reason for the higher SOC in grassland. For example, in managed grasslands, between 60% and 90% of the ingested plant biomass is returned to soil in the form of manure (Haynes and Williams, 1993; Wells and Dougherty, 1997). Thus, grazed grasslands contain little plant litter (thatch), but a significant amount of SOC and TN in the soil (Bardgett et al., 1996). The lower values of SOC in other land use systems could be due to less physical protection, because tillage periodically breaks up macro-aggregates and exposes previously protected organic matter (Islam and Weil, 2000). Tripathi and Singh (2009) also showed cultivation of soil previously supporting natural vegetation could lead to considerable losses of soil organic matter and microbial biomass. Soil physical, chemical and biological parameters showed that the lowest soil quality was observed in fallow land, and it might be attributed to the current management practices in the study area. Fallow fields are considered as grazing grounds for different species of livestock even though the primary purpose of fallowing by individual farmers is to restore soil fertility. In addition, crop residues are removed for domestic use, either as a source of fuel or animal feed. Such practice leaves the land bare and exposes it to surface run-off during rainy season. Many studies (e.g. Cai and Qin, 2006; Hati et al., 2007; Lemke et al., 2010) have shown that increases in SOC levels was directly related to the amount of organic residues added to soils. Therefore, the lowest soil fertility status (low values of pH, SOC, AvP, Mg^{2+}, Ca^{2+}, MBC and MBN) in fallow land was due to removal of crop residues and the washing away of nutrients by intense rainfall during fallow period.

The study clearly demonstrated that applications of lime significantly raised soil pH, and drastically reduced exchangeable acidity. When lime is added to acid soils that contain high aluminum and H^+ concentrations, it dissociates into Ca^{+2} and OH^- ions. The hydroxyl ions will react with hydrogen and aluminum ions forming aluminum hydroxide and water, thereby increase soil pH in the soil solution. Numerous authors have reported decreases of Al in the soil solution as well as in the exchange complex upon (Prado et al., 2007; Álvarez and Fernández, 2009). However, highly weathered acid soils in the study area would not recover rapidly after short-term fallow periods of 18 months. Similar to this finding, short-term fallow (four years) in Senegal did not increase SOC or nutrient content (Masse et al., 2004). On the other hand, even though, it is generally believed that plantations of *Eucalyptus* bring about a decrease in soil fertility, the absence of significant variation between *Eucalyptus* and cropland/limed lands in most of the soil physical and chemical parameters is not clear, and needs further investigation. However, Danju et al. (2012) reported restoration of soil fertility following plantation of *Eucalyptus grandis* in south-western China. In their study, they found that SOC content, C to N ratio, and MBC and MBN concentrations showed an initial phase of decline and then increased significantly over time in the upper soil layers of *E. grandis* plantations aged from 1 to 4 or 5 years. Similarly, Tilashwork (2009) also reported that soils under cropland and *Eucalyptus* did not vary significantly in texture, bulk density, organic matter, pH, exchangeable K and available water content in the highland of north western Ethiopia.

Soil microbial biomass and its related parameters such as MBC/SOC and MBN/TN have been used in comparing different land use types and are considered as early indicators of soil quality attributes, particularly when comparing lands under different agricultural uses (Chen et al., 2010; Kaschuk et al., 2010). In this study, differences in MBC, SOC, MBC/SOC, MBN and TN for the five land use and management systems were observed. The most important biological soil properties such as MBC/SOC and MBN/TN showed lower values in fallow lands and croplands relative to grasslands or limed lands. Similar to this result, cultivation of soils in the central highlands of Mexico with maize reduced MBC, and Reyes-Reyes et al. (2007) reported that converting soil under natural vegetation to arable soil was not only detrimental for soil quality, but also unsustainable when organic matter input is limited. The ratios of MBC to SOC has been suggested as a sensitive indicator of soil organic matter changes (Anderson and Domsch, 1989; Sparling, 1992), partly because the ratio will normalize some of the variability caused by temporal fluctuations in microbial biomass (Rice et al., 1996). A low MBC/SOC indicates a reduced pool of available carbon in soil (Klose et al., 2004). Therefore, this work suggested that the ratio of MBC to SOC and MBN to TN could be useful tools to assess biological soil quality differences due to the conversion of grasslands to other land use and management systems in highly weathered acidic soils of the central highlands of Ethiopia. However, we cannot ascertain the universality of these results across a wide range of acidic soils due to variation in climate, soil types and land use and management systems.

5 Conclusions

As evidenced from soil physical, chemical and biological properties, conversions of grasslands to either cropland or *Eucalyptus* plantations or fallowing in the central highlands of Ethiopia deteriorate the functional capacities of soils. Particularly, the lower values of biological attributes observed in these land uses and management system could be an early indication of soil quality deterioration. Soil organic carbon, the ratio of MBC to SOC and MBN to TN could be considered as the three most important bio-chemical parameters to assess functional capacities of soils for soil acidity affected areas in the central highlands of Ethiopia. Therefore, integration of these parameters with soil chemical properties is considered to be more useful than only chemical/physical properties in describing soil quality of the area. The traditional way of restoring soil fertility by fallowing land after a cropping period of 18 months would jeopardize further the functional capacities of soils to irrevocable levels in the long-term. These results, therefore, seriously dispute the current short-term fallowing practice by small-scale farmers in the study area. Hence, improving soils conditions in the current land use system in sustainable way requires improving and maintaining soil productivity. This includes crop residues retention in crop fields after harvesting, avoiding bare fallows and judicious application of lime along with phosphate fertilizers and/manure would be sustainable options for the current soil acidity problem that has resulted in land use change.

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Chapter III

Soil carbon mineralization kinetics as influenced by changes in land use and soil management in the central highlands of Ethiopia

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Soil carbon mineralization kinetics as influenced by changes in land use and soil management in the central highlands of Ethiopia

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Abstract

To understand carbon mineralization processes, a 62-day laboratory incubation experiment was carried out using soil samples collected from five adjacent land uses and management systems (grassland, cropland, *Eucalyptus* plantations, limed land and fallow land) in the central highlands of Ethiopia. Total carbon mineralized and the mineralization rates were consistently higher in grasslands both in 0-10 cm and 10-20 cm as compared to the other land uses and management systems. The cumulative CO_2 release followed the order: grassland> cropland> *Eucalyptus*> fallow land> limed land. Among six kinetic models tested, a first-order model [$C_t = C_o (1-e^{-kt})$] was selected and fitted well to describe C mineralization of the experimental data. Grassland in both depths and cropland in the surface layer (0- 10 cm) had significantly higher mean values of potentially mineralizable carbon (C_o) as compared to each depth in different land uses. Metabolic quotient (qCO_2) observed in limed land and fallow land in 10 -20 cm depth was significantly higher than the other land uses and management systems. Similarly, soils under grassland had significantly ($p<0.001$) higher soil organic carbon (SOC) and microbial biomass carbon (MBC) than the adjacent cropland, *Eucalyptus* plantations, limed land and fallow land. SOC and MBC were positively correlated with C_o, k and C_o*k, and negatively correlated with $t_{1/2}$ and qCO_2. Hence, SOC, MBC, C_o, C_o*k and qCO_2 were better discriminators among different land uses and management systems, and therefore, could be used as a sensitive indicators of ecosystem change in the study area.

Keywords: Microbial biomass, Carbon mineralization, Elevated CO_2, Labile carbon

1. Introduction

Conversions of natural vegetations to other land use and soil management systems are often accompanied by changes in soil properties and have environmental implications. Such changes in land use and agricultural practices have affected soil carbon pools and contributed to increased atmospheric CO_2 concentrations (Smith and Conen, 2004). Soils play an important role as a sink or source of large quantities of carbon to the atmosphere through soil respiration. Globally, C losses from land use changes have been steadily increasing over the last century, approaching rates of about 1.4 Pg C yr^{-1} (Le Quéré, 2010). Therefore, understanding the manifestation of the biological activities of soils from different land uses and variations occurring in the organic carbon pool has paramount importance in sustainable management of ecosystem. Soil respiration, which involves the emission of CO_2 during the decomposition of organic matter carried out by the metabolic activity of the plant roots and soil microorganisms, is a fundamental process in the carbon cycle and represents the main pathway whereby carbon fixed by the soil is returned to the atmosphere (Fernandez et al., 2006). Thus, even small changes in soil respiration may greatly influence atmospheric carbon and heat balance (Veenendaal et al., 2004; Kane et al., 2005). Consequently, soil respiration has received considerable attention in recent years because of the release of large quantities of CO_2 from the soils to the atmosphere. Therefore, assessing the impact of land use changes on soil respiration is of vital significance to understand the interactions between belowground metabolism and regional carbon budgets (Sheng et al, 2010). Particularly, the description of the dynamics of C mineralization in incubation studies by fitting the experimental data to kinetic models may be of great interest for the prediction of the ability of soils in supplying potentially mineralizable organic carbon and, more generally, for the organic matter balance (Alessandro et al., 2014).

Previous reports have found that a zero-order equation more adequately describes C mineralization (Seyfried and Rao, 1988). However, a first-order equation has been frequently used to describe the carbon mineralization process of SOC (Dossa et al, 2009; Aulen et al, 2012). Alternatives to the simple first-order model, Delphin (1988) successfully used a two-part parabolic equation that assumes soil organic carbon can be divided into two components, a labile fraction and a more recalcitrant one, each decaying exponentially at rates characterized by its own constant (k and h, respectively). Putting the above points in view, numerous field and laboratory incubation studies have been conducted worldwide (Campos et al., 2006; Davidson et al., 2006; Sheng et al., 2010; Fazle et al., 2014). However, most of these studies on the effects of land use changes on soil respiration have only focused on temperate environments (Carlisle et al., 2006; Kellman et al., 2006, Alessandro et al., 2014) and tropical Latin America (Salimon et al., 2004; Campos, 2006). On the other hand, soil microbial activities, populations and communities are governed by site characteristics, such as soil type and texture, temperature, moisture or pH. It also varies with type of vegetation and its management practices, environmental conditions and land use types (Frank et al., 2006).

In the highlands of Ethiopia, where low soil pH and associated problems are among the major impediment to agricultural productivity, conversions of natural vegetations/agricultural land to other land use and management systems have been in practice since several decades. However, the native soil organic carbon dynamics in different land uses and its concomitant contribution to CO_2 fluxes have so far rarely been investigated, and virtually nothing is known about CO_2 emissions from different land uses and management syetems. Given that soil microbial parameters are commonly affected by land use, quantifying them can help evaluate the changes in soil microbial functions driven by changes in land use (Bastida, 2006). Therefore, the objectives of this study were: (1) to assess the C-mineralization potentials of soils from five adjacent land uses and management systems (grassland, cropland, *Eucalyptus* plantation, limed land and fallow land) by laboratory incubation; (2) to compare the effectiveness of some commonly used decay models for describing rates and amounts of C mineralization; (3) to evaluate selected soil microbial parameters and their relationships with the C mineralization parameters derived from the best model.

2 Materials and Methods

2.1 Site characteristics

Soil samples were collected from Wetabecha Minjaro, (9° 05′ 55″ N; 38° 36′ 21″ E) in the central highlands of Ethiopia. The area receives about 1100 mm of rainfall annually.

The mean decadal monthly maximum and mean decadal monthly minimum temperatures are 23.3 °C and 8.7 °C, respectively. According to the local agro-climatic classifications, it belongs to moist highland agro-climatic zone with two distinctive rainy periods; the main rainy season which occurs from June to September, and the short rainy season extending from February to April. The soils are classified as Nitisols with deep, red, well- drained tropical soils (IUSS, 2006). In these soils, soil acidity (pH< 5) and associated low nutrient availability are constraints to crop production.

2.2 Soil sampling and respiration measurements

In July, August and September, 2012, composite soil samples were randomly collected from eight sites encompassing five adjacent land uses and management systems (grassland, cropland, *Eucalyptus* plantation, limed land and fallow land) in two depths (0- 10 cm and 10- 20 cm), from plots of 10 x 10 m area in a complete random design. Besides using the eight sites as a replicates, samples were also replicated twice in the laboratory during incubation. The samples for *Eucalyptus* plantations (*Eucalyptus globulus* L.) were collected from plantations that were 6 -7 years old. In this context, fallow land was referred to mean a resting period of 18 months without crop cultivation. The samples from limed lands were collected after three years of liming acid soils. Prior to analysis, all the samples were air-dried, thoroughly mixed and sieved at 2 mm, plant roots and other residues were removed from the samples. Soil particle size distribution was determined by hydrometric method (Bouyoucos, 1962). Soil pH was determined by using a pH meter in a 1:2.5 soil/water suspension, soil organic carbon by Walkley and Black method (Walkley and Black, 1934). Total nitrogen (TN) was analyzed by wet oxidation procedure of the kjeldhal digestion, distillation and titration method (Bremner and Mulvaney, 1982).

2.3 Microbiological analysis

For measuring microbial activity, thirty grams of dry soil samples were wetted to 60 % of water holding capacity and incubated in 0.5 L air tight jars at 28 °C. The CO_2 evolved was trapped in plastic vials containing 10 ml of 0.5 M NaOH. The moisture content was kept constant by weighing at each sampling date. The amount of CO_2 evolved was measured after 8, 18, 26, 36, 45, 54 and 62 days of incubation by titrating with 0.5 M HCl against a phenolphthalein indicator after precipitation with $BaCl_2$ (0.5 M). Soil microbial biomass carbon (MBC) and nitrogen (MBN) were determined by the chloroform fumigation extraction method, using 0.5 M K_2SO_4 as extractant (Vance et al., 1987). Carbon and nitrogen contents in the fumigated and non-fumigated extracts were determined using SKALAR FormacsHT total organic carbon analyzer for liquid samples. The metabolic quotient qCO_2 [(mg CO_2-C. h^{-1}. g^{-1} MBC] was calculated from respiration values with formula: qCO_2 = [(CO_2-C mineralized/MBC] (Anderson and Domsch, 1985). It is considered as an index of microbial efficiency in utilizing the available resources (high efficiency for low values of qCO_2).

2.4 Carbon mineralization kinetic models

Descriptive and graphical analyses of the CO_2 respiration values obtained during the 62 days incubation from different land uses and depths were carried out to detect anomalies. In addition, six different models were used to describe the CO_2 respiration (Table 1). They were obtained from the scientific literature. The models were tested to know which one was the best to our data. The convergence, the values of adjusted coefficient of determination ($R^2_{adj.}$), the squared sum error (SSE) and the mean squared error (MSE) were important criterions for choosing the best model. Model fitting were carried out with MODEL procedures of the SAS/STAT® statistical program (SAS Institute Inc., 2001).

