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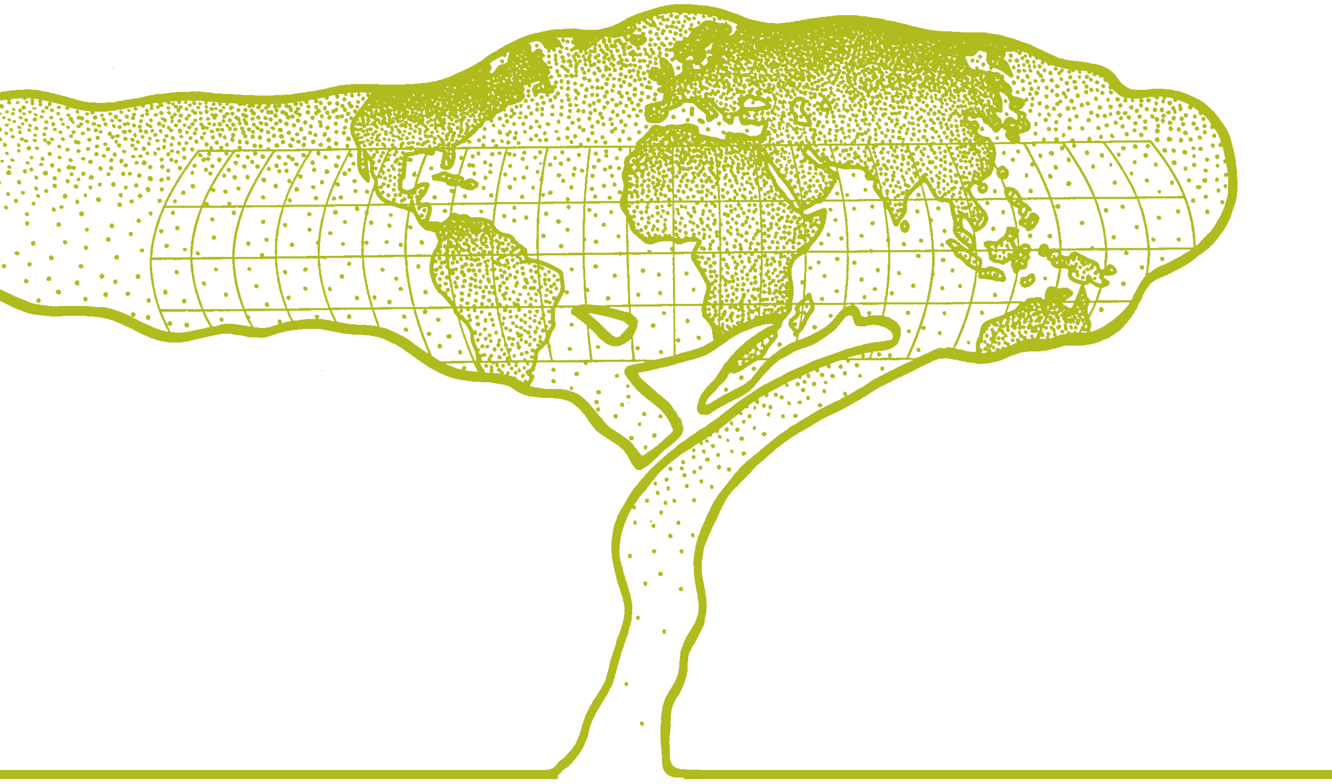

Mesele NEGASH

The indigenous agroforestry systems of the south-eastern Rift Valley escarpment, Ethiopia: Their biodiversity, carbon stocks, and litterfall

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TROPICAL FORESTRY REPORTS

TROPICAL FORESTRY REPORTS contains (mainly in English) doctoral dissertations, original research reports, seminar proceedings and research project reviews connected with Finnish-supported international development cooperation in the field of forestry.

Publisher Viikki Tropical Resources Institute (VITRI)
P.O. Box 27, FI-00014 University of Helsinki, Finland
(address for exchange, sale and inquiries)

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Website http://www.helsinki.fi/vitri/

Cover Design Lesley Quagraine

Suggested reference abbreviation:
Univ. Helsinki Tropic. Forest. Rep.

The indigenous agroforestry systems of the south-eastern Rift Valley escarpment, Ethiopia: Their biodiversity, carbon stocks, and litterfall

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Academic dissertation
for the degree of Doctor of Science (DSc) in Agriculture and Forestry

Department of Forest Sciences
Faculty of Agriculture and Forestry
University of Helsinki

To be presented, with the permission of the Faculty of Agriculture and Forestry of the University of Helsinki, for public discussion in Walter Hall, Viikki EE-Building, Agnes Sjöbergin katu 2, Helsinki on 22 November 2013, at 12 o'clock noon.

Helsinki 2013

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ISBN 978-952-10-9414-9 (pbk.)
ISBN 978-952-10-9415-6 (PDF)
ISSN 0786-8170
Unigrafia Oy
Helsinki 2013

ABSTRACT

Agroforestry systems integrate trees into agricultural landscapes and provide a number of ecosystem services. Studies on agroforestry systems have so far mainly focused on their spatial design, food production, soil fertility management and system interactions, and little attention has been given to their ecosystem services, such as biodiversity conservation and carbon sequestration.

The objectives of the study were to determine and evaluate the floristic diversity, the above- and below-ground biomass carbon (C) and soil organic carbon (SOC) stocks, and the litterfall production and associated C and nitrogen (N) fluxes of three indigenous agroforestry systems in south-eastern Rift valley escarpments, in Gedeo, Ethiopia.

Three indigenous agroforestry systems studied were Enset (*Ensete ventricosum* (Welw.) Cheesman), Enset-coffee, and Fruit-coffee. C stocks in biomass and soil (0–60 cm layer) (Mg C ha^{-1}) were determined for each agroforestry system, and litterfall collected for seven woody species for a period of 12 months. Allometric equations were derived to estimate the biomass of enset and coffee while published allometric equations were used to determine the biomass of other tree and shrub species. The biomass values were then converted into C stocks.

A total of 58 woody species, belonging to 49 genera and 30 families were recorded. Of all woody species identified, 86% were native. The Enset and Enset-coffee systems contained the highest proportion native woody species (92% and 89%, respectively). In all, 22 native woody species were recorded as “of interest for conservation” using International Union for Conservation of Nature (IUCN) Red lists and local criteria.

The square power equation using stump diameter at 40 cm (d_{40}), $Y = b_1 d_{40}^2$ ($R^2 > 0.80$) and the power equation using d_{10} (diameter at 10 cm height) and height, $Y=b_1 d_{10}^{b2} h^{b3}$ ($R^2 > 0.90$) were found to be the best for predicting aboveground biomass of coffee (*Coffea arabica* L.) and total biomass of enset, respectively. The agroforestry C stock (biomass C plus SOC) was the highest for the Enset-coffee system (293 Mg C ha^{-1}) and the lowest for the Enset (235 Mg C ha^{-1}) system. Biomass (above- and belowground) C stocks were the highest for the Enset-coffee system (116 ±65 Mg C ha^{-1}), followed by Fruit-coffee (79 ±24) and Enset (49 ±44) systems. Trees (fruit and non-fruit) formed 81, 89 and 80% of total biomass C stocks for Enset, Enset-coffee and Fruit-coffee agroforestry systems, respectively; the remainder being coffee, enset, litter, herbaceous plants, and fine root biomass. SOC to biomass C ratios were 4:1 for the Enset system, 2:1 for Fruit-coffee system, and 1.5:1 for the Enset-coffee system.

Monthly litterfall production per unit crown area decreased in the order: *Croton macrostachyus* Del. > *Erythrina brucei* Schweinf. > *Cordia africana* Lam. > *Persea americana* Mill. > *Mangifera indica* L. > *Coffea arabica* L. > *Millettia ferruginea* (Hochst.) Bak. The annual litterfall production (sum of seven species) averaged 7430 kg ha^{-1}(land area) for the Enset system, 10187 for the Enset-coffee system and 12938 for the Fruit-coffee system. The associated annual C fluxes (kg ha^{-1}) were 2803 (Enset system), 3928 (Enset-coffee system) and 5145 (Fruit-coffee system) and the corresponding N fluxes were 190 (kg ha^{-1}), 257 and 278.

This research shows that the native woody species and C stocks observed in the three indigenous agroforestry systems were among the highest reported for tropical agroforestry systems. Thus, it should be given more attention, to counteract the local threat of these species from the wild and offset greenhouse gases (GHGs) emission. The indigenous agroforestry systems of the south-eastern Rift Valley escarpment in Ethiopia form a win-win opportunity by supporting livelihoods and providing food for a dense human population while also maintaining native floristic diversity and mitigating climate change through carbon sequestration.

Key words Biomass, Carbon sequestration, Coffee, Enset, Floristic diversity, Gedeo, Indigenous agroforestry system, Litterfall fluxes, South-eastern Ethiopia

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PREFACE

First and for most, Praise be to the almighty GOD and to the Blessed Virgin Mary mother of God who have helped me to materialize my study in peace and with great honour. My mother Mrs. Kelemua Meta who gave me her love and care, and for bringing me up in the education ladder deserves especially thanks.

I was first inspired by the marvels of natural resource management practice of the Gedeo farmers, south Ethiopia, when I went to the area for a commissioned research in 2005. Of course, farmers practice such land use not for academic or scientific purposes, but it is their livelihoods. The indigenous agroforestry system on steep terrain (up to 70% slope) is forest-like landscape and carries among the highest population density in Africa (up to 1300 persons/ km^2). My observation, as a researcher, went far beyond appreciating the system. Two important points have initiated the study: the need to know the contribution of the indigenous agroforestry system to biodiversity conservation and climate change mitigation. In my opinion, local smallholder farmers should be rewarded for their roles in maintaining ecosystem services besides production benefits. In order to replicate the sound and time-tested Gedeo agroforestry systems in different parts of Ethiopia and the tropics at large, it is necessary to produce empirical scientific evidences. The results of this study can be used to persuade the scientific community, environmental advocates, policy makers and donors to take into account agroforestry in their natural resource management strategies. Thus, above all the Gedeo farmers deserve especial acknowledgment.

This study would have not been possible without funding by different institutions such as Finnish Cultural Foundation, Swedish SIDA, International Foundation of Science (IFS), Finnish Society of Forest Science, Viikki Tropical Resources Institute (VITRI), and Department of Forest Sciences/University of Helsinki. Thank you all. I deeply acknowledge my home institution Wondo Genet College of Forestry and Natural Resources, Hawassa University for allowing me to carry out the postgraduate study and for their material and logistical supports during the field work.

I deeply acknowledge my three supervisors: my heartfelt gratitude goes to my main supervisor Associate professor Mike Starr for his excellent guidance, constructive comments and unfailing support throughout the study. Besides, I learnt a lot from him especially on precision and accuracy on data management and commitment in scientific writing process. I also deeply acknowledge my supervisor Prof. Markku Kanninen for his excellent guidance and constructive comments on the study. Especially, I gained a lot from our discussion on allometric equations and sharing relevant and latest scientific literature on the subject studied. My heartfelt gratitude also goes to Dr. Eshetu Yirdaw for his excellent guidance, constructive comments and valuable help from the beginning of the study. Especially, I got a good exposure from him to use the software Non-metric multidimensional scaling (NMDS). His support was not only scientific guidance but also brotherly advice and consultation on personal matters. Last, but not least, I am deeply indebted to Prof. Em. Olavi Luukkanen for accepting me as a doctoral student and to join VITRI at the very beginning of the study. I also thank Dr. Laekmariam Berhe, co-author for one of the articles, for his excellent consultation on the use of R statistical Software.

I am very indebted to the reviewers of this dissertation, Dr. Pekka Nygren and Dr. Erik Karltun for their thorough and constructive comments. Their inputs have greatly improved the quality of the dissertation. Special thanks also go to Dr. Melaku Bekele, Dr. Abdu Abdulkadire, Dr. Abedela Gure (Wondo Genet College Staff), Dr. Vesa Kaarakka (Ministry of Foreign affair of Finland) and Dr. Mats Sandwall (SLU) who facilitated and supported my study at the beginning. My friends and officemates Adrián Monge, Dipjoy Chakma, Jouni Pasanen and Michael Poku-Marboah are also greatly acknowledged for friendly sharing of ideas in our spare time. I would also like to extend my sincere thanks to my former and present colleagues and friends of VITRI, namely, Dr. Mohamed El Fadl, Dr. Jörn Laxén, Dr. Kurt Walter, Dr. Fobissie Kalame, Dr. Seyd Ashraful, Dr. Loice Omoro, Dr. Salla Rantala, Dr. Kourosh Kabiri, Mamo Kebede, Mustafa Fahmi, Biar Deng, Minna Stubina, Wafa Abakar, Daniel Etongo and Yitagesu Tekle.