2.5 Biochemical parameters related to organic carbon

Once the model was fitted, different parameters were determined to analyze: a) the potentially mineralizable C (C_o), b) the rate constant of carbon mineralization (k) that represents the slope of the curve, c) the initial potential rate of C minerlization (C_o*k), as the product between C_o and k, and d) the half-life time of carbon ($t_{1/2}$), that represents the time needed for half of the initial C to decay away necessary to reach a half of the maximum mineralization. A mixed model was applied in order to detect significant differences in the measured variables as a function of land uses and management systems in two depths. The depth was considered as a repeated measures factor. The statistical model was expressed as follows: [Eq. 1]

$$Y_{ij;k} = \mu + \alpha_i + \beta_j + \gamma_k + \beta\gamma_{jk} + \varepsilon_{ij;k} \quad \text{[Eq. 1]}$$

with i=1,…,8 for the sites, j=1,…,5 for the land uses and k=1,2 for the two depths, and being:

$Y_{ij;k}$ = observed value of the dependent variable for the land use j at depth k in site i.

$\mu =$ general mean effect; $\alpha_i =$ main effect of the site I; $\beta_j =$ main effect of the land use j; $\gamma_k =$ main effect of the depth k; $\beta\gamma_{jk} =$ interaction effect of the land use j with the depth k; $\varepsilon_{ij;k} =$ random error in the dependent variable for the land use j at depth k in the site i. The assumptions for the model were:

- $\varepsilon_{ij;k} \sim N(0, \sigma_k^2)$, with σ_k^2= random variance for errors at depth k.
- $Cov(\varepsilon_{ij;k}, \varepsilon_{i'j';k'}) = \begin{cases} \omega & \text{if } i = i', j = j' \text{ and } k \neq k' \\ 0 & \text{if } i \neq i' \text{ or } j \neq j' \end{cases}$, with ω=covariance between

errors at different depths. Therefore, the model included three variance parameters, which were estimated using the restricted maximum likelihood method (REML). Finally, Tukey´s HSD procedure was used for multiple comparisons of mean physical, chemical and microbiological properties of the soil under different land use systems.

3 Results and discussions

3.1 Soil respiration rates

Carbon dioxide-C mineralization rates during the 62-days incubation period followed similar general pattern across in all land uses and management systems; an initial increase at the beginning of the incubation followed gradual decreases as the incubation time progresses (Fig. 1 and 2).

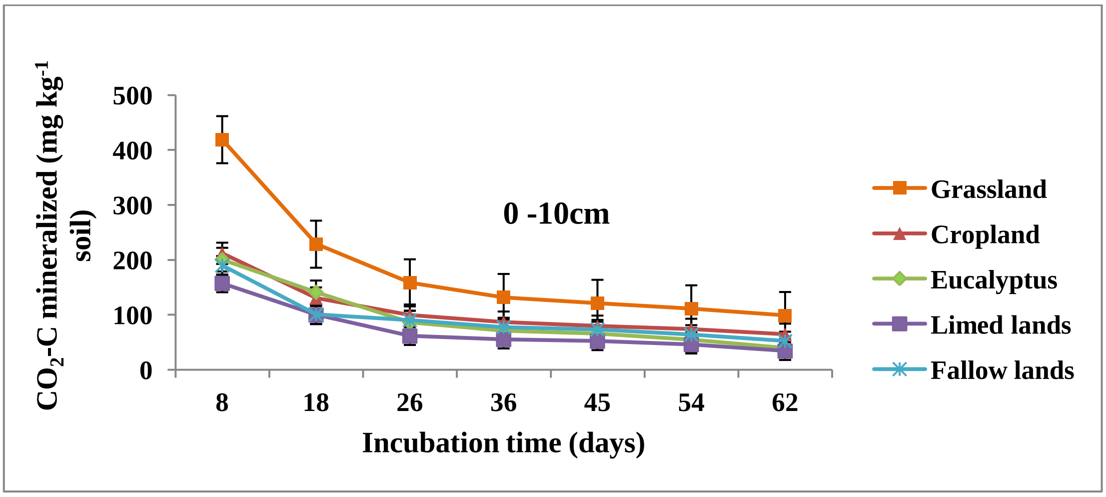

Fig. 1 Carbon mineralization rates for different land uses during 62 days of laboratory incubation with standard error (n=8).

The higher amount CO_2 evolved at initial stage indicate a rapid depletion of an easily mineralizable fraction (labile SOC) while the slow-steady phases in which mineralization declined to a fairly constant rate indicate that the most active fraction has exhausted and the resistant and stable fraction of SOC was being mineralized (Wander et al. 1994).

The CO_2 release in 0 -10 cm followed the order: grassland> cropland> fallow land> *Eucalyptus*> limed land. However, in 10 -20 cm the order was; grassland> fallow land > *Eucalyptus*> limed land> cropland. In grassland, the emission was higher in both 0 -10 cm and 10-20 cm than the other land uses and management systems. The higher CO_2 release in grassland could be attributed to the higher organic matter content as compared to cropland, *Eucalyptus*, fallow land and limed land. Mukhopadhyay and Maiti (2014) reported higher CO_2 flux under grassland as compared to afforested land because of higher root density in grasslands, which conserves moisture and enhances root and microbial respiration. Similarly, Chen et al. (2010) also reported significantly higher microbial respiration in grasslands as compared to other land uses in North Eastern Tibetan plateau. High rates of soil respiration can occur as a result of large pool of labile C substrates or rapid oxidation of smaller pool (Islam and Weil, 2000). Thus, high basal respiration may indicate ecological stress and degradation or a high level of ecosystem productivity.

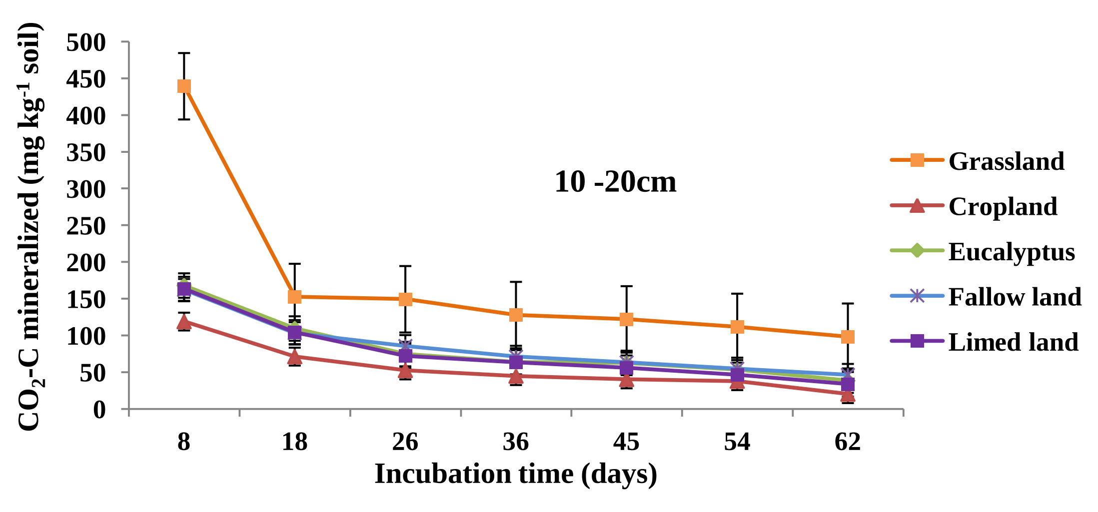

Fig. 2 Carbon mineralization rates for different land uses during 62 days of laboratory incubation with standard error (n=8).

3.2 Cumulative CO_2-C mineralization

The cumulative CO_2 evolved during 62 days incubation period as affected by different land uses and management under the two depths is presented in Fig. 3. In general, at any given time, cumulative CO_2 evolved was significantly greater in grassland as compared to other land uses and management systems. The cumulative CO_2 production was in the order: grassland> *Eucalyptus*> fallow land> crop land> limed land over the entire incubation period. The cumulative amount of CO_2 released from surface (0-10 cm) and sub-surface (10-20 cm) soil samples were also greater in grassland (Fig. 3). However, the four land uses, i.e. cropland, fallow land, *Eucalyptus* and limed land were not significantly ($p<0.05$) different from each in both depths, except in cropland, where significantly lower cumulative CO_2 was recorded in 10- 20 cm soil depth.

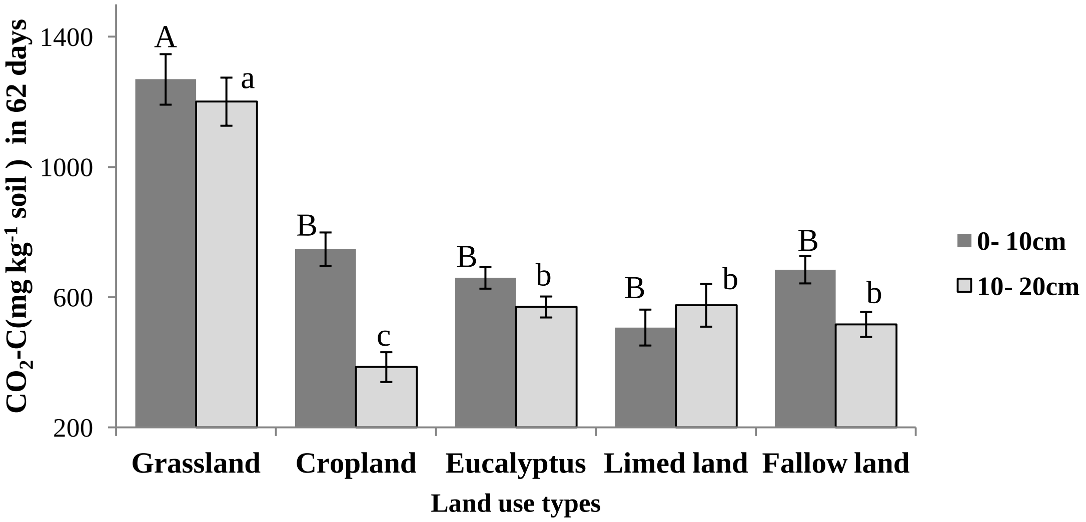

Fig. 3 Cumulative CO_2 evolved at the end of 62 days of laboratory incubation for the different land uses and soil depth. Bars are standard error of the mean (n=8). Similar letters above the vertical bars within similar depth across land uses denote no significant differences at $p<0.05$. Upper case letters refer to 0- 10 cm and lower case letters refer to 10- 20 cm depths.

According to Frank et al. (2006), higher SOC and MBC lead to higher soil respiration, and lowest values of soil respiration corresponded to sites with lowest MBC. The relatively greater C to be mineralized in grasslands indicates that grasslands contained easily decomposable organic matter than the other land uses and management systems.

This finding is in line with the results of Haiqing et al. (2009), where they reported higher mineralized carbon under grassland and reduced tillage due to less disturbance, promotion and stabilization of aggregates compared to plowed soils in Southern Germany. Nonetheless, the decrease in the C mineralization in 10- 20 cm might be due to lower organic carbon content and relatively smaller number of microbes as soil depth increases. These results agree with the reports of Taylor (2002), where reduced activities of microbial and fungal were reported in deeper versus surface soil layers.

3.3 Carbon mineralization kinetics

Kinetic models used in to describe soil carbon mineralization were presented in Table 1. In the process of selecting the best model, some of the models showed lack of convergence in most of the sites, land uses and depths (model 5 and 6). Models 3 and 4 showed higher values of the statistical parameters, but they were smaller than those obtained in model 1. Therefore, based on convergence, statistical parameters of the fitting, and the significance of the estimated parameters, the first-order model [$C_t = C_o (1-e^{-kt})$] was selected for the experimental data. This kinetic model provided a good fit to C mineralization with R^2 ranging from 0.90 to 0.99 for all land uses and management systems.

Table 1. Kinetic models used in to describe soil carbon mineralization.

No.	Model	Equation	References
1	First order	$C_t = C_o(1-e^{-kt})$	Murwira et al. (1990)
2	First order special	$C_t = C_o(1-e^{-kt})+C_1$	Jones (1984)
3	Linearized power funcion	$C_t = kt^m$	Standford and Smith, (1972)
4	Zero order	$C_t =a+ kt$	Seyfried and Rao (1988)
5	Two simultanenous reactions	$C_t = C_1(1-e^{-kt})+C_2(1-e^{-ht})$	Delphin (1988)
6	Special model	$C_t=C_1(1-e^{-k*t})+ht$	Bonde and Rosswall (1987)

Note: C_t, C_o, C_1 and C_2= Cumulative carbon mineralized after time t (mg C-CO_2/kg soil), potentially, easily, slowly mineralizable carbon (mg C-CO_2/kg soil), respectively; a= intercept; k, m and h= rate constants (day^{-1}); t= time from the start of incubation.

The first- order kinetic model used to describe the C mineralization process of soil organic matter assumes that the microbial biomass is constant and the rate of decomposition only depends on the available substrate. Many researchers have fitted C mineralization data with first-order model (Dossa et al., 2009; Aulen et al., 2012). Analysis with PROC MIXED showed that significant interaction between land use/management with soil depth for the C_o, k, $t_{1/2}$ and qCO_2 parameters (Table 2). This implies that the values of each parameter in each land use/management depended on the depth of soil sampling (Table 3). In the surface layer (0-10 cm), significantly higher mean values of C_o were observed in grassland. However, this value was not significantly different from mean value of C_o observed in cropland.

Table 2. Summary of ANOVA for C_o, k, C_o*k, $t_{½}$, Ct and qCO_2 estimated according to first-order decay equation.

Parameter	Land use and management (LUM)	Depth (D)	LUM x D
Ct	***	**	ns
C_o	***	**	***
k	***	ns	**
C_o*k	***	*	ns
$t_{½}$	***	ns	**
qCO_2	***	***	**

Note: Ct: total carbon mineralized in 62days, C_o: potentially mineralizable carbon, k: rate constant of carbon mineralization C_o*K: initial potential rate of C mineralization, $t_{1/2}$: half- life time, qCO_2: metabolic quotient, ns: no significant, *$p<0.05$, **$p<0.01$ and ***$p<0.001$

Potentially mineralizable carbon recorded in cropland and fallow land also did not differ statistically. Similarly, C_o values that were recorded in *Eucalyptus* and limed land were not statistically different from each other both in 0-10 and 10-20 cm soil depth. But it was significantly lower than cropland and fallow land in 0- 10 cm depth. In 10-20 cm depth, the lowest C_o was observed in cropland, which was not statistically different from *Eucalyptus*, limed land and fallow land. Decreases in C_o either suggest a lower activity of microbial community or residues more difficult to decompose, due to a different chemical composition. In general microbial biomass carbon is commonly described as a living or active pool in models that simulate organic C turnover in soils, and the size of this pool directly affects the model outputs (Probert et al., 1998). Therefore, differences in SOC and MBC could substantially contribute to the differences observed in the outputs of carbon kinetic models in this study.

Table 3. Parameters of microbial mineralization activity of soils sampled from five land uses and two depths, estimated according to first-order equation.