I am also indebted to my brother Mr. Eyob Tadesse for his great assistance during the field inventory work. Mr. Estifanos (laboratory assistant), Mr. Milkiase Safa, Mr. Aleyemhau Abiso, Mr. Shubisa Godana and Mr. Botela Gujo (drivers) are also greatly acknowledged for their help during sample collection on the field. I am also pleased to forward my great appreciation to Gedeo zone, Bule, Wonago and Dilla Zuria districts' Agricultural offices for allowing me and facilitation of the field work in their respective localities. I am sincerely indebted for the field assistants, namely, Mr. Mangistu, Mr. Asrat, Mr. Eliase, Mr. Seme, Mr. Muluken, Ms. Etabeze, Ms. Berhane, Mr. Shebru, Mr. Bogale and Mr. Gedamu for their assistance during field data collection. My special thanks also go to Ms. Tensaye and her family for their unreserved support during my stay at the study sites. I also sincerely thank my colleagues and friends, Dr. Zebene Asfaw, Dr. Tefera Mangistu, Dr. Bekele Lemma, Dr. Fantaw Yimer, Dr. Birahanu Biazene, Dr. Girma Keleboro, Mr. Bereket Roba, Mr. Megressa Debele, Mr. Habtamu Tadesse, Mr. Abrham Belay, Ms. Genet Negash and Mr. Tariku Olana for their moral support and encouragement during the study.

I also wish to express my gratitude to Ethiopian PhD students at University of Helsinki for sharing information in our spare times, namely, Feven Tigistu, Aregu Asrese and Brook Tekele. It is also worthy to mention my deep gratitude to Ethiopian friends living in Helsinki, Mr. Bruck Tadesse, Mr. Sehemles Tafesse, Dr. Dawite Admase, Mr. Keffyalew Gebremedhin, Mr. Daniel Mamo, Mrs. Meaza, Dr. Yeshetela Degefu, Mr. Wondemu, Mrs. Solome, Dr. Yodit, Mr. Demese, Mrs. Yemeserach, Mr. Zewdu and Mrs. Tirsit. They made me to feel at home during my stay in Helsinki. I also acknowledge all individuals and institutions that are not mentioned but directly or indirectly have contributed to my study.

Finally yet importantly, my heartfelt appreciation and thanks go to my wife Eyerusalem Demissie for her great commitment, endurance and taking care of our lovely kids Surafel Mesele and Rodas Mesele. My gratitude and cheers also go to my brothers Abiy Sahelu, Million Sahelu, Samson Sahelu and Tsegawe Sahelu for their moral support and encouragement.

Mesele Negash
November, 2013

LIST OF ORIGINAL PUBLICATIONS

This doctoral dissertation is based on five articles, which are roman numbered I−V. Articles (I, II, and III) are reprinted with the kind permission of the publishers, and the articles IV and V are the author version of the submitted manuscripts.

I. Mesele Negash, Eshetu Yirdaw, Olavi Luukkanen. 2012. Potential of indigenous multi-strata agroforests for maintaining native floristic diversity in the south-eastern Rift Valley escarpment, Ethiopia. Agroforestry Systems 85:9–28. DOI 10.1007/s10457-011-9408-1.

II. Mesele Negash, Mike Starr, Markku Kanninen, Leakemaraiam Berhe. 2013. Allometric equations for estimating aboveground biomass of *Coffea arabica* L. grown in the Rift Valley escarpment of Ethiopia. Agroforestry Systems 87:953–966. DOI 10.1007/s10457-013-9611-3.

III. Mesele Negash, Mike Starr, Markku Kanninen. 2013. Allometric equations for biomass estimation of Enset (*Ensete ventricosum*) grown in indigenous agroforestry systems in the Rift Valley escarpment of southern-eastern Ethiopia. Agroforestry Systems 87:571–581. DOI 10.1007/s10457-012-9577-6.

IV. Mesele Negash, Mike Starr, Markku Kanninen. 2013. Carbon stocks in the indigenous agroforestry systems of the south-eastern Rift Valley escarpment, Ethiopia. Submitted.

V. Mesele Negash, Mike Starr. 2013. Litterfall production and associated carbon and nitrogen fluxes of seven woody species grown in indigenous agroforestry systems in the south-eastern Rift Valley escarpment of Ethiopia. Submitted.

AUTHOR'S CONTRIBUTION

I. Mesele Negash planned the study, carried out the fieldwork, analysed the dataset, wrote the first version and finalized the manuscript. Eshetu Yirdaw together with Mesele Negash run the software Non-metric multidimensional scaling (NMDS), commented on the planning stage of the study and the first version of the manuscript. Olavi Luukkanen commented on the planning stage of the study.

II. Mesele Negash planned the study, carried out the fieldwork, analysed the dataset, and wrote the first version of the manuscript. Mike Starr commented on the planning stage of the study, revised and helped to finalize the manuscript with Mesele Negash. Leakemariam Berhe together with Mesele Negash analysed the allometric equations on the first version of the manuscript. Markku Kanninen commented on first version of the manuscript.

III. Mesele Negash planned the study, carried out the fieldwork, analysed the dataset, and wrote the first version of the manuscript. Mike Starr commented on the planning stage of the study, revised and helped to finalize the manuscript with Mesele Negash. Markku Kanninen commented on first version of the manuscript.

IV. Mesele Negash planned the study, carried out the fieldwork, analysed the dataset, and wrote the first version of the manuscript. Mike Starr commented on the planning stage of the study, revised and helped to finalize the manuscript with Mesele Negash. Markku Kanninen commented on the first version of the manuscript.

V. Mesele Negash planned the study, carried out the fieldwork, analysed the dataset, and wrote the first version of the manuscript. Mike Starr commented on the planning stage of the study, revised and helped to finalize the manuscript with Mesele Negash.

SYNONYMS AND ACRONYMS

AF	Agroforestry
AGB	Aboveground Biomass
ANOVA	Analysis of Variance
BGB	Belowground Biomass
CBD	Convention of Biological Diversity
CDM	Clean Development Mechanism
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
E	Enset system
E-C	Enset-Coffee system
FAO	Food and Agricultural Organization of the United Nations
F-C	Fruit-Coffee system
GHGs	Greenhouse Gases
GRDAO	Gedeo Rural Development and Agricultural Office
ha	hectare
ICRAF	International Centre for Research in Agroforestry
IPCC	Intergovernmental Panel for Climate Change
IUCN	International Union for Conservation of Nature
LOI	Loss-On-Ignition
LSD	Least Square Difference
MA	Millennium Ecosystem Assessment
MAB	Mean Absolute Bias
Max	Maximum
Mg	Mega grams (1 Mg=10^6 grams)
Mha	Million hectares
Min	Minimum
MoARDE	Ministry of Agriculture and Rural Development of Ethiopia
N_2O	Nitrous oxide
NMDS	Non-metric Multidimensional Scaling
Pg	Peta grams (1 Pg=10^{15} grams=1 billion tone)
PRESS	Prediction Residuals Sum of Squares
REDD	Reducing Emission from Deforestation and Forest Degradation
SD	Standard Deviation
SE	Standard error of the Mean
SEE	Standard Error of Estimate
SNNPRs	Southern Nations, Nationalities' and Peoples' Regional State
SOC	Soil Organic Carbon
UNFCC	United Nations Framework Convention on Climate change

SYMBOLS

B	bias
ca	crown area
ch	crown height
CN	Sørensen's quantitative index
cw	crown width
D	Index of agreement

d_{10}	basal diameter at 10 cm height
d_{30}	stump diameter at 30 cm height
d_{40}	stump diameter at 40 cm height
d	diameter at breast height
d_{130}	diameter at breast height
d_{200}	bole diameter at 200 cm height
d_i	diameter of the ith stem at breast height or stump height
Dmg	Margalef's diversity
E1/D	Simpson's evenness index
h	total height
H′	Shannon diversity index
h_{dom}	dominant height
h_p	pseudostem height
l	length
w	width
y	year

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1. INTRODUCTION

1.1 Agroforestry for ecosystem services

An ecosystem is part of the environment in which plant, animal and microorganism communities interact with each other and with the chemical and physical environment (Harrington et al. 2010). Linking ecosystems with human-welfare has led to the recognition of ecosystem services. The term ecosystem services first was used by Ehrlich and Ehrlich in 1981, but was originally termed as 'nature's services' by Westman in 1977 (Fisher et al 2009). The Millennium Ecosystem Assessment (2005) defines ecosystem services as "the benefits people obtain from ecosystems" while Fisher et al. (2009) defined ecosystem services as: "aspects of ecosystems utilized (actively or passively) to produce human well-being". Fisher et al. (2009) are emphasised two major aspects of ecosystem services: (1) they must be ecological phenomena, and (2) they have to be directly or indirectly utilized goods and services that have value to people. Ecosystem services are categorized into provisioning services (products obtained from ecosystems such as food, fuel, water, timber, and fibre), regulating services (benefit obtained from regulation of ecosystem processes including climate regulation, water purification, flood protection, disease protection, and waste management), cultural services (non-material benefits that provide recreational, education, aesthetic, and spiritual benefits) and supporting services (services that are important for provision of other services including biodiversity conservation, soil formation, oxygen production, photosynthesis, and nutrient cycling) (MA 2005, Harrington et al. 2010). The purpose of the Millennium Assessment (MA) is to assess the impact of ecosystem change on human well-being and to establish a scientific basis for the sustainable conservation and utilization of ecosystems. The assessment includes ecosystems ranging from undisturbed natural forests to ecosystems intensively managed and modified by humans, such as agricultural land (Fisher et al. 2009).

Agricultural land, including agroforestry and land for bioenergy crops (e.g. palm, corn, sugarcane, *Jatropha curcas* L.), is estimated to cover 40−50% of the Earth's land surface (Smith et al. 2007), occupying some of the most productive and carbon-rich soils. In the tropics, the area of agricultural land is rapidly increasing at the expense of natural forests (De Beenhouwer et al. 2013). About half of agricultural land has greater than 10% tree cover and, in some regions, the average tree cover reaches 30% (Garriety et al. 2010).

Agroforestry system is defined on the basis of components, structural arrangement, ecological and socioeconomic interactions within the system. The earlier definition by Lundgren (1982), agroforestry system is an interaction of woody species (trees and shrubs) with herbaceous plants (crops, pastures) and/or animal where there are ecological and economic interactions among the components. While Young (1983) defined agroforestry system as any land use that contributes to increase productivity of forest crops, food crops and livestock at the same land unit alternatively or simultaneously under local people's management practices, and ecological and economic condition of the area. The definition by Nair (1993) is similar with Young (1983) but in the Nair case, maintaining and integrating of various components in agroforestry system is intentional and carried out under levels of low technical inputs and in marginal lands. The above definitions more focussed on the productivity and components interactions in agroforestry. The most compressive and explicit definition of agroforestry system was given by International Centre for Research in Agroforestry (ICRAF 2000). Agroforestry is defined as "an ecologically based natural resource management system that integrates trees (for fibre, food and energy) with crop and/or animal on farms with aim of diversifying and sustaining income and production while maintaining ecosystem services" (ICRAF 2000). There are several forms of agroforestry but they are commonly classified into agrisilviculture (crops + trees), silvopasture (trees + animals) and agrosilvipasture (crop + trees + animals) systems (Nair 1985). Structurally, agroforestry systems can be classified into crop under tree cover, multi-strata agroforestry, agroforestry in linear arrangement, animal agroforestry, sequential agroforestry and minor agroforestry techniques (Torquebiabu 2000).