Depth	LUM	C_o (mg CO_2-C /kg soil)	k (day^{-1})	$t_{1/2}$ (day)	qCO_2[(mg CO_2-C h^{-1}) /g MBC]
0-10 cm	Grassland	1387.5A a	0.03411A a	20.7B a	1.063BC a
	Cropland	1339.2AB a	0.01468C b	67.0A a	1.225BC a
	Eucalyptus	744.7CB a	0.03302A a	22.4B a	1.125BC a
	Limed land	523.0CB a	0.03132AB a	23.1B a	0.750C b
	Fallow land	928.2B a	0.02013BC a	37.9AB a	1.738AB b
10-20 cm	Grassland	1325.3A a	0.03243A a	22.8C a	1.263BC a
	Cropland	453.6C b	0.02914A a	25.9BC b	1.012C a
	Eucalyptus	706.6BC a	0.02670AB a	28.7BC a	1.613BC a
	Limed land	681.0BC a	0.02879A a	25.0BC a	1.988AB a
	Fallow land	950.4AB a	0.01605B a	56.2AB a	2.600A a

Note: Different upper case letters show significant differences in each depth between different land uses; different lower case letters show significant differences in each land use between the two depths. LUM: land use and management, C_o: potentially mineralizable carbon, *k*: rate constant of carbon mineralization, $t_{1/2}$: half- life time, qCO_2: metabolic quotient.

Rate constant (k) for C mineralization was significantly higher in soils of grasslands in 0-10 cm soil profile. But, it was not statistically different from soils of *Eucalyptus* and limed land with similar depth. The k values observed in cropland and fallow land in 0-10 cm soil depth were significantly lower than the other land uses/management systems studied. In 10- 20 cm soil profile, mean k values were similar in all land uses and management systems except fallow land where the lowest mean value of k was recorded. However, k value recorded in fallow land and *Eucalyptus* were not different. All values of k fell within relatively narrow range except cropland and fallow. This implies that microbial respiration and metabolized organic compounds were similar or had the same degree of availability (Riffaldi et al., 1996; Alessandro et al., 2014), and no significant correlations between k and both potentially and easily mineralizable, indicating that differences in k values among soils cannot be attributed to differences in the relative sizes of the C pools (Riffaldi et al., 1996). Cropland exhibited significantly higher values of $t_{1/2}$ as compared to the other land uses and management systems.

However, significant changes in $t_{1/2}$ were not detected among grassland, *Eucalyptus*, limed land and fallow land in 0-10 cm soil depth. In 10- 20 cm, fallow land recorded higher values of $t_{1/2}$, which was not statistically different from the other land uses except grassland. The half-life time observed in grassland was lower than the other land uses and management systems. Half-life time is a more clearly interpretable parameter, where high levels are associated with ecosystem stresses (Anderson and Domsch, 2010). Therefore, the higher half-life time in fallow land and cropland indicates lower carbon mineralization rates.

Even though, higher contents of MBC and soil respiration generally indicate better soil quality, these parameters do not always show the same change tendency. Thus, metabolic quotient (qCO_2) is used to evaluate the efficiency of soil microbial biomass in utilizing the organic carbon compounds (Anderson and Domsch, 1990). In 0- 10 cm, the qCO_2 observed in fallow land was higher than the other land uses and management system. Higher values of qCO_2 imply a higher requirement of maintenance energy or lower metabolic efficiency in the utilization of both the native organic matter and the added plant material. The mean value of qCO_2 recorded in limed land was significantly lower than grassland, cropland, *Eucalyptus* and fallow land. Similar to 0- 10 cm, the qCO_2 observed in fallow land in 0- 20 cm was significantly higher than the other land uses and management system except limed land. However, there was no evidence of significant differences among grassland, cropland, and *Eucalyptus* in 10- 20 cm. In ecological terms, a high qCO_2 reflects a high maintenance carbon demand, and if the soil system cannot replenish the carbon which is lost through respiration, microbial biomass must decline (Anderson and Domsch, 2010). The lower qCO_2 value observed in 0-10 cm soil depth indicate more stable ecosystems, with greater efficiency of microorganisms to convert organic waste into microbial biomass and with greater sustainability. Our results are consistent with results published elsewhere (Gil-Sotres et al., 2005). Agricultural liming which is generally used to overcome the problem of acidification, would result in higher abundance and diversity of detritivorous soil fauna such as some species of earthworms (Bishop, 2003); contribute to an improved organic matter decomposition and nutrient mineralization (Bradford et al., 2002). Hence, the beneficial effect of liming was conspicuously observed by significantly lowering the values of qCO_2 only in 0- 10cm soil depth. However, the applied lime could not change the qCO_2 value in 10- 20 cm soil profile due to the fact that lime moves very slowly in soil and its ameliorative effect is limited to the top few centimeters of the soil profile. The qCO_2 also indicates the changes in microbial activity between natural and disturbed ecosystems more clearly (Islam and Weil 2000; Bastida et al., 2008). Hence, the relatively higher qCO_2 values observed in soils of fallow land in both depths and limed land in 10-20 cm indicate greater stress of the microbial community compared to soils with more stable ecosystems (Islam and Weil, 2000). Soil chemistry affecting substrate availability also changes dramatically with depth. In this study, results of the carbon kinetics parameters were significantly affected by depth of sampling in some of the land uses. Cropland showed significantly higher mean values of C_o and $t_{1/2}$ in 0- 10 cm as compared to 10- 20 cm soil depth. In 0- 10 cm, mean values of qCO_2 recorded in limed land and fallow land were significantly lower than the values in 10-20 cm. Generally, soils of grassland and *Eucalyptus* were not affected by depth of sampling relatively implying stable ecosystem in these land use systems.

*3.4 Soil organic carbon, MBC, Ct and C_o*k*

Soils under grassland had significantly ($p<0.001$) higher SOC and MBC than the adjacent cropland, *Eucalyptus* plantations, limed land and fallow land (Table 4). However, mean values of SOC among cropland, *Eucalyptus*, limed land and fallow land did not show any evidence of statistical difference. The lower levels of SOC in soils of these land uses/management systems could be due to a combination of lower carbon inputs through biomass return and greater C losses by soil erosion after tillage. Losses in soil C caused by the conversion of natural to cultivated vegetation is well documented. Cultivation of land that was previously covered in perennial vegetation, SOC can be rapidly lost due to enhanced C decomposition and erosion brought about by soil disturbance (Lal, 2005; Van der Werf et al., 2009). Guo and Gifford (2002) conducted a meta-analysis of land-use change experiments and showed that converting grassland to croplands caused significant loss of SOC, whereas conversion of forestry to grassland did not result in SOC loss in all cases.

Table 4. Soil organic carbon, MBC, Ct, C_o*k as affected by land use and soil depth, with standard error and p-values of ANOVA.

LUM	SOC [g/kg soil]	MBC [mg/kg soil]	Ct [mg CO_2-C /kg soil]	C_o*k [mg C-CO_2 /kg soil day]
Grassland	43.6a	763.7a	614.3a	45.2a
Cropland	23.2b	342.6b	243.7bc	15.6b
Eucalyptus	24.5b	345.0b	311.7b	21.2b
Limed land	24.0b	335.7b	255.7bc	18.6b
Fallow land	23.2b	190.8c	224.1c	14.9b
S.e	1.27	35.25	19.56	1.63
Depth (D)				
0- 10 cm	28.5	485.4a	362.7a	24.9a
10 -20 cm	26.9	305.8b	297.1b	21.3b
S.e	0.81	18.46	12.54	1.04
ANOVA				
LUM	***	***	***	***
D	ns	***	***	*
LUM x D	ns	ns	ns	ns

Note: LUM= land use/management, SOC: organic carbon, MBC= microbial biomass carbon, Ct: total carbon mineralized in 62 days, C_o*k: initial potential rate of C mineralization, S.e: standard error, †Mean values with similar letters in each column indicate non significant differences at *p<0.05, ** p< 0.01, *** 0.001, ns = non significant

On the other hand, the increased carbon content in grasslands suggests that grassland soil could serve as a C sink in a given ecosystem. The fact that MBC declines with depth partly explains the lower microbial activity in 10 -20 cm soil depth. Clay content controls availability of exchangeable ions, and organic matter controls the abundance and availability of dissolved and available sorbed organic nutrients, both decreases with depth (Konopka and Turco, 1991).

The total amount of carbon mineralized in 62 days of incubation period in grassland was significantly superior to the other land uses. However, Ct observed in fallow land was the lowest, and was not different from cropland and limed land. Similarly, mean values of C_o*k recorded in grassland was higher than the other land uses and management systems. Statistically, cropland, *Eucalyptus*, limed land and fallow land did not differ from each other in mean values of C_o*k. As expected, Ct and C_o*k were significantly higher in 0- 10 cm depth compared to 10- 20 cm. Because, higher values of SOC and MBC were recorded in 0- 10 cm and these parameters have high association with Ct and C_o*k. The microbial activity decreased clearly with increasing depth in response to the decreasing labile C pools (Agnelli et al., 2004).

3.5 Relationships between different soil variables

The ability of SOC to predict C_o in 62-days was evaluated by sketching a linear regression using eighty observations (Fig. 4). Good fits of correlation between MBC or OC and C mineralization parameters suggests that C mineralization depends on the MBC and OC availability to microbial activity.

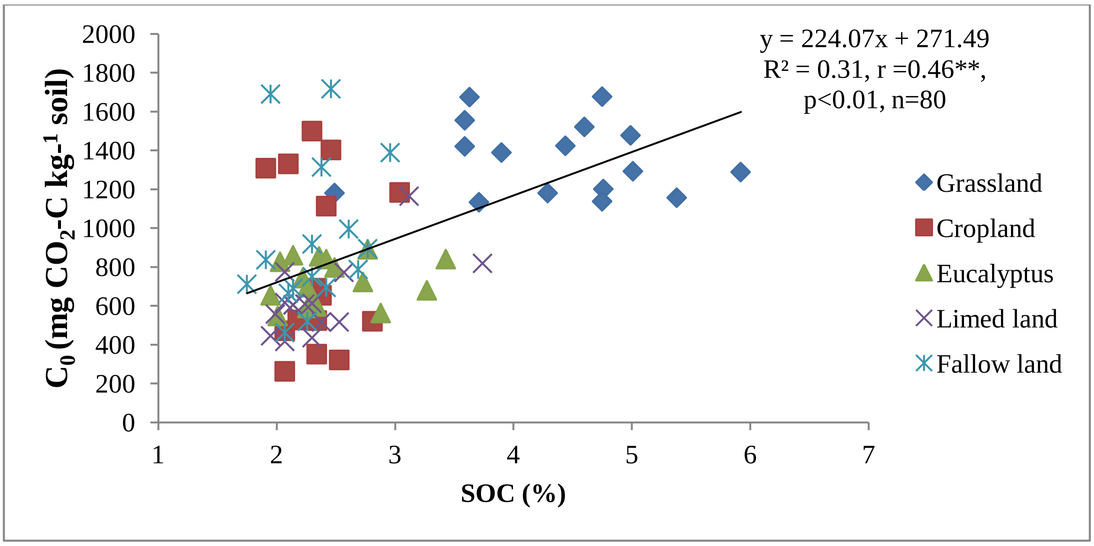

Fig. 4 Linear regression between C_o and SOC. The significance of the regressions is reported in the figure.

Figure 5 shows the relationship between qCO_2 and MBC: SOC, where both soil biological parameters are inversely related. The figure shows that higher values of qCO_2 reflect difficulties in the use of organic substrates by microbial biomass due to low levels of MBC: SOC. Klose et al. (2004) also reported that a low MBC: SOC ratio indicates a reduced pool of available carbon in soil.

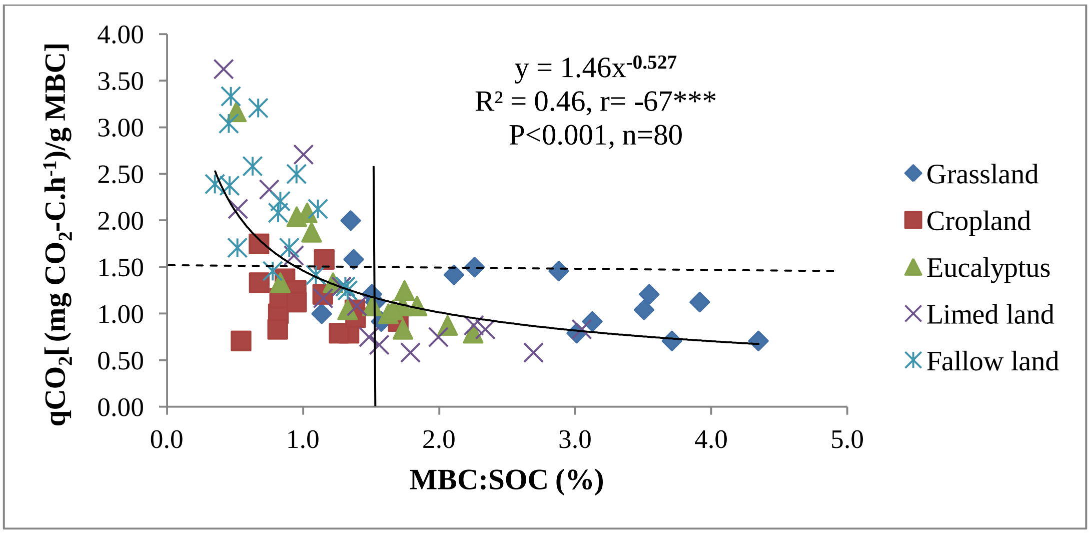

Fig. 5 Linear regression between qCO_2 and MBC: SOC. The significance of the regressions is reported in the figure.

On the other hand, our results clearly showed that soils that have values of MBC: SOC higher than 1.5 had efficient microorganisms in utilizing the available substrates than soil with MBC: SOC lower than 1.5. The observed increase in the ratio of MBC: SOC in the grassland as compared to other land uses might be due to lesser disturbances and the presence of readily available C as compared to the other land uses. Powlson (1994) also reported MBC to SOC ratio as an effective early warning of the improvement or deterioration of soil quality.

Simple correlation coefficients (r) between some selected physical, chemical and microbiological parameters are reported in Table 5. Results demonstrated a clear positive correlation between SOC and C mineralization parameters (C_t, C_o, k and C_o*k) estimated according to first-order mineralization model. Similarly, these C mineralization parameters had significant positive associations with MBC. However, both SOC and MBC were negative correlated with $t_{1/2}$ and qCO_2. These findings are in agreement with the findings of Beck et al. (1997) who reported significant correlations between the above C-mineralization parameters with both SOC and MBC.

Table 5. Spearman correlation coefficients between C-mineralization parameters of the first order model and soil characteristics.