Agroforestry provides various ecosystem services. It is not only provides provisioning services such as diversification of household income, fibre, food and energy to local communities, but also provides cultural services such as agro-tourism, aesthetic values, demonstration and education. On top of this agroforestry provides regulating services such as soil conservation, watershed protection, pest control (Pandey 2002) and sinks for carbon and thereby contributing to the mitigation of global climate change (Nair 1998, IPCC 2000, Albrecht and Kandji 2003, Upadhyay et al. 2005, Schoeneberger 2008, Jose 2009, Jose and Bardhan 2012). Organic matter inputs from trees, crops and/or livestock in agroforestry systems improve soil fertility, primary productivity and biotic diversity, which are considered as supportive services. Despite a wide range of ecosystem services, little scientific attention has been paid to the role of agroforestry systems to conservation of native floristic diversity and climate change mitigation (Nair 2001, Kumar and Nair 2004, McNeely and Schroth 2006). Most studies on agroforestry systems in the tropics have focussed on experimental design, food production and soil fertility management. However, several studies have recommended the need for research into the role of agroforestry systems to native floristic diversity conservation and climate change mitigation (Backes 2001, Boffa et al. 2005, Albrecht and Kandji 2003, Montagnini and Nair 2004, Schoeneberger 2008, Jose 2009, Jose and Bardhan 2012, Nair 2012, De Beenhouwer et al. 2013). In this study, I have attempted to show how three indigenous agroforestry systems in the south-eastern Rift Valley escarpment of Ethiopia contribute to maintaining native trees and shrubs and the accumulation of ecosystem carbon stocks. The links among the study components are shown in Figure 1.

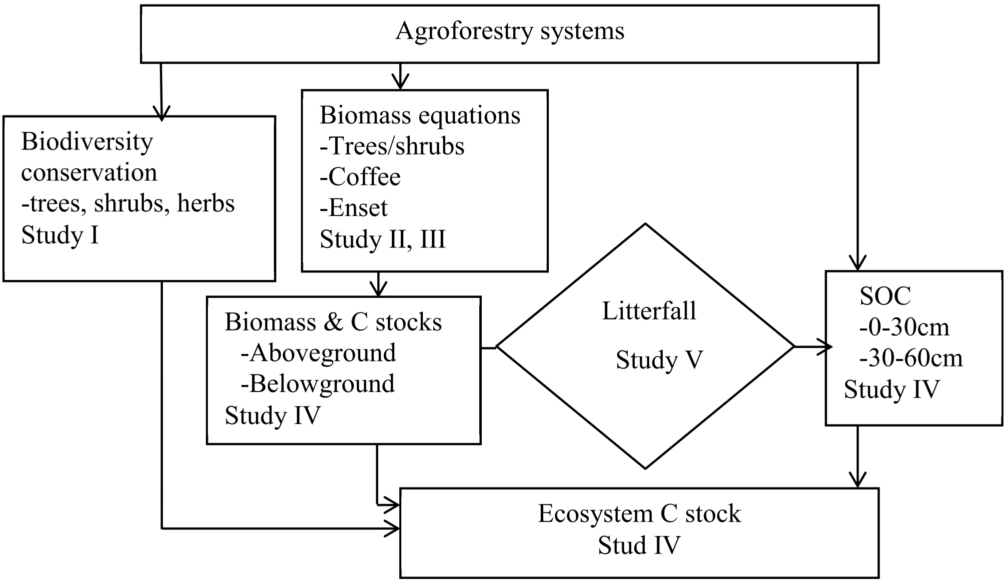

Figure 1. Links among the different components of the study.

Study I deals with the floristic composition of the three agroforestry systems. Since there are no allometric equations for estimating coffee and enset biomass (carbon) in these systems site, specific equations (Study II and III) were developed using sample plant harvesting and the inventory data obtained from study I. Study IV used the inventory data from Study I and the allometric equations developed for coffee and enset (Study II and III) and the results from soil sampling and analysis to determine and compare the carbon stocks of the three indigenous agroforestry systems. Study V was conducted to determine and compare the litterfall production of the dominant woody species (inventoried in study I) and the associated fluxes of C and N to the soil in the three agroforestry systems.

1.2 Agroforestry for biodiversity conservation

Biodiversity is the variability of all life forms across all levels of biological organization, i.e. from gene to ecosystem, and it includes the diversity within and between species, and between ecosystems (Zeide 1997, Atta-Krah et al. 2004, Magurran 2004). This variability reflects differences in the ecology, evolution and habitat of species, and to differences in the climatic, geographical and hydrological conditions of sites (Gascon et al. 2004).

In agricultural landscapes, biodiversity occurs as a mosaic of farms with differing crops and vegetation actively managed by farmers (Cromwell et al. 1999). Agroforestry often increases biodiversity through the integration of trees, shrubs, crops and/or animals into the system. Agroforestry contributes to biodiversity conservation through: (i) the provision of supplementary habitats for species that tolerate lower levels of disturbance (Jose 2009); (ii) conservation of remnant native species and their gene pools (Das and Das 2005; Harvey and Villalobos 2007); (iii) erosion control and water recharge thereby preventing the degradation and loss of surrounding habitat; (iv) buffering the pressure on deforestation of the surrounding natural habitat; and v) provision of corridors and stepping stones for persistence and movement of area-sensitive floral and faunal species through linking fragmented habitats in the landscape (Nyhus and Tilson 2004, McNeely and Schroth 2006, Bhagwat et al. 2008, Jose 2009).

Agroforestry systems also help to maintain a high number of species outside their native forest habitat. Conservation of woody species on smallholder farms for various traditional uses is an age-old practice, particularly in the tropics. For example, forest gardens in Sumarta and west Kalimantan, Indonesia have 50–80% of the diversity of comparable natural forest (Nobel and Dirzo 1997). De Beenhouwer et al. (2013) showed that converting coffee and cocoa agroforestry systems to plantation reduced total species richness by 46% while the conversion of natural forest to agroforestry resulted in only an 11% reduction in species richness. Farmers have a tradition of keeping valuable tree species and their farms act as islands or refuges (Tolera et al. 2008). At the landscape level, agroforestry has been shown to provide habitats suitable for a large number of native fauna and refuges including birds, bats, frogs, lizards, bees, beetles and ants (Schroth et al. 2004, Wilkie and Lee 2004, Vaughan and Black 2006, Harvey et al. 2006, Faria et al. 2007, Harvey and Villalobos 2007, Philpott et al. 2008, Uezu et al. 2008, Hoehn et al. 2010, Peters and Carroll 2012, Dáttilo et al. 2012, Poch and Simonetti 2013). Several studies also reported high number of plants species in tropical agroforestry systems (Table 1). So far, more than 3000 tree species have been documented (Simons and Leakey 2004).

There are considerable differences in species richness between agroforestry systems. Reviews show that the highest numbers of plant species are in traditional agroforestry systems, followed by coffee systems, tree-crop systems and cocoa systems, suggesting that traditional

Table 1. Floristic diversity reported in various agroforestry systems, the value in the parenthesis shows percentage of tree species recorded of the total number of species.

Agroforestry system	Place	Growth forms	No. species	Reference
Coffee systems				
Rustic coffee plantations	Rancho Grande, Mexico	Trees, shrubs, palms, herbs	45 (76)	Bandeira et al. (2005)
Multistrata coffee systems	Chiapas, Mexico	Shade trees	74	Soto-Pinto et l.(2007)
Coffee shade trees	Tacuba,El Salvador	Tree species	48−93	Méndez et al. (2009)
Coffee agroforests	Guinée Forestiére, Guinea	Mature trees	94	Correia et al. (2010)
Coffee–banana, Chagga homegardens	Mt. Kilimanjaro, Tanzania & Kenya	Woody, herbs, lianas, epiphytes, 400 crops	523 (16)	Hemp (2006)
Cocoa systems				
Cocoa farms with shade trees	Mount Cameroon	Tree species	50	Laird et al. (2007)
Cocoa forest gardens	Southern Cameroon	Non-cocoa tree species, herbs	362(33)	Hervé & Vidal (2008)
Cocoa agroforest + Mixed food crops	South-eastern Ghana	Tree species	27−34	Asase & Tetteh (2010)
Traditional homegardens				
Homegardens	South-western Bangladesh	Tree, shrub (51%), herb, climber	419(35)	Kabir &Webb (2008)
Homegardens	Bangladesh	Tree species	91	Bardhan et al.(2012)
Forest gardens	Central Sulawesi, Indonesia	Tree species	19–35	Kessler et al. (2005)
Java Homegardens	West Java, Indonesia	*All floristic species	602	Kumar & Nair (2004)
Urban & peri-urban gardens	Niamey, Niger	Fruit , non-fruit trees, vegetables	116(72)	Bernholt et al.(2009)
Traditional & modern homegardens	Kerala, India	Trees, shrubs, food crops	132(85)	Peyre et al.(2006)
Traditional agroforestry	Bungoma, Kenya	Trees, shrubs, lianas	253(67)	Backes (2001)
Tree-crop systems				
Tree species on agricultural land	Western Kenya	Woody plant species	70	Kindt et al. (2006)
Trees on farms	Mount Kenya	*Trees, shrubs, herbs	424	Kehlenbeck et al.(2011)
Crop fields and woody hedgerows	Peterborough, Ontario	*Woody species, herbs	193	Boutin et al. (2008)

*the share of tree species could not be traced in the report.

agroforestry systems are better for conservation of species than non-traditional systems. This difference in species richness is mainly due to management practices. The four tropical agroforestry systems with the highest recorded number of plant species are: (1) homegardens in west Java, Indonesia, (2) homegarden in Chagga, board between Tanzania and Kenya, (3) trees on agricultural land on Mount Kenya, and (4) traditional homegardens, south-west Bangladesh (Table 1). Kabir and Webb (2009) reported 419 plant species (59% native, including six species Red Listed by International Union for Conservation of Nature (IUCN)) in homegardens from six regions across south-western Bangladesh.

Agroforestry systems are therefore compliant with the Convention of Biological Diversity (CBD) (McNeely and Schroth 2006) and successfully make trade-offs between sustainable biodiversity conservation, resource utilization and human needs (Boffa et al. 2005). The biodiversity of agroforestry systems also enhances food security (Pandey 2002) and livelihoods (Atta-Krah et al. 2004, Boffa et al. 2005, Philpott et al. 2008).

1.3 Agroforestry and carbon storage

The carbon (C) sequestration capacity of agroforestry systems have been shown to vary with species composition, age, geographical location of the system (Jose, 2009), previous land use (Albrecht and Kandji 2003, Mutuo et al. 2005, Sauer et al. 2007), climate, soil characteristics, crop-tree mixture, and management practices (Pandey 2002, Montagnini and Nair 2004, Dossa et al. 2008, Schulp et al. 2008).

The average aboveground C storage potential of agroforestry systems in semiarid, sub-humid, humid and temperate regions has been estimated to be 9, 21, 50 and 63 Mg C ha^{-1}, respectively (Montagnini and Nair 2004). Extensive reviews by Luedeling and Neufeldt (2012) for West African Sahel countries (from arid Sahara desert to humid region Guinea) showed biomass C stocks ranging from 22.2 to 70.8 Mg C ha^{-1}. A study by Mutuo et al. (2005) of agroforestry systems in humid tropics showed that they could sequester up to 70 Mg C ha^{-1} in aboveground biomass. The range in biomass C storage of various agroforestry in systems is shown in Table 2. The highest aboveground and total biomass C stock was recorded in traditional agroforestry systems and the least for silvopastoral systems.

The amount of soil organic carbon (SOC) in agroforestry systems differs with region, agroforestry system and soil depth (Table 3). From table 3 it can be seen that cacao systems accumulate 83−89%, 43% and 58−66% more SOC (1 m depth) than tree-crop, silvopastoral and traditional agroforestry systems, respectively. Studies in Brazil have also shown that SOC stocks to 1 m depth could reach 408 Mg C ha^{-1} for silvopastoral systems (Nair et al. 2011). SOC stocks in the 0−40 cm layer were the highest for silvopastoral systems, followed by tree-crop, coffee and traditional systems. SOC stocks to 2 m depth in coppiced woodlots were higher than a tree-crop system consisting of *Gliricidia sepium* (Jacq.) Kunth ex Walp. intercropped with maize.

Litterfall also contributes to C stock accumulation in soil. It is the most important known pathway connecting vegetation and soil, and is a good indicator of aboveground productivity (Köhler et al. 2008, Silva et al. 2011). Little has been reported on the contribution of litterfall production in agroforestry systems. For instance, Beer et al. (1988) reported litterfall production of 2100−20000 kg ha^{-1} y^{-1} and 114–461 kg N inputs ha^{-1} y^{-1} in tropical coffee agroforestry systems. Brown and Lugo (1982) reported that litter accounted for 1% of the organic matter storage in tropical forests. Litterfall production and quality varies with stand characteristics (tree size, species, foliar biomass and age), geographic location (climate), site (soil), season, and management practice (Ulrich et al. 1981, Breymeyer et al. 1996, Liu et al. 2004, Starr et al. 2005, Dawoe et al. 2010, Murovhi et al. 212).