Paremeter	Sand	Clay	pH	SOC	TN	MBC	MBN
C_t	ns	0.294*	0.370**	0.659**	0.632**	0.653**	0.446**
C_o	ns	0.350*	ns	0.456**	0.431**	0.384**	0.307*
k	0.274*	ns	0.404**	0.330*	0.350*	0.346*	ns
C_o*k	ns	0.278*	0.389**	0.639**	0.618**	0.586**	0.353*
$t_{1/2}$	-0.274*	ns	-0.404**	-0.330*	-0.350*	-0.346*	ns
qCO_2	ns	0.241*	-0.390**	ns	ns	-0.668***	-0.651***

Note: Ct=total carbon mineralized in 62days, C_o=potentially mineralizable C, k=C mineralization rate, C_o*K= initial potential rate of C mineralization, $t_{1/2}$= half- life time SOC= soil organic carbon, TN=total nitrogen, MBC= microbial biomass carbon, MBN= microbial biomass nitrogen, ns= non significant, *p<0.05, **p<0.01 and ***p<0.001

Good fits of correlation (r = 0.63, 0.43 and 0.62) were also found between TN, and C_t, C_o and C_o*k respectively. Correlations between qCO_2 and MBN was negative and statistically significant ($p<0.001$). This might be due to high values of qCO_2 that are associated with soil degradation brought about by poor agricultural management practices (Islam and Weil, 2000).

4 Conclusions

The amounts of C mineralized during 62-days of soil incubation period were different in different land uses and management systems. Grassland had higher C-CO_2 mineralized than adjacent cropland, *Eucalyptus* plantations, limed land and fallow lands, indicating high rates of biological activity and C cycling relative to the land uses. Among six kinetic models tested, a first-order model [$C_t = C_o (1-e^{-kt})$] provided a good fit to C mineralization data with R^2 ranging from 0.90 to 0.99. Land use change from grassland to other land uses/management systems drastically decreased soil SOC and MBC. Grassland promoted soil SOC accumulation and decomposition both in surface and subsurface soil compared to cropland, *Eucalyptus* plantations, limed land and fallow land. Parameters estimated according to first-order model like C_o, Co*k and qCO_2 were better discriminators among different land uses and management systems. Hence, these parameters along with SOC and MBC were sensitive to land use change, and could be considered as a good indicator of soil quality change in the study area.

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Chapter IV

Effects of short-rotation *Eucalyptus* plantations on soil quality attributes in highly acidic soils of the central highlands of Ethiopia

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Effects of short-rotation *Eucalyptus* plantations on soil quality attributes in highly acidic soils of the central highlands of Ethiopia

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Abstract

In the last several decades, converting agricultural land to short-rotation (5 -10 years) *Eucalyptus* plantations has become common in Ethiopian highlands. Yet we have a poor understanding of these land conversions on soil quality attributes under acidic soil conditions. We compared soil physical, chemical and biological properties under 5- and 10-year-old *Eucalyptus* plantations with adjacent grassland soils. Results showed that soil bulk density recorded in adjacent grassland was significantly lower than in the two *Eucalyptus* age groups. Mean values of soil pH, organic carbon, total nitrogen, calcium and cation exchange capacity (CEC) in adjacent grassland were higher in both 0-10 cm and 10-20 cm depths when compared to 5- and 10-year-old *Eucalyptus* plantations. Available phosphorus, exchangeable potassium and magnesium were not significantly affected in the three land use systems. Generally, no significant differences were observed in available phosphorus, potassium, calcium and magnesium concentrations, as well as in CEC in the two sampling depths (0-10 and 10-20 cm). The microbial biomass carbon and microbial biomass nitrogen recorded in 5- and 10-year-old *Eucalyptus* plantations were comparable, and significantly lower than in adjacent grasslands. Kinetics parameters calculated using first-order equation ($C_t = C_o\ (1-e^{-kt})$) showed potentially mineralizable carbon (C_o) was significantly higher ($p< 0.001$) under grassland as compared to 5- and 10-year-old *Eucalyptus* plantations.

Key words: Grassland, land use change, *Eucalyptus*, microbial biomass, kinetic models

1. Introduction

Eucalyptus is one of the fastest growing woody plant species in the world, with high productivity and good adaptability (Yusong et al., 2010; Hunter, 2001). It has been widely introduced in many countries throughout the world because of its growth and the rising demand for paper and plywood (Turnbull, 1999; Cossalter and Pye-Smith, 2003). In tropical zones, plantations of *Eucalyptus* cover about 12 million ha, and about 90% of them have been planted since 1955 (Turnbull, 1999). In Ethiopia the genus *Eucalyptus* was introduced in 1894/95 (Von Breitenbach, 1961) with the objective of meeting an ever-increasing demand for fuel wood and timber for construction in the new and growing capital city, Addis Ababa (Yitebitu, 2010). According to Demel (2000) and Amare (2002), the area of *Eucalyptus* in Ethiopia was then estimated to be 477,000 ha and 506,000, respectively. The area increase is due to rapid conversions of agricultural lands and natural vegetation such as natural grasslands to *Eucalyptus*. As a result the area of *Eucalyptus* is doubling every decade and more and more smallholder farmers are growing it primarily on land previously used for grazing/crop production. At the moment, the country has the largest area of *Eucalyptus* plantations in east Africa, and is one of the 10 pioneering countries that introduced *Eucalyptus* (FAO, 2011).

Numerous studies have been conducted with commercial *Eucalyptus* plantations on their environmental impact on soil chemical properties (Laclau et al., 2005; Maquere et al., 2008), soil organic matter dynamic (Mendhama et al., 2002; Zinn et al., 2002; Epron et al., 2009) and soil microbial biomass (Behera and Sahani, 2003; Yusong et al., 2010; Araújo et al., 2010; Wu et al., 2013). Even though a wealth of information is available on *Eucalyptus*, assessments on the effect of *Eucalyptus* on soil and water depletion, the allelopathic effect on nearby plants and the difficulty involved in future land use change to crop use are still debatable (Birru et al., 2013). Results are inconsistent and controversial mainly depending on previous land use before *Eucalyptus* and the soil types of the study areas.

In the highlands of Ethiopia, plantations of *Eucalyptus globulus* are being established on land that has previously been used for conventional agriculture and huge areas of grassland are being converted to short harvest rotation of *Eucalyptus* (5-10 years) annually. Indeed, socio-economic evaluations of *E. globulus* and *E. camaldulensis* in the country revealed that planting the genus made a substantial contribution to household income, even more than agricultural crops did, especially where the indigenous woodland was degraded and the people were suffering from fuel shortages, water scarcity, erosion and land degradation (Tesfaye, 2009; Amare, 2002; Zerihun Kebebew, 2002; Daba, 1998, cited in FAO, 2011). However, under such type of rotations large amounts of nutrients are exported every five years due to biomass removal. Previous attempts to study the effect of short-rotation *Eucalyptus* on soil resources were primarily focused on some selected physical and chemical properties of soils. Even though these parameters are useful in soil quality for practical purposes, biological indicators are more sensitive to changes than other indicators and could describe soil quality in a broader picture (Bastida et al., 2008). Moreover, relative to soil physico-chemical properties, biological parameters are increasingly used as indicators of soil quality due to their sensitivity, rapid response to disturbances (which makes them tools of great potential to determine short-term effects) and capacity to provide information that integrates many environmental factors (Hernández-Allica et al., 2006; Mijangos et al., 2009). Therefore, land use changes that overlook biological aspects may diminish the soil resource over time. In spite of this, little is known about the effect of short-rotation *Eucalyptus* on soil quality parameters in highly acidic soils of the highlands of Ethiopia. Therefore, the objectives of this study were: (1) assess the effects of grassland conversion to short-rotation *Eucalyptus* on soil physical, chemical and biological properties, and (2) investigate whether the soil quality parameters differ due to plantation ages and soil sampling depths.

2 Materials and Methods

2.1 Descriptions of the study area

The study was conducted at Wetabecha Minjaro in the central highlands of Ethiopia, situated at (9° 05´ N and 38° 36´ E), at an altitude of 2650 m.a.s.l, and about 25 km away from the capital, Addis Ababa. The area is characterized by sub-tropical climate with an average annual temperature of 16 °C, and highest and lowest average monthly temperatures of 23.3°C and 8.7°C respectively. The area receives about 1100 mm rainfall annually in two distinct seasons (short and long rainy seasons). The short rainy season extends from March to April, and the long rainy season occurs between June and September. The soils are Nitisols characterized by low inherent soil fertility and low pH. *Eucalyptus globulus* plantations are widespread and 95% of the community grows *Eucalyptus* on private and communal land or around homesteads. The harvest rotations of the plantations vary between 5-10 years depending on the purpose utilization. Literally, there is no/very few indigenous tree species in the area that have a similar rapid growth as *Eucalyptus* and thereby satisfy the high demand of biomass energy, poles for construction, and use for farm implements. This is one of the main reasons that *Eucalyptus* is voraciously integrated into the farming systems of the area. Mixed crop-livestock type of agriculture is the main source of livelihood for the population in the region. More than 95% of the farmers are poor subsistence farmers with a low input-output production system. As a result, external inputs are not applied either to *Eucalyptus* or grassland.

2.2 Experimental design and sampling

In July, August and September, 2012, five locations where 5- and 10-year-old *Eucalyptus* plantations and grassland exist adjacent to each other were randomly selected. An area of 10 m x 10 m (100 m^2) was demarcated in each location, and soil samples were randomly collected from each sampling point using an auger from two depths (0 -10 cm and 10 -20 cm) for the three land uses. About ten sub-samples were collected from each demarcated area and then bulked to make a composite sample for the analysis of physical, chemical and biological properties. As much as possible, the sampling area within each land use was chosen very carefully to represent the land uses under investigation. A total of 30 soil samples (5 sites * 3 land uses * 2 depths) were collected in randomized complete block design for laboratory analysis. Samples were gently sieved through a 2 mm mesh to remove stones and roots, and were sealed in plastic bags before analysis. In the laboratory, analysis each sample was made in duplicates.

2.3 Soil analysis

2.3.1 Soil physical and chemical analysis

Physical and chemical properties of soils were analyzed following standard methods. Soil moisture was determined gravimetrically by drying fresh soil at 105 °C. Bulk density (BD) was determined using a core sampler of a known volume following the procedures of (Blake, 1965). Soil particle size distribution was determined by hydrometric method (Bouyoucos, 1962). Soil pH was determined by using a pH meter in a 1:2.5 soil/water suspension, and soil organic carbon (SOC) by the Walkley and Black (1934) method. Total nitrogen (TN) was analyzed by wet oxidation procedure using the Kjeldhal digestion, distillation and titration method (Bremner and Mulvaney, 1982). The available phosphorus (AvP) content of the soil was determined using 0.5M sodium bicarbonate extraction solution (Olsen and Sommers, 1982). Exchangeable bases were established by the ammonium acetate extraction method, and from extracts: concentrations of Ca, Mg, K and Na were determined by atomic absorption spectrophotometer. Exchangeable acidity (EXa) was determined in 1 M KCl extracts titrated with 0.01 M NaOH.

2.3.2 Soil biological analysis

Microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) were estimated by the chloroform fumigation extraction method (Brookes et al., 1985; Vance et al., 1987). Twenty grams of dry weight-equivalent soil samples were fumigated with $CHCl_3$ for 24 hours in the dark in vacuum desiccators. After removal of chloroform by three repeated evacuations, the soil samples were extracted by using 0.5 M K_2SO_4 (with a soil: extractant ratio of 1:4). Similarly, the unfumigated controls were also subjected to 0.5 M K_2SO_4 extraction. After shaking for 30 minutes in an automatic shaker, the extracts were filtered through No.42 Whatman filter paper. The filtrates were analyzed for organic C and total N by using SKALAR TOC/TN automatic analyzer. The difference in the C content of the extracts from fumigated and unfumigated samples was converted to biomass-C by dividing the value obtained by a factor (K_C) of 0.45 (Vance et al., 1987). The results are expressed as µg g^{-1} soil of oven-dried soil. The difference in the content of N of the extractants was converted to biomass nitrogen by dividing the value obtained by a factor (K_N) of 0.54 (Brookes et al., 1985). Carbon mineralization was determined in closed jars according to Isermayer (1952) under laboratory-controlled conditions. About 30 grams of dry soil samples were wetted to 60 % of water holding capacity and incubated in 0.5 L jars at 28 °C to measure the amount of CO_2 evolved. The moisture content was kept constant by weighing at each sampling date.

The CO_2 evolved was trapped in plastic vials containing 10 ml of 0.5 M NaOH. The amount of CO_2 evolved was measured after 4, 10, 17, 27, 42, 48 and 60 days of incubation by titrating with 0.5 M HCl against a phenolphthalein indicator after precipitation with $BaCl_2$ (0.5 M).

2.3.3 Modelization of carbon mineralization kinetic

The curves for cumulative C mineralized over time were fit to five different models to describe the C mineralization patterns in the soil samples of the three land uses at two depths. For modelization of the C mineralization the SPSS statistical package for Windows was used. The comparison of model fits was evaluated by the coefficient of determination, R^2 (Cameron and Windmeijer, 1997). Among the different models tested, the simple first-order model was found to be the best based on observed highest R^2 values.

2.*4 Statistical analysis*

For the statistical analysis, we used a linear mixed model of variance analysis using SAS 9.1 (SAS Institute Inc. 2001) with two between-subject factors (locality and age) and one within-subject factor (depth). The mathematical formulation of the model is as follows:

$$Y_{ij;k} = \mu + \alpha_i + \beta_j + \gamma_k + \beta\gamma_{jk} + \varepsilon_{ij;k}$$

with i=1,…,5 for the sites, j=1,…,3 for the land uses and k=1,2 for the two depths, and being:

$Y_{ij;k} =$ observed value of the dependent variable for the land use j at depth k in site i.

$\mu =$ general mean effect; $\alpha_i =$ main effect of the site I; $\beta_j =$ main effect of the land use j; $\gamma_k =$ main effect of the depth k; $\beta\gamma_{jk} =$ interaction effect of the land use j with the depth k; and $\varepsilon_{ij;k} =$ random error in the dependent variable for the land use j at depth k in the site i.

The assumptions for the model were:

- $\varepsilon_{ij;k} \rightsquigarrow N(0, \sigma_k^2)$, with σ_k^2= random variance for errors at depth k.
- $Cov(\varepsilon_{ij;k}, \varepsilon_{i'j';k'}) = \begin{cases} \omega & \text{if } i = i', j = j' \; and \;\; k \neq k' \\ 0 & \text{if } i \neq i' \; or \;\; j \neq j' \end{cases}$, with ω=covariance between errors at different depths.

When the effect studied turned out significant, differences among levels were evaluated using the Tukey test. Pearson correlation coefficients were also used to assess the significance of the relationships between the variables measured.

3 Results and discussion

3.1 Soil physico-chemical properties

Analysis of variance for soil physical, chemical and biological properties under the three land uses and two depths, their interactions are summarized in Table 1.

Table 1. Summary of ANOVA for land-use, depth and its interactions on soil properties.

Soil parameters	Land use	Depth	Land use*depth
Sand	ns	ns	ns
Silt	ns	ns	ns
Clay	ns	ns	ns
pH	**	ns	ns
SOC	**	*	ns
TN	**	ns	ns
AvP	ns	ns	ns
K^+	*	ns	ns
Na^+	*	ns	ns
Ca^{2+}	*	ns	ns
Mg^{2+}	ns	ns	ns
CEC	**	ns	ns
EXa	**	ns	ns
MBC	**	**	ns
MBN	**	**	ns

AvP=available phosphorus; CEC=cation exchange capacity; EXa=Exchangeable acidity; MBC=microbial biomass carbon; MBN=microbial biomass nitrogen; SOC=organic carbon; TN=total nitrogen,*Significant at $p<0.05$, **Significant at $p<0.01$, ns=non significant

Soil physical and chemical characteristics data under grassland and 5- and 10-year-old *Eucalyptus* plantations are presented in Tables 2, 3, and 4. Results revealed that converting of grassland to *Eucalyptus* plantations had no significant ($p<0.05$) effect on the textural classes of the three different soils under study (Table 2). As a result proportions of sand, silt and clay are the same at different land uses in the two sampling depths. This might be due to the fact that the mineral particles of the studied soils are not readily subjected to change as a result of land use change.

Table 2. Soil particle size distribution and exchangeable acidity as affected by land use and sampling depth.

Depth	Land use type	Sand (%)	Silt (%)	Clay (%)	EXa*
0 -10 cm	Grassland	14.5a†	43.5a	42.0a	0.56b
	5-year-old Euc.	11.5a	45.5a	43.0a	3.23a
	10-year- old Euc.	11.5a	39.0a	49.5a	2.23a
10 -20 cm	Grassland	13.0a	35.5a	51.5a	1.0b
	5-year-old Euc.	19.3a	35.0a	45.8a	3.6a
	10-year- old Euc.	18.8a	37.0a	44.3a	2.2ab

†Mean values with similar letters within a soil depth in a column are not significantly different at $p<0.05$.
*Exa= exchangeable acidity ($\text{cmol}_+ \text{ kg}^{-1}$).

Similar non significant textural classes due to land use changes were reported by Behera and Sahani (2003) by comparing three land uses in Western Orissa. Prasad and Power (1997) also indicated that a soil textural class is a permanent characteristic of a soil that gives a general picture of soil's physical properties, i.e., density, porosity, consistency, water holding capacity, and suitability for plant growth. Soils under 5- and 10-year-old *Eucalyptus* plantations had comparable gravimetric moisture content and bulk density. Our results are in line with the findings of Wu et al. (2013), where soil moisture remained constant under different ages of *Eucalyptus* in China. However, in our study, the adjacent grassland had lower bulk density and higher moisture content as compared to the two age groups of *Eucalyptus*.

Table 3. Effects of sampling depth on soil pH, soil organic carbon (SOC), total nitrogen (TN) and available phosphorus (AvP).

Depth	Land use type	pH (H_2O)	SOC (%)	TN (%)	AvP (mg/kg)
0 -10 cm	Grassland	4.9a†	4.6a	0.41 a	5.8a
	5-year-old Euc.	4.3b	2.4b	0.20b	3.9a
	10-year- old Euc.	4.4b	2.3b	0.23b	6.0a
10 -20 cm	Grassland	5.0a	3.8a	0.36a	5.0a
	5-year-old Euc.	4.3b	2.1b	0.18b	3.4a
	10-year- old Euc.	4.5b	2.4b	0.22b	5.0a

†Mean values within a column with similar depth that share the same letters are not significantly different within land use type. AvP=available phosphorus, SOC=soil organic carbon; TN=total nitrogen.

The higher SOC content observed in grassland might be a probable reason for a lower bulk density in grassland. Similar low BD in grassland as compared to other land uses was reported by Celik (2005). According to the results of a linear mixed model, the mean values of pH, SOC, TN, exchangeable Ca^{2+} and cation exchange capacity in adjacent grassland were higher than plantations of 5- and 10-year-old *Eucalyptus* (Tables 3 and 4). However, the two age groups of *Eucalyptus* did not differ from each other in the above parameters. Land use conversions from grassland to *Eucalyptus* resulted in higher soil acidity, and lower SOC and TN. Relative SOC of grassland, and SOC of 5- and 10-year-old plantations decreased by 48% and 44% respectively. Similarly, TN was decreased by 50% and 42% in 5- and 10-year-old *Eucalyptus* plantations respectively.

Table 4. Concentrations of soil K, Ca, Mg and Na as affected by soil depth in the three land use systems.

Depth	Land use type	K^+	Ca^{2+}	Mg^{2+}	Na^+
		---------------(cmol(+)/kg)------------------			
0 -10 cm	Grassland	0.8a†	15.3a	2.9a	0.14a
	5-year-old Euc.	0.7a	10.3ab	2.2a	0.23a
	10-year- old Euc.	0.8 a	7.8b	2.4a	0.22a
10-20 cm	Grassland	0.8 a	13.4a	2.9a	0.19a
	5-year-old Euc.	0.6a	12.3a	2.6a	0.28a
	10-year- old Euc.	0.7a	9.6a	2.8a	0.18a

†Mean values within a column within a similar depth that share the same letters are not significantly different within land use type.

Lower SOC and TN in *Eucalyptus* plantations agree with reports from Balagopalan and Jose (1995), Animon et al. (1999) and Behera and Sahani (2003). Generally, the observed low percentages of N in the study area might be associated to low organic matter contents of the soils. Our results revealed a non-significant ($p > 0.05$) observation in terms of AvP, K^+ and Mg^{+2} under the three land use systems. Contrary to this finding, afforestation of grasslands in the Argentine pampas with *Eucalyptus camaldulensis* was found to decrease mineral soil cations by redistribution from soil to biomass pools (Jobbagy and Jackson, 2003). The amount of exchangeable Na^+ in 5-year-old *Eucalyptus* was much higher than in soils of adjacent grassland and 10-year-old

Eucalyptus. In agreement with this result, Sean et al. (2009) also observed higher concentrations of exchangeable Na^+ in plantations across diverse plantation types including *Eucalyptus*. Exchangeable acidity of soils under the two age groups of *Eucalyptus* was also higher than under adjacent grassland. The increased acidity under *Eucalyptus* plantations is probably associated with increased cation uptake by trees and consequent changes in the proportions of adsorbed cations to the soil exchange complex. In general, soil pH, SOC and TN between 0- 10 and 10- 20 cm depths did not differ under the three land use systems. However, soils under grassland showed higher values of the above parameters, in both 0- 10 cm and 10- 20 cm soil depths. On the other hand, depth of sampling had no significant effect on mean values of AvP, exchangeable K^+, Ca^{2+} and Mg^{2+} and CEC in the three land use systems.

3.2 Microbial biomass carbon and nitrogen

Mean values of MBC, MBN, ratios of MBC to SOC and MBN to TN are presented in Table 5. Mean values of microbial biomass carbon and nitrogen recorded in grassland were significantly higher than in both 5- and 10-year-old *Eucalyptus* plantations. In comparison with grassland MBC, MBC in 5- and 10-year-old plantations decreased by 45% and 58% respectively. Similarly, mean values of MBN in 5- and 10-year-old *Eucalyptus* plantations decreased by 62% and 60% respectively. However, the MBC and MBN in 5 and 10-year-old *Eucalyptus* plantations were not significantly different from each other. Soil microbial biomass greatly depends on soil organic matter as substrate; a decrease in SOM causes a reduction in soil microbial biomass (Chen et al., 2005). Hence, the higher MBC and MBN in grassland is mainly attributed to greater availability of organic matter. The lower microbial biomass under *Eucalyptus* plantations could possibly be due to the toxic effects of harmful allelochemical compounds released from *Eucalyptus* leaf litter (Rice, 1984). Harmful effects of *Eucalyptus* leaf litter on microbes were also reported by Dellacassa et al. (1989) and Sankaran (1993). The ratio of MBC to organic carbon (MBC: SOC) represents microbial biomass per soil organic carbon. It is considered as an important index that reflects soil microbial activity.

Table 5. Soil biological parameters as affected by land use types.

Land use	MBC ($\mu g\ g^{-1}$ soil)	MBN ($\mu g\ g^{-1}$ soil)	MBC: SOC (%)	MBN: TN (%)
Grassland	669.3a†	81.5a	1.7a	2.0a
5-year-old *Eucalyptus*	365.4b	30.5b	1.7a	1.6a
10-year-old *Eucalyptus*	280.2b	32.5b	1.2a	1.5a

†Means within a column that share the same letters are not significantly different within land use type. MBC=microbial biomass carbon; MBN=microbial biomass nitrogen; MBC: SOC= ratio of MBC to organic carbon; MBN:TN= ratio of microbial biomass nitrogen to total nitrogen

In this study, MBC: SOC did not show remarkable differences among land uses. However, the lower ratio of MBC: SOC observed in 10-year-old *Eucalyptus* plantations could be considered as an indication of damage that has occurred to the soil ecosystem. Ratio of microbial biomass nitrogen to total nitrogen is another soil quality attribute, where a high MBN: TN represents high nitrogen supplying ability of soils. Our data showed that MBN: TN in grassland and 5- and 10-year-old *Eucalyptus* were 2.0, 1.6 and 1.5 respectively.

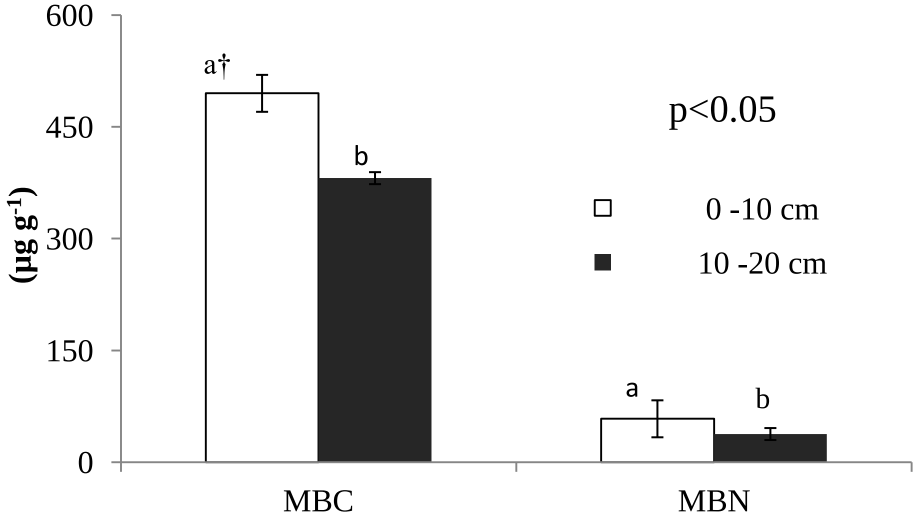

Fig. 1 Soil microbial biomass carbon and N as affected by depth of sampling

†Mean values with different depths that share different letters do differ significantly at $p<0.05$

This indicates that the nitrogen supplying ability of *Eucalyptus* plantations is gradually decreasing as the age of the plantations progresses. Low ratios of microbial biomass and nitrogen in *Eucalyptus* plantations were also reported by Yu et al. (2008). Both soil

MBC and MBN were significantly higher in 0 -10 cm depth as compared to 10 -20 cm (Fig. 1). This might be attributed to a decline in carbon availability and more occurrence of microbial biomass in the surface of 10 cm soil profile. In agreement with this finding, Yang et al. (2010) and Murphy et al. (1998) also reported that microbial biomass decreased as depth increased.

Our findings on relationships between biological parameters showed a strong positive correlation between SOC and MBC (r =0.66, n=30.), SOC and TN (r =0.74, n=30), MBN and TN (r = 0.69, n= 36.), and MBC and MBN (r =0.74, n=36.). The three land use types did not significantly differ in the relationships of SOC with MBC or MBN with TN or SOC with TN and MBC with MBN (Fig. 2).

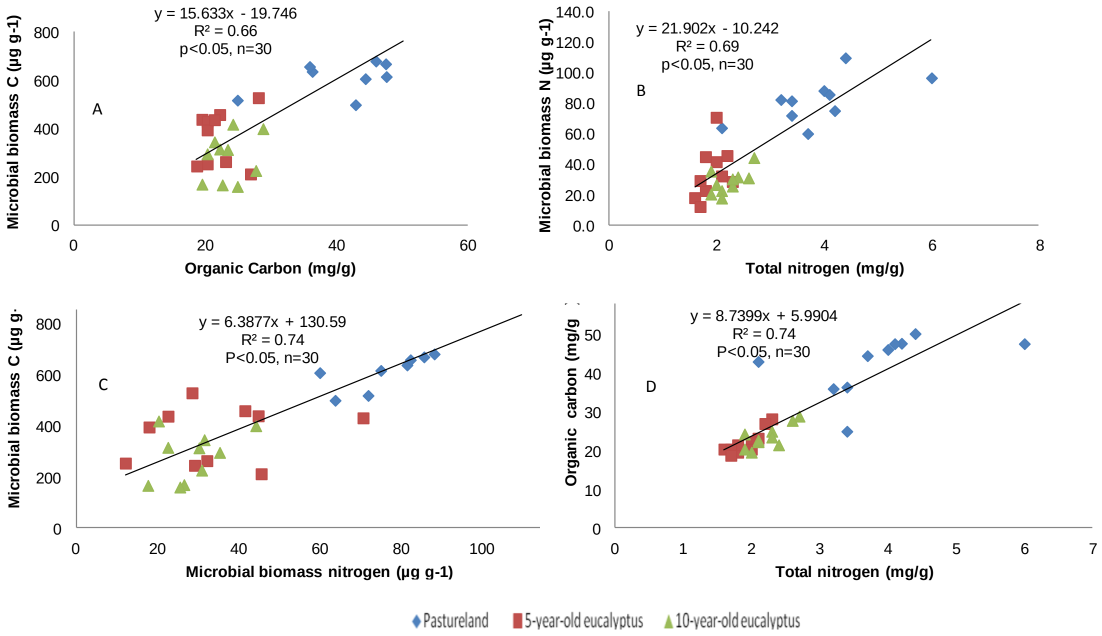

Fig. 2 Relationships between microbial biomass C and soil organic carbon (A), Microbial biomass N and Total N (B), Microbial biomass C and N (C) and organic carbon and total nitrogen under three land use systems.

3.3 Kinetics of C mineralization

Carbon mineralization data fitted well (R^2= 0.93-0.99) to first-order kinetic equation ($C_t = C_o (1-e^{-kt})$) for the three land uses. The cumulative mineralized C presented a curvilinear relationship with time in both 0-10 and 10-20 cm soil profile over the 60-day incubation period (Fig. 3 and 4).