1.4 Agroforestry and climate change

Increases in the emissions of the Greenhouse Gases (GHGs) –carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are causing climate change (IPCC 1992). Agricultural land is a major contributor of GHGs, accounting for 14% of global emissions (Schaffnit-Chatterjee 2011). In east and west Africa, GHG emissions from agriculture in the mid 2000 were reported to be 129 million Mg CO_2e y^{-1} (CO_2e = carbon dioxide equivalent –the atmospheric forcing capacity of various greenhouse gases) excluding irrigated rice cultivation, of which 84% was accounted for by livestock, 11% by conversion of native land to crop land, and the remainder from nitrogen fertilizer consumption and fires on grazing land (Brown et al. 2012). Annual GHG emissions from the agricultural sector in Ethiopia for the period 2001−2006 were estimated to be 50.9 million Mg CO_2e y^{-1}, of which conversion of native land to cropland accounted for 14%, livestock sector 82% and the rest accounted for use of nitrogen fertilizers and grazing area burned (Brown et al. 2012). If the current rate of land use conversion continues, GHG emissions from Ethiopia will increase from 150 million Mg CO_2e in 2010 to 400 million Mg CO_2e in 2030 (Bishaw et al. 2013).

Carbon sequestration refers to removal of C from the atmosphere and deposition or storage in a reservoir such as oceans, vegetation or soil (Jose 2009). According to United Nations Framework Convention on Climate Change (UNFCC) in 1997, there are two ways to reduce levels of atmospheric CO_2: reduce emissions or increase C sequestration (Nair 1998, Montagnini and Nair 2004). Carbon sequestration can be increased by increasing the amount of standing biomass and increasing the rotation length of trees and shrubs, and in converting the biomass into durable products, (Montagnini and Nair 2004, Dossa et al. 2008, Jose 2009). Also, enhance the carbon sinks in soil (Smith et al. 2007).

The Intergovernmental Panel for Climate Change (IPCC) has only recently recognized the role of agroforestry system in C sequestration and climate change mitigation (Smith et al. 2007). Agroforestry systems have been shown to sequester large amounts of CO_2 (Unruh et al. 1993, Losi et al. 2003, Montagnini and Nair 2004, Schoeneberger 2008). Many trees species in agroforestry systems can sequester C for 30−50 years until they attain rotation age, and in some cases, trees can be maintained in the system for up to 300 years (Pandey 2002). Agroforestry systems have been shown to have greater C stocks than field crops or pastures (Unruh et al. 1993, Albrecht and Kandji 2003, Nair et al. 2009, Nair 2011, Demessie et al. 2013). Of all land uses analysed in the Land-Use, Land-Use Change and Forestry report of the IPCC, agroforestry has been shown to offer the highest potential for C sequestration in developing countries by 2040 (IPCC 2000, Verchot et al. 2007). This is not because agroforestry has the highest carbon density, but because there is such a large area that is susceptible for the land use change (Verchot et al. 2007).

Agroforestry land area , which has greater than 10% crown cover, is estimated to cover 1 billion ha of which 32% is in south America, 19% in sub-Saharan Africa, 13% in south-east Asia and the reminder in Europe and North America (Zomer et al. 2009). Depending on the area assumed feasible for agroforestry, various estimations of the C sequestration potential of agroforestry systems are given (Table 4). The estimate by Jose (2009) is for only aboveground biomass stocks. The estimates by Jose and Bardhan (2012) include carbon stocks in both biomass and the soil. From Table 4 it can be inferred that the global potential area for agroforestry ranges from 1000−1480 Mha with estimated C sequestration potential of

44.8−466.5 C Pg y^{-1} (in biomass and soil), assuming the biomass carbon sequestration potential of agroforestry systems ranges from 0.29 to 15.21 Mg C ha^{-1} y^{-1} and 30 to 300 Mg C ha^{-1} up to 1 m depth in the soil (Nair et al. 2010). Additionally, a further 630 Mha of unproductive cropland and grassland could be converted into agroforestry system. This would add 391000 Mg C y^{-1} at present and 586000 Mg C y^{-1} by 2040. If tree management practices on existing agroforestry systems are improved, they could sequester an additional 12000 Mg C y^{-1} at present and 17000 Mg C y^{-1} by 2040 (IPCC 2000).

The global soil C pool to 1 m depth is estimated to be 2300 Pg C, which is 3.3 times the atmospheric pool (770 Pg C) and 4.5 times the vegetation pool (610 Pg C) (Nair et al. 2009, Srivastava et al. 2012). Thus, any change in the soil C pool would have a significant effect on the global C budget. According to the IPCC, the soil C sequestration potential of agricultural land worldwide is estimated to 400–800 Million Mg C y^{-1} for the next 50 to 100 years (Smith et al. 2007). Smith et al. (2007) also reported the global C sequestration potential of agriculture to be 5500–6000 Million Mg CO_2e y^{-1} by 2030, of which 89% is from soil C sequestration.

Oelbermann et al. (2004) reviewed the potential to sequester C in aboveground components in agroforestry systems is estimated to be 2.1×10^9 Mg C y^{-1} in tropical and 1.9×10^9 Mg C y^{-1} in temperate biomes. In a review by Nair et al. (2009), the global C sequestration potential of agroforestry systems (above- and belowground biomass only) varied from 0.29 Mg C ha^{-1} y^{-1} for a fodder bank agroforestry system in West African Sahel to 15.21 Mg C ha^{-1} y^{-1} for a mixed species stand of *Casuarina equisetifolia* L., *Eucalyptus robusta* Sm. and *Leucaena leucocephala* (Lam.) de wit at age of 4 year-old in Puerto Rico. Montagnini and Nair (2004) give an estimate of the C sequestration of mainly tropical agroforestry systems of 1.5–3.5 Mg C ha^{-1} y^{-1}. In sub-Saharan African, C sequestration in agroforestry systems (park land, live fence, and homegardens) range from 0.2 to 0.8 Mg C ha^{-1} y^{-1} while in rotation woodlots C sequestration ranges from 2.2 to 5.8 Mg C ha^{-1} y^{-1} (Luedeling et al. 2011). The C sequestration potential in biomass and soil of agroforestry systems in east and west Africa is estimated to be 6–22 Mg CO_2e ha^{-1} y^{-1} (Brown et al. 2012). In general, temperate agroforestry systems have lower C sequestration rates than tropical agroforestry systems (Nair et al. 2009, Srivastava et al. 2012).