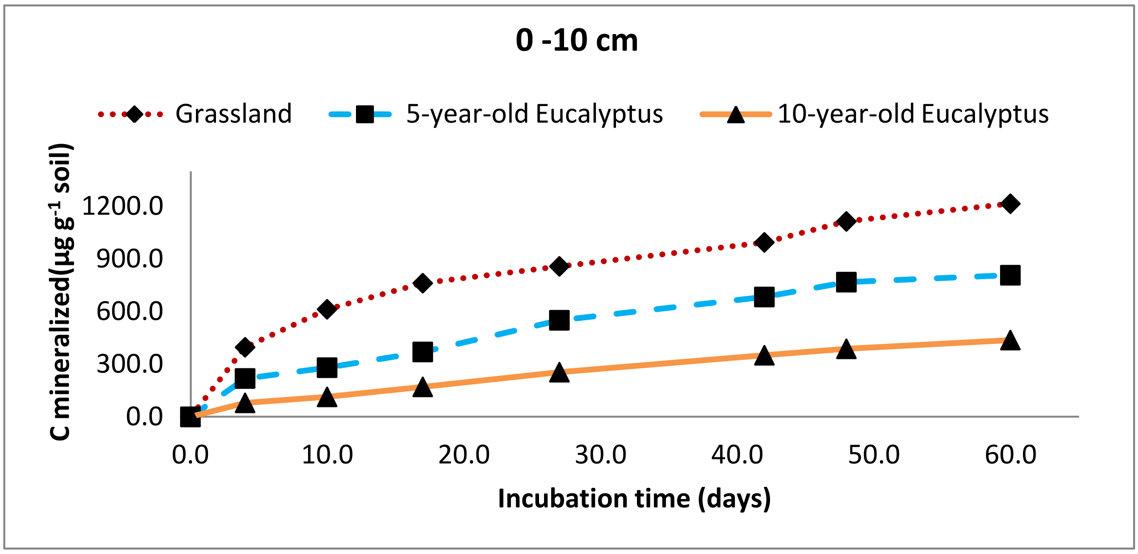

Fig. 3 Cumulative carbon mineralized for the three land uses at 0-10 cm soil depth over 60 days of soil incubation.

The curvilinear nature of C mineralization due to the presence of different pools of soil organic carbon releasing C at different rates has been reported (Shahriari et al., 2011).

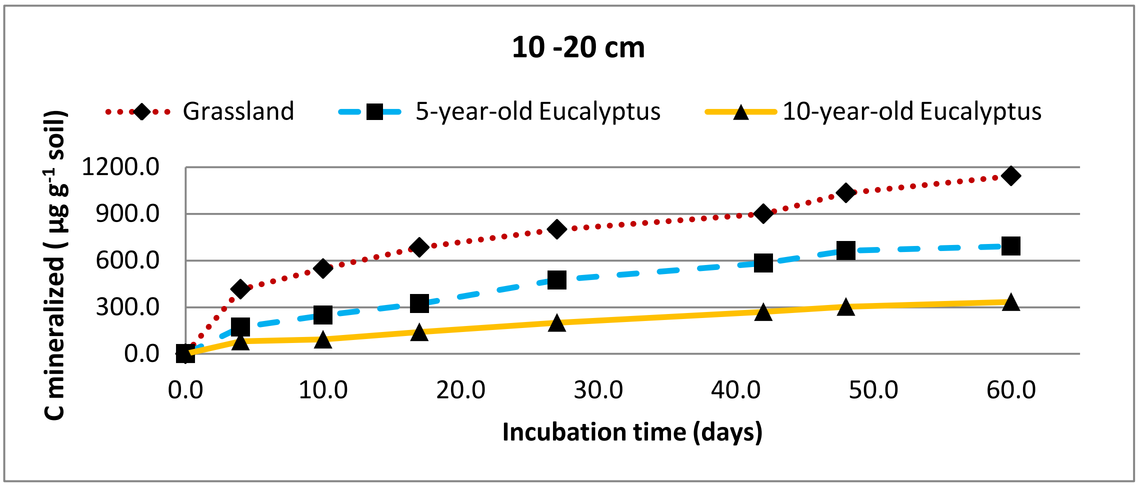

Fig. 4 Cumulative carbon mineralized for the three land uses from 10-20 cm soil depth over 60 days of soil incubation.

The potentially mineralizable C (C_o) and rate constants for C mineralization (k_C) estimated from the equations are presented in Table 6. Land use changes affected carbon mineralization in the study sites. The values of C_o were significantly higher ($p<0.001$) under grassland as compared to 5- and 10-year-old *Eucalyptus* plantations.

Conversion of grassland to 5-year-old and 10-year-old *Eucalyptus* reduced the values of C_o by 21% and 43% respectively. Similarly, rate constant of mineralization and initial potential rate of C mineralization were also reduced in plantations. However, half-life time rate of mineralizable carbon and C_o/SOC were significantly higher under 10-year-old *Eucalyptus* plantations as compared to grassland and 5-year-old *Eucalyptus* plantation. In contrast, *Eucalyptus* establishment induced a sharp and significant ($p<0.01$) decrease in C_o, k and C_o*k. The largest significant decrease was observed under 10-year-old *Eucalyptus* plantations. High sand content in the upper (0-10 cm) soil might be the reason for the increase in carbon mineralization under grassland soils. The influence of soil texture on C mineralization has been widely studied (e.g., Khalil et al., 2005) and greater mineralization rates in soils with higher sand contents have previously been reported for different organic materials. The highest significant ($p<0.01$) half-life time value (43.74) was observed in 10-year-old *Eucalyptus*, indicating that the carbon mineralization rate was the slowest in this land use type.

The study demonstrated that more C mineralization happens in the first 0-10 cm than in 10- 20 cm, indicating rapid activities of microbes that mineralize C within the surface of the soil profile. The decrease in the C mineralization in 10-20 cm might be due to lower organic carbon content at 10- 20 cm depth and relatively smaller number of microbes. These results are in line with the findings of Taylor (2002), who found reduced microbial and fungal activities in deeper versus surface soil layers. Similarly, comparable decreases in C amounts, mineralization and heterotrophic respiration rates with soil depth have previously been observed (Nadelhoffer et al., 1991; Gill et al., 1999; Gill and Burke, 2002) and related to changes in profile variables (Davidson et al., 2006). Furthermore, the degree of nitrogen and phosphorus limitation to C mineralization increased with depth (Fierer et al., 2003).

Table 6. Parameters of carbon mineralization activity estimated according to the first-order equation.

Land use (Lu)	C_o [mg C-CO_2/kg soil]	K [day^{-1}]	C_o*k [mg C-CO_2/kg soil day]	$t_{1/2}$ [day]	C_o/SOC [C-CO_2/g SOC]
Grassland	1100.0a†	0.07a	77.4a	10.3b	26.45
5-year-*Eucalyptus*	877.4b	0.04b	31.3b	19.7b	25.63
10-year-*Eucalyptus*	629.7c	0.018c	10.6c	43.7a	26.96
Standard error	69.8	0.003	4.15	3.29	3.11
Depth (D)					
0-10 cm	940.9	0.4	42.9	23.4	32.19
10-20 cm	797.1	0.4	36.5	25.7	30.28
Standard error	57.0	0.003	3.39	2.7	2.53
Analysis of variance					
lu	**	***	***	***	ns
D	ns	ns	ns	ns	ns
Lu*D	ns	ns	ns	ns	ns

C_o: potentially mineralizable C; *k*: rate constant of mineralization representing the slope of the curve; C_o**k:* initial potential rate of C mineralization; OC: organic carbon; $t_{1/2}$: half- life time that represents the time necessary to reach a half of the maximum mineralization; Different letters within a column represent a significant difference between land uses. †mean values within a column that share similar letters are not significantly different; ** $p< 0.01$; *** 0.001; ns = not significant

4 Conclusions

Conversions of grassland to *Eucalyptus* plantations obviously decreased soil quality indicators as evidenced from the mean values of soil physical, chemical and biological parameters. Specifically, soil bulk density and exchangeable acidity were increased due to conversions of grassland to *Eucalyptus globulus* plantations. Similarly, mean values of total nitrogen, organic carbon and cation exchange capacity of the soils were greatly reduced. Notably, this study revealed that soil microbial biomass carbon and nitrogen were also substantially decreased in *Eucalyptus* plantations. However, our results clearly demonstrate that deterioration in soil quality parameters is more pronounced in 10-year-old *Eucalyptus* plantations than in 5-year-old *Eucalyptus*. Consequently, grasslands sustain soil ecosystem functioning and environmental sustainability better than *Eucalyptus*. However, considering the current high demand of *Eucalyptus* for construction, fuel wood and farm implements, cautions should be taken in large scale conversion of grasslands to short-rotation *Eucalyptus* in the central highlands of Ethiopia.

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Chapter V

Effect of lime and phosphorus fertilizer on acid soils and barley (*Hordeum vulgare* L.) performance in the central highlands of Ethiopia

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Effect of lime and phosphorus fertilizer on acid soils and barley (*Hordeum vulgare* L.) performance in the central highlands of Ethiopia.

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Abstract

Low soil pH and associated soil infertility problems are considered to be among the major challenges to boost barley production in the highlands of Ethiopia. In response to this, an experiment was conducted at low soil pH (< 5 H_2O) site on the effects of different levels of lime and phosphorus (P) fertilizer on soil pH, exchangeable cidity, grain yield and yield components of barley during 2010 and 2011 cropping seasons. The experiment comprised factorial combinations of five lime rates (0, 0.55, 1.1, 1.65 and 2.2 Mg ha^{-1}) in the form $CaCO_3$ and four P rates (0, 10, 20 and 30 kg ha^{-1}) in the form of triple super phosphate in a randomized complete block design in three replications. The amount of lime that was applied at each level was calculated on the basis of exchangeable acidity. Results of soil analysis after two years of liming showed that liming significantly ($p<0.05$) increased soil pH, and markedly reduced exchangeable acidity. Liming at the rate of 0.55, 1.1, 1.65 and 2.2 Mg ha^{-1} decreased acidity by 0.88, 1.11, 1.20 and 1.19 $cmol_+$ kg^{-1}, and increased soil pH by 0.5, 0.7, 0.8 and 1.1 units respectively. Grain yield obtained by applications of 1.65 and 2.2 Mg ha^{-1} lime was statistically comparable, but significantly ($p<0.05$) superior to control as well as 0.55 and 1.1 Mg ha^{-1}. By additions of 10, 20 and 30 kg P ha^{-1}, grain yield of barley increased by about 29, 55 and 66 % as compared to control (without P). During 2010, however, the combined applications of 1.65 Mg ha^{-1} lime and 30 kg P ha^{-1} gave 133 % more grain yields of barley relative to control (without P and lime additions). Therefore, sustainable barley production on acid soils in the central highlands of Ethiopia should entail combined applications of both lime and P fertilizer.

Keywords: Aluminum toxicity, Soil pH, tropical soils, highlands, $CaCO_3$

1 Introduction

It has long been recognized that soil acidity is one of the most serious challenges to agricultural production worldwide in general, developing countries in particular. Area affected by acidity is estimated at 4 billion ha, representing about 30% of the total ice-free land of the world (Sumner and Noble, 2003). It is mostly distributed in developing countries, where population growth is fast and demands for food and fiber is increasing. In Ethiopia, about 41 % of the total land mass is affected by soil acidity and 33% of this area has Al-toxicity (Schlede, 1989). The highlands of Ethiopia (areas >1500 m above sea level) are particularly the most affected region by the problem. The cause of soil acidity is high amount of precipitation that exceeds evapo-transpiration, which leaches appreciable amounts of exchangeable bases from the soil surface. As a result, most of the soils have a pH range of 4.5 to 5.5, contain low organic matter (<20 g kg^{-1}) and low nutrient availability (Temesgen et al., 2011). Increased soil acidity causes solubilization of aluminum, which is the primary source of toxicity to plants at pH below 5.5, and deficiencies of P, Ca, Mg, Mo, N, K, and micronutrients (Ernani et al., 2002; Mesfin, 2007; Kariuki et al., 2007). Theoretically, soil acidity is quantified on the basis of hydrogen (H^+) and Al^{3+} concentrations of soils. For crop production, however, soil acidity is a complex of numerous factors involving nutrient/element deficiencies and toxicities, low activities of beneficial microorganisms, and reduced plant root growth which limits absorption of nutrients and water (Fageria and Baligar, 2003). However, aluminum toxicity is one of the major limiting factors for crop production on acid soils by inhibiting root cell division and elongation, reducing water and nutrient uptake (Wang et al., 2006), poor nodulation or mycorrhizal infections (Kochian et al., 2004; Delhaize et al., 2007), leading to poor plant growth and yield of many crops.

Several agricultural practices have been recommended to overcome the problem of tropical acid soil infertility worldwide. Among them, the most common and widely used method is liming, which is defined as the application of ground calcium and/or magnesium carbonates, hydroxides, and oxides aiming at increasing the soil pH, modifying its physical, chemical and biological properties (Edmeades and Ridley, 2003). Because of its great ameliorative effect, lime is commonly called the foundation of crop production or ‘‘workhorse’’ in acid soils (Fageria and Baligar, 2008). Upon liming, numerous authors have reported decreases of Al^{3+} in the soil solution as well as in the exchange complex (e.g., Delhaize et al., 2007; Prado et al., 2007; Álvarez and Fernández, 2009), improved soil structure (Crawford et al., 2008), significant yield increases (Buri et al., 2005; Fageria and Baligar, 2008), increases in P uptake by plants (Haynes, 1982; Fageria and Santos, 2008), higher abundance and diversity of earthworms (Bishop, 2003); and improved organic matter decomposition and nutrient mineralization (Bradford et al., 2002).

Acid soils have also high phosphorus fixing capacity. Therefore, In addition to Al^{3+} toxicity, low P availability to crops is also cited as another factor limiting crop production on acid soils (Barber, 1995). Phosphorus deficiencies and aluminum toxicities often occur simultaneously in many acid soils and are thought to be responsible for poor crop yields in acid soils. Therefore, applications of both lime and phosphorus fertilizer is frequently required for successful crop production. However, as the fixed phosphorus would be released for plant uptake after liming, the amount of additional phosphorus needed has to be determined experimentally (Waigwa et al., 2003).

Tolerance to Al toxicity or acidic soils differs greatly among cereal species, and barley is usually considered the most susceptible member of the Poaceae (Garvin and Carver, 2003). The Al tolerance order as reported is maize> rye> triticale> wheat> barley (Polle and Konzak, 1985), rye> oats> millet> bread wheat> barley> durum wheat (Bona et al., 1993), and rice> maize> pea> barley (Ishikawa et al., 2000). Barely is more tolerant to alkaline soils, and a pH of 6- 8.5 is generally acceptable. Fifty per cent yield reductions in barley were reported when grown in naturally acidic soils (pH 4.9) compared to that grown on pH 5.8 (Gallardo et al., 1999).

In Ethiopia, barley is the most important cereal crop with total area coverage of 1,046,555 hectares and total annual production of about 1.7 million tons during main growing season (CSA, 2011). Even though, the problem of soil acidity is considered to be one of the major bottlenecks for barley production in the highlands of Ethiopia, it is still a problem that has not been addressed in depth, and yet widespread decline in barley productivity has been observed in the country. Liming is not a common practice used for barley production in the highlands of Ethiopia. To mitigate the negative effects soil acidity, and low soil fertility, traditionally farmers practice barley-fallow production system. Such practice seems to degrade the soil resource in the long-run, and will not be sustainable due to severe soil erosion from bare fallows. In such type of production system, application of phosphorus fertilizer is not commonly practiced by farmers. To protect a potential loss of grain yield, at least a maintenance application of 10 kg P ha^{-1} is needed for responsive sites that had soil test P levels above the critical levels (Getachew and Berhane, 2013). However, it varies depending on the soil type, preceding crop, barley variety used and the prevailing environmental conditions. Therefore, aluminum toxicity and Phosphorus deficiency are the two major factors limiting barley production on acid soils, and are partly responsible for the seasonal food shortages in some parts of the highlands of Ethiopia. Hence, liming and phosphorus fertilization appears to be among the most important operations required to boost barley productivity in this regions. There is no or little research information available in literature on the effect of lime and phosphorus fertilizer in barley-fallow based production systems in the highlands of Ethiopia. In response to this, field experiments were conducted to fill the gap with the following objectives; (1) quantify changes that would occur on soil pH and exchangeable acidity as a consequence of applications of different rates of lime; (2) assess the effects of different levels of lime and phosphorus on barley grain yield and yield components.; (3) determine the optimum combinations of lime and phosphorus fertilizer required to increase barley productivity.

2 Materials and Methods

2.1 Site descriptions

The study was carried out during 2010 and 2011 cropping seasons on an experimental field located at Wetabecha Minjaro (9° 05′ 55″ N, 38° 36′ 21″ E, altitude 2565 m a.s.l.) in the central highlands of Ethiopia. The site is typically characterized by flat plains with cool subtropical climate. Annually, about 1100 mm rainfall is received, and the rainfall pattern is bimodal in distribution (short and long rainy season). The experiment was conducted during long rainy season which extends from June to September. The soils are classified as Nitisols with deep, red, well-drained tropical soils (IUSS, 2006). In these soils, soil acidity (pH< 5) and associated low nutrient availability are constraints to crop production. The major cereal crop grown in the area is food barley. The crop is stable food and source of cash income for the majority of the people living in higher altitudes in the country.

2.2 Field operations, experimental design and treatments

Before the start of the experiment, soil samples were collected from the experimental plot for analysis of selected soil physical and chemical properties (Table 1).

Table 1. Selected soil properties before establishment of the experiment.

Parameters	Values
Particle size distribution	
Sand	21.25
Silt	38.75
Clay	40.00
Bulk density (g cm^{-3})	1.15
pH (H_2O 1:2.5)	4.8
Exchangeable acidity (cmol($_+$)/kg)	1.32
Organic carbon (%)	2.46
CEC (cmol ($_+$) kg^{-1})	19.36
Total nitrogen (%)	0.22
Available phosphorus (mg kg^{-1})	9.4
Exchangeable K (cmol ($_+$) kg^{-1})	1.09
Exchangeable Na (cmol($_+$) kg^{-1})	0.15
Exchangeable Ca (cmol($_+$) kg^{-1})	0.17
Exchangeable Mg (cmol($_+$) kg^{-1})	1.43

Land preparation was uniformly performed across all plots by tractor mounted moldboard plough to 30 cm soil depth. Subsequent tilling operations were done by harrowing to about 10 cm depth by conventional tillage. Lime was evenly applied to treatment plots one month ahead of planting. A high quality limestone (98 % CaCO3, 99.5 % <250 µm in diameter) was used. All plots were hand weeded at 30 and 60 days after sowing. Faba bean (*Vacia faba L.*) was the preceding crop for barley. The amount of lime that was applied at each level was calculated on the basis of exchangeable acidty concentration of the site (Kamprath, 1984), assuming that one equivalent of exchangeable acidity would be neutralized by an equivalent of $CaCO_3$. The mean exchangeable acidty of the study site was 1.32 $cmol_+ \ kg^{-1}$. The liming experiment consisted factorial combinations of five levels of lime (0.0x, 0.5x, 1.0x, 1.5x and 2.0x) and four levels of Phosphorous (0, 10, 20 and 30 kg P ha^{-1}) in a randomized complete block design. The corresponding lime rates were 0, 0.55, 1.10, 1.65 and 2.2 Mg ha^{-1}. A total of twenty treatments in three replications were used in the experiment. Phosphorus was broadcast applied in the form of triple superphosphate (TSP), and the recommended rate of nitrogen for barley i.e. 50 kg ha^{-1} was applied uniformly to all treatments including control plots. A high yielding barley variety named HB-1307 was used as a test crop at a seed rate of 125 kg ha^{-1}. The plot size used was 4.5 ×5.1 meters (22.95 m^2). Data were collected on barley grain yield and yield components. At crop maturity, the whole plot area (22.95 m^2) was hand harvested at ground level from each plot for determination of grain yield and biomass yield. Grain yield was adjusted to 12.5% moisture content. Data on yield components were determined from random sample measurements of each parameter following the standard procedures of Anderson and Simmons (2002). Soil samples were randomly collected prior to experimentation and after harvesting for analysis of soil pH and exchangeable acidity. Soil pH was determined by using a pH meter in a 1:2.5 soil/water suspension using pH meter, and exchangeable acidity was extracted by 1M KCl (Mclean, 1965).

2.3 Statistical analysis

Analysis of variance was performed using SAS statistical software version 9.1 (SAS Institute, 2001). A Proc GLM model was constructed to compare the measured agronomic parameters for both years separately as well as combined over years. Significance differences were set at $p<0.05$. When the effects were found significant, further analysis was made using Tukey multiple comparison test. Pearson correlation coefficients were also used to assess the significance of the relationships between yield and yield components.

The mathematical formulation of the model is:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + \beta\gamma_{jk} + \varepsilon_{ijk}$$

with i=1, 2, 3 for the blocks, j=1,…,5 for the levels of lime and k=1,..,4 for the levels of phosphorus fertilizer, and being:

$Y_{ijk} =$ observed value of the dependent variable for the level of lime j and level of phosphorus k in the block i.

$\mu =$ general mean effect; $\alpha_i =$ main effect of the block i.; $\beta_j =$ main effect of the level of lime j; $\gamma_k =$ main effect of the level of phosphorus k; $\beta\gamma_{jk} =$ interaction effect of the level of lime j with the level of phosphorus k; $\varepsilon_{ijk} =$ random error in the dependent variable for the level of lime j and level of phosphorus k in the block i; The assumptions for the model were:

- ε_{ijk} independent and identically distributed
- $\varepsilon_{ijk} \sim N(0, \sigma^2)$ with σ^2= random variance for errors.

3 Results

3.1 Soil pH and exchangeable acidity

A soil analysis result after two years of liming is depicted in Fig. 1 and 2. Results indicated that soil pH was significantly ($p<0.05$) increased and exchangeable acidity was markedly reduced to a negligible level.

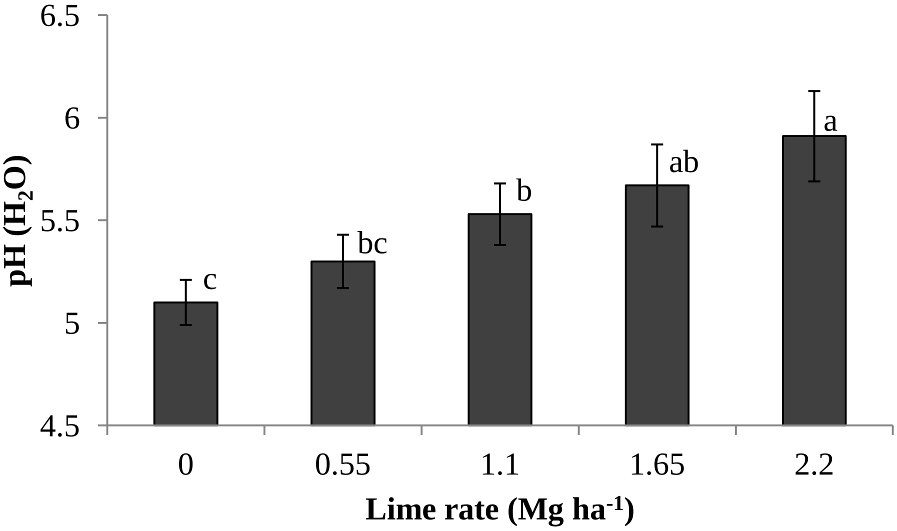

Fig. 1 Soil pH as affected by successive applications of lime (after two years of lime application). Bars are standard error of the mean (n=3). Similar letters above the vertical bars with same letters denote no significant difference at $p<0.05$.

Liming at the rate of 0.55, 1.1, 1.65 and 2.2 Mg ha^{-1} increased soil pH by 0.5, 0.7, 0.8 and 1.1 units, and decreased exchangeable acidty by 0.88, 1.11, 1.20 and 1.19 cmol$_+$ kg^{-1}, and respectively. Generally, with successive increase in the amounts of lime, soil pH values increased with a corresponding decrease in exchangeable acidty of the soil.

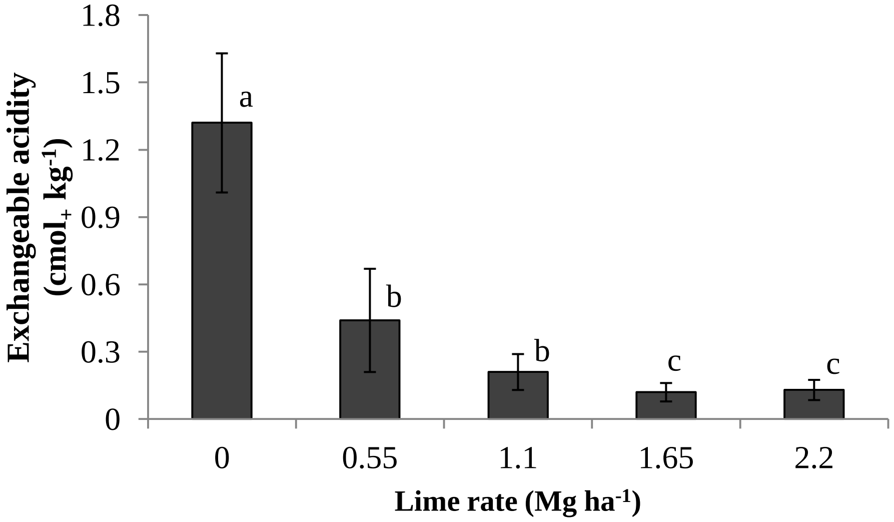

Fig. 2 Exchangeable acidity as affected by successive applications of lime (after two years of lime application). Bars are standard error of the mean (n=3). Similar letters above the vertical bars with same letters denote no significant difference at $p<0.05$.

3.2 Grain yield and yield components

Mean thousand seed weight (TSW), number of seeds per spike (NSPS) and hectoliter weight (HLW) as affected by different levels of lime and phosphorus fertilizer is presented in Table 2. Since the interaction effects of lime and P were not significant for yield components, their individual effects are presented. Analysis of variance showed that all limed treatments had higher mean values of TSW, NSPS and HLW relative to control (no lime and P) in both 2010 and 2011 cropping seasons. Among the liming treatments, the highest rate (2.2 Mg ha^{-1}) of lime recorded the highest mean values TSW, NSPS and HLW during both years. However, applications of 2.2 Mg ha^{-1} lime were not statistically different from lime rate of 1.65 Mg ha^{-1}. Similarly, successive applications of phosphorus fertilizer also resulted in increased yield components of barley. Hence, the highest significant ($p<0.05$) mean values of TSW and NSPS were recorded with highest dose (30 kg P ha^{-1}) of phosphorus during both years.

Table 2. Mean values of thousand seed weight (TSW), number of spikes per seed (NSPS) and hectoliter weight (HLW) of barley as affected by different rates of lime and phosphorus.

	TSW (grams)		NSPS		HLW	
Lime rate (Mg ha^{-1})	2010	2011	2010	2011	2010	2011
0	43.4c†	46.9	34.3d	28.2c	63.3b	65.9b
0.55	45.7b	47.2	40.0c	29.1c	64.2a	66.0ab
1.10	47.3ab	47.2	43.3b	36.0b	64.5a	66.1ab
1.65	47.6a	47.6	45.9ab	44.3a	64.8a	66.2ab
2.20	48.1a	47.6	47.1a	45.5a	64.8a	66.6a
LSD (0.05)	1.7	ns	3.1	3.4	0.8	0.7
Phosphorus (kg ha^{-1})						
0	44.9c	46.3b	36.4c	27.2c	63.7b	66.0
10	45.8bc	47.5ab	40.2b	34.4b	64.1ab	66.0
20	47.1ab	47.7a	45.2a	41.2a	64.6a	66.3
30	47.9a	47.7a	46.7a	43.7a	64.8a	66.3
LSD (0.05)	1.5	1.3	2.7	2.9	0.7	ns

†Mean values within a column that share similar letters are not significantly different at $p<0.05$

Table 3 shows grain yield (2011), biomass yield, plant height at harvest, and number of tillers (2010 and 2011) as affected by different levels lime and phosphorus fertilizer. The highest mean grain yield, biomass yield, plant height and number of tillers were recorded in the lime amended plots. In 2011, grain yield obtained by applications of 1.65 and 2.2 Mg ha^{-1} lime was statistically comparable, and significantly superior to 0.55 and 1.1 Mg ha^{-1} lime rates. Similarly, grain yield obtained by application of 20 and 30 kg P ha^{-1} were also comparable, and significantly ($p<0.05$) higher than the control and applications of 10 kg P ha^{-1}. As expected, the lowest grain yield was recorded in control plots, with no lime, no P addition.

Table 3. Grain yield, biomass yield, plant height and number of tillers as affected by different levels of lime and phosphorus fertilizer on acid soils.

	Grain yield (kg ha^{-1})	Biomass yield (kg ha^{-1})		Plant height at harvest (cm)		Number of tillers /m^{-2}	
Lime rate (Mg ha^{-1})	2011	2010	2011	2010	2011	2010	2011
0	2895.8c†	7641d	7598.3d	97.3c	103.1b	261c	309.8b
0.55	3691.9b	9850.5c	8990.0c	105.9b	108.3a	283.4b	320.5b
1.10	3937.5b	11947.5b	10062.5b	108.7ab	109.8a	304.3a	322.8b
1.65	4340.0a	12790.9ab	11122.5ab	111.6a	110.8a	315.5a	327.7ab
2.20	4572.8a	13196.7a	11454.2a	112.4a	111.8a	320.0a	354.5a
LSD (0.05)	367	1146.8	1065.1	3.9	4.1	19.1	28.5
P levels (kg ha^{-1})							
0	3132.1c	8111.8d	7113.3c	101.1c	104.4b	263.7c	301.3b
10	3710.1b	10462.7c	9855.3b	106.3b	108.8a	288.6b	324.8ab
20	4258.1a	12254.4b	10982a	109.5ab	110.5a	313.3a	336.4a
30	4449.6a	13512.3a	11431.3a	112.0a	111.2a	321.8a	345.7a
LSD (0.05)	328.2	1025.7	952.6	3.5	3.7	17.1	25.5

†Mean values within a column that share similar letters are not significantly different at $p<0.05$

During first year (2010 cropping season), interaction effects of lime and P were observed on grain yield of barley (Fig. 3). Accordingly, the highest mean grain yield was obtained by applications of 1.65 Mg ha^{-1} and 30 kg P per hectare. However, successive applications of lime beyond 1.65 Mg ha^{-1} and phosphorus beyond 30 kg P per hectare could not successively increase barley grain yield.

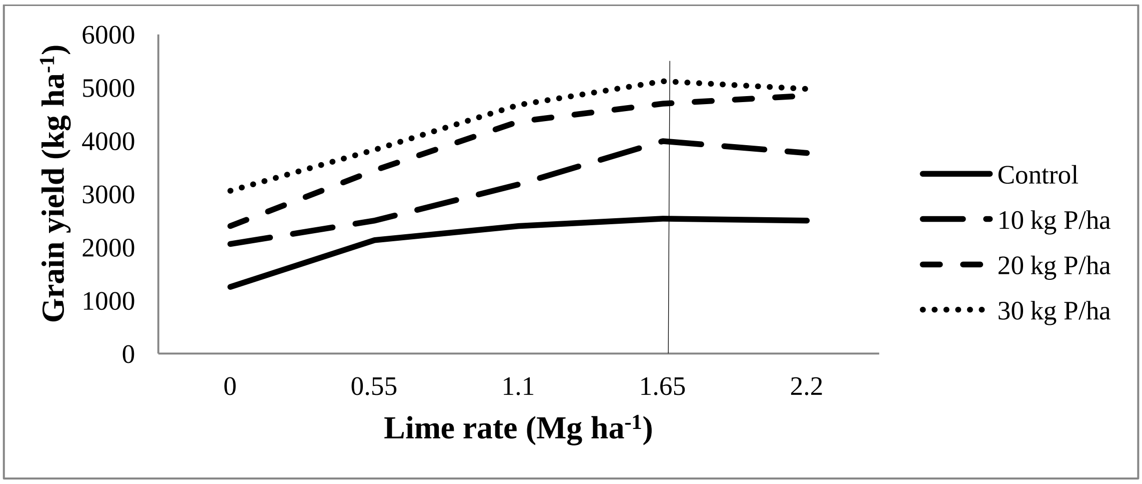

Fig. 3 Barley grain yield (kg ha^{-1}) in 2010: Interaction between rate of lime (Mg ha^{-1}) and rate of P (kg ha^{-1}) applied ($p<0.05$). The perpendicular line depicts where combined application of lime and P rate resulted in maximum grain yield.

Table 4. Number of tillers per square meter, TSW, HLW, grain yield, biomass yield and plant height as affected by lime and phosphorus fertilizer combined over two years.

Lime rate (L) (Mg ha^{-1})	No.of tillers/m^2	NSPS	TSW	HLW	Grain yield (kg ha^{-1})	Biomass yield (kg ha^{-1})	Plant height (cm)
0	285.4d†	31.2d	45.2b	65.0a	2544.4d	7619.7d	100.2c
0.55	303.1c	34.6c	46.6a	65.2a	3334.9c	9420.3c	107.1b
1.10	312.4bc	39.7b	47.2a	65.2a	3796.0b	11005.0b	109.3ab
1.65	323.8ab	45.1a	47.6a	65.4a	4213.1a	11956.7a	111.6a
2.20	335.0a	46.3a	47.7a	65.5a	4297.5a	12325.4a	111.7a
LSD (0.05)	16.9	2.2	1.1	ns	200.5	770.5	2.8
Phosphorus (P) (kg ha^{-1})							
0	282.5c	31.8d	45.6c	64.8b	2648.1d	7612.6d	102.7c
10	306.7b	37.3c	46.8b	65.2ab	3405.8c	10159.0c	107.5b
20	324.8a	43.2b	47.3ab	65.3ab	4103.9b	11618.2b	110.3a
30	333.8a	45.2a	47.8a	65.6a	4390.9a	12471.8a	111.3a
LSD (0.05)	15.1	2.0	0.9	0.5	179.4	689.2	2.5
Year (Y)	**	**	*	**	**	**	ns
LxP	ns	ns	ns	ns	ns	ns	ns
YxL	ns	**	**	**	ns	ns	ns
YxP	ns	*	ns	ns	**	**	ns
YxLxP	ns	ns	ns	ns	ns	ns	ns

Note: NSPS= number of seeds per spike; TSW= thousand seed weight; HLW= hectoliter weight; †Mean values within a column that share similar letters are not significantly different at $p<0.05$; $^{*,\ **}$Significant at $P < 0.05$ and $P < 0.01$ probability levels, respectively; ns = Not significant

The effects of lime and P fertilizer on grain yield and yield components of barley combined over two years is presented in Table 4. Our results showed that the highest significant grain yield and biomass yield were obtained by application of 1.65 and 2.2 Mg ha^{-1} lime. Statistically, these two lime rates were comparable, and significantly ($p<0.05$) superior to control (no lime), 0.55 and 1.1 Mg ha^{-1} of lime. Phosphorus applications combined over two years also significantly ($p<0.05$) affected yield and yield components of barley. Accordingly, the highest significant barley grain yield was obtained by application of 30 kg P ha^{-1}. Additions of 10, 20 and 30 kg P ha^{-1} have also increased grain yield by about 29, 55 and 66 % as compared to control without P additions. Year of cultivation had also significant effect on the yield and yield components of barley in this study (Fig. 4). Hence, grain yield of barley obtained during 2011 was significantly higher than the yield obtained in 2010.

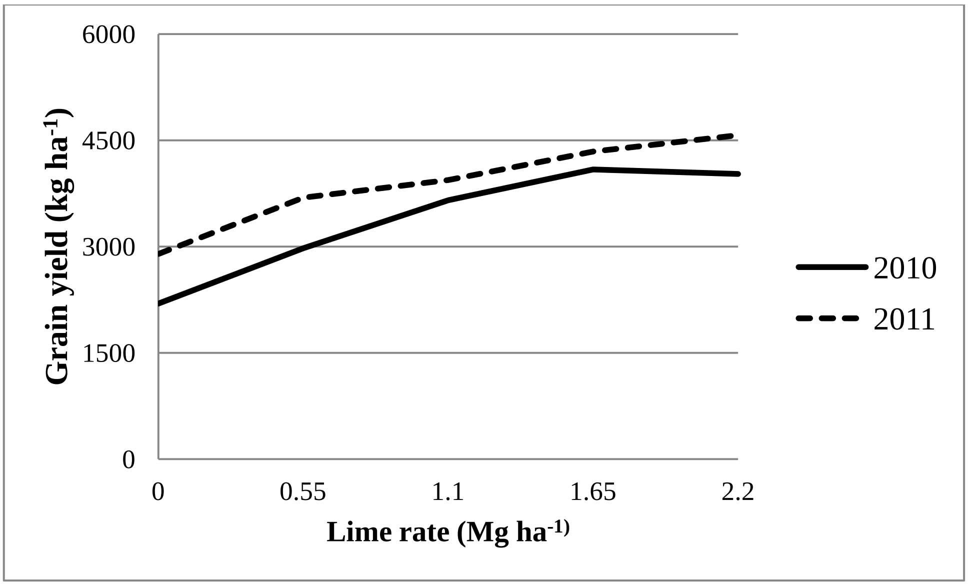

Fig. 4 Mean grain yield of barley as affected by year cultivation

3.3 Relationships between grain yield and yield components

The correlation between grain yield and yield components is presented in Table 5. Grain yield was positively correlated with plant height, number of tillers per square meter, TSW and biomass yield, and the correlation was significant at $p<0.0001$. However, grain yield was most strongly correlated with biomass yield (r =0.76), followed by number of tillers per square meter (r = 0.71) and plant height (r = 0.71). Similarly, biomass yield had positive and significant correlation coefficients with plant height, number of tillers per square meter, TSW and NSPS. However, there was no significant ($p>0.05$) correlation between biomass yield and HLW.

Table 5. Correlation matrix among grain yield and yield components in acid soils amended with lime and P fertilizer.

Parameters	GY	BY	Ph	NTM^2	TSW	HLW
GY						
BY	0.76***					
Ph	0.71***	0.65***				
NTM2	0.71***	0.53***	0.51***			
TSW	0.54***	0.45***	0.51***	0.51***		
HLW	0.37***	0.07ns	0.33***	0.45***	0.33***	
NSPS	0.66***	0.78***	0.52***	0.41***	0.29***	- 0.06ns

Note: GY= grain yield; BY= biomass yield; Ph= plant height; NTM^2= number of tillers in square meter; TSW= thousand seed weight; HLW= hectoliter weight, ***=$P<0.001$, ns= not significant

4 Discussion

4.1 Soil pH and exchangeable acidity

Soil pH generally increased in a linear fashion with increasing lime rate. The increase was highest with applications of the maximum rate (2.2 Mg ha^{-1}) of lime. When lime is added to acid soils that contain high aluminum and H^+ concentrations, it dissociates into Ca^{+2} and OH^- ions. The hydroxyl ions will react with hydrogen and aluminum ions forming aluminum hydroxide and water, thereby increase soil pH in the soil solution. Meanwhile, applications of the highest rate of lime appreciably reduced soil echangegeable acidty, which was 1.32 cmol$_+$ kg^{-1} at the start of the experiment to a negligible level of 0.12 cmol$_+$ kg^{-1} after two years. Many authors (e.g., Fageria and Stone, 2004; Fageria, and Baligar, 2008; Álvarez and Fernández, 2009) have also reported that liming raises soil pH, base saturation, and Ca and Mg contents, and reduces aluminum concentration.

4.2 Effect of P on grain yield and yield components

In our study successive applications of P fertilizer increased grain yield and yield components, and counteracted Al toxicity by precipitating exchangeable acidity as $AlPO_4$. This could be the reason why large applications of phosphate fertilizers to acid soils overcome the toxic effects of Al and thereby improve growth of plants. A major characteristic of Al toxicity is an inhibition of the uptake and translocation of P by plants (Foy and Fleming, 1978). Thus, liming acid soils often increases P uptake by plants by decreasing A1 toxicity rather than by an effect on soil P availability, per se (Haynes and Ludecke, 1981). After reviewing of liming on phosphate availability, Haynes (1982) concluded that large additions of phosphates to acid soils reduce the injurious effects of Al ions by precipitating it from the soil and supplying sufficient phosphate for plant metabolic activity. However, the classical explanation of increased phosphate availability following liming is that in the short-term, the increased pH results in the hydrolysis of strengite and variscite with the release of phosphate ions into soil solution (Negeri, 1984).

4.3 Effect of lime on grain yield and yield components

An increasing response to applied P with increasing rates of added lime have been attributed to either an improved rate of P supply by the soil or an improved ability of the plant to absorb P when Al toxicity has been eliminated. Hence, liming induced favorable conditions for plant growth was the main reason for yield increment of barley in this study. Numerous authors (Scott et al., 1999; Farhoodi and Coventry, 2008; Álvarez and Fernández, 2009) also reported that application of lime at an appropriate rate brings several chemical and biological changes in the soil, which is beneficial or helpful in improving crop yields in acid soils. Studies elsewhere (e.g., Farhoodi and Coventry, 2008; Wang et al., 2011) reported that yield increase from liming is mainly associated with an increase in soil pH and a reduction in plant uptake of Al and Mn. Responses of applied lime could be affected by many factors in soil. However, type of crop species, time of application and environmental variables such as moisture have subtle effect on applied lime. In this study, the higher grain yield observed in 2011 might be attributed to solubility and downward movement of lime as the time progresses, and normal rainfall with uniform distribution throughout growing season in 2011 as compared 2010. Similar yield increments with time in limed plots were reported by (Meng et al., 2004).

4.4 Mechanisms of yield increase due to lime and P applications

Several mechanisms are involved in increasing yield and yield components of barley when lime and P are used to ameliorate acid soils. Past laboratory and field studies conducted to determine how phosphorus availability responds to lime addition reported that liming enhances P uptake by alleviating Al toxicity and thereby improving root growth (Bolan, 2003; Haynes, 1982; Fageria and Santos, 2008). The improved root growth would allow a great volume of soils to be explored. This in turn favors improvement of barley grain yield and yield components. Many authors (e.g., Meng et al., 2004, Moir and Moot, 2010) also reported that liming increased soil pH and significantly reduced the concentrations of exchangeable acidity in the soil. The observed significant lime×P interaction is in the first year (2010) is typical of P deficient, highly-weathered, acid soils (Friesen et al., 1980).

4.5 Correlations of yield and yield components

Grain yield in cereals is the product of its yield components. Consequently, yield components of barley such as number of tillers per square meter, NSPS, TSW and biomass yield were highly correlated with its grain yield. Numerous authors (Ortiz et al., 2002; Abledo et al., 2003) have also reported significant associations of barley grain yield with its yield components. Results obtained in the present investigation on soil applications of lime and phosphorus fertilizer clearly showed that the remarkable increase in number of seeds per spike has greatly contributed to increase in grain yield barley during 2010 as well as 2011. Many previous authors (Baethgen et al., 1995; Pablo, et al., 2004) have also reported increase in grain yield due to number of grains per unit land area.

5 Conclusions

For long time, soils of the study area were considered less suitable for crop production. The results of this study, however, clearly demonstrated that these soils are responsive to lime and phosphate fertilizer applications. Overall, results showed that there were significant changes in soil pH and exchangeable acidity as a result of amendment through liming. Applications of 1.65 Mg ha^{-1} lime drastically decreased the exchangeable acidity to the minimum level, and raised soil pH close to the optimum pH requirement of barley. Hence, for sustainable and higher productivity, barley production in the highlands of Ethiopia should entail applications of 1.65 Mg ha^{-1}, 30 kg P ha^{-1}, and use of improved high yielding barley varieties. However, as soils vary from site to site, the amount of lime applied should be based on the concentrations of exchangeable acidity of site. Therefore, in light of this finding, short-fallow periods currently practiced by farmers to mitigate the negative effects of soil acidity would not be a long-term solution due to rapidly growing population, and prevalence of severe soil erosion from bare fallow fields. The lime and P rates obtained in this study could serve as a reference to boost barley production in the study area and areas with similar ago-ecology having soil acidity problems.

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