1.5 Agroforestry systems in Ethiopia

Agroforestry practice in the tropics and sub-tropics is probably as old as agriculture itself (Atta-Krah et al. 2004, Kumar and Nair 2004, McNeely and Schroth 2006). In Ethiopia, the integration of trees and shrubs into agriculture emerged some 7000 years ago (Brandt, 1984; Edmond et al. 2000), and has developed during subsequent millennia into number of distinct indigenous agroforestry systems (Getahun 1974, Kanshie 2002). In ancient times, the cultivation of domesticated and wild fruit trees was concentrated in monasteries and isolated churches as major source of food for the nuns, monks, hermits and warriors (Getahun 1974). The historical development of gardening in Ethiopia also followed the human settlement history and thus is much older in northern Ethiopia than in the southern Ethiopia (Pankhurst 1993).

Currently, agricultural land in Ethiopia is estimated to cover 52.62 Mha (46% of the country's total area) (Brown *et al.*, 2012) and to support the livelihoods of 83% of the population, form 80% of export earnings and 73% of the raw materials in agro-based industries (Bishaw et al. 2013). The area of agroforestry systems in Ethiopia is not well documented but some 2.32 Mha are considered as agroforestry land use according to some estimates based on satellite

Table 2. Above (AG), Belowground (BG) and Total (AG+BG) biomass C stocks (Mg C ha^{-1}) in varies agroforestry systems.

Agroforestry system	Place	AG	BG	Total	Reference
Coffee systems					
Coffee agroforests	Guatemala	73.2	16.2	89.4	Schmitt-Harsh et al. (2012)
Coffee agroecosystems	Southern Costa Rica	11.0−31.6	−	−	Polzot (2004)
Shade coffee plantation	South-western Togo	67.0	15.0	82.0	Dossa et al. (2008)
Coffee agroforestry systems	Central Valley of Costa Rica	24.8	4.8	29.6	Häger (2012)
Cacao systems					
Cocoa +*Erythrina* spp.	Bahia, Brazil	32.7	−	−	Gama-Rodrigues et al. (2011)
Cocoa+ *Gliricidia* spp.	Bahia, Brazil	32.5	−	−	Gama-Rodrigues et al. (2011)
Cocoa–*Gliricidia* spp., 15 year-old	Central Sulawesi, Indonesia	−	−	31.5	Smiley & Kroschel (2008)
Traditional agroforestry					
Traditional agroforests	Ipetí-Emberá, Panama	81.6	18.0	99.6	Kirby & Potvin (2007)
Agroforests – 60 year-old	South-east Asia	−	−	350.0	Roshetko et al. (2007)
Homegardens	Western Kenya	17.3	−	−	Henry et al. (2009)
Tree-crop systems					
Erythrina poeppigiana alley cropping	Turrialba, Costa Rica	−	−	40.0	Oelbermann et al. (2006)
[a]Parkland agroforestry	Ségou, Mali	0.7–54.0	−	−	Takimoto et al. (2008)
Temperate tree-intercropping systems	Southern Ontario, Canada	−	−	6.4–15.1	Peichl et al. (2006)
Trees on agricultural landscapes	Western Kenya	20.8	−	−	Kuyah et al. (2012b)
Trees on agricultural landscapes	Western Kenya	17.4	−	−	Kuyah et al. (2012a)
Silvopastoral systems					
Silvopastoral-*Pinus ponderosa* P. Lawson & C. Lawson	Chilean Patagonia	21.2	9.4	30.6	Duba et al. (2011)
Woodlots					
Acacia spp. 5 year-old	Mkundi village,Tanzania	−	−	11.6−25.5	Kimaro et al. (2011)
Five *Leucaena* spp. 7 year-old	Eastern Zambia	24.5−55.9	8.1−17.6	32.6−73.9	Kaonga & Bayliss-Smith (2012)
Other systems					
Various agroforestry systems	Chiapas, Mexico	−	−	58.5−151.0	Soto-Pinto et al. (2010)
Various agroforestry systems	Claveria, Philippines	18.8−159.7	−	−	Brakas & Aune (2011)

[a] *Faidherbia albida* (Delile) A. Chev., *Vitellaria paradoxa* C.F. Gaertn.

Table 3. Soil organic carbon (SOC, Mg C ha^{-1}) in varies agroforestry systems.

Agroforestry system	Place	SOC	Depth, cm	Reference
Coffee systems				
Coffee agroforests	Guatemala	38.2	0−10	Schmitt-Harsh et al.(2012)
Coffee agroforestry	Central Valley, Costa Rica	63.1	0−25	Häger (2012)
[a]Coffee agroforestry	Southwest Togo	97.3	0–40	Dossa et al. (2008)
Shade coffee agroforestry system	Sumber-Jaya, Indonesia	82	0-30	van Noordwijk et al. (2002)
Cacao systems				
Cacao agroforestry, (Cacao + *Erythrina* spp.+ *Gliricidia* spp.)	Bahia, Brazil	302.0	0−100	Gama-Rodrigues et al. (2011)
Cacao agroforestry	Southern Bahia, Brazil	93.8	0–50	Barreto et al. (2010)
Cocoa–*gliricidia* agroforests, 15 year-old	Central Sulawesi, Indonesia	160.0	0–100	Smiley & Kroschel (2008)
Tree-crop systems				
[b]Alley cropping, 24 year-old	Turrialba, Costa Rica	162.0	0–40	Oelbermann et al. (2006)
Agrisilviculture (*Gmelina arborea* Roxb, ex Sm.+ crops)	Chhattisgarh, India	27.4	0–60	Swamy & Puri (2005)
Parkland agroforestry (*Faidherbia albida* +*Vitellaria paradoxa)*	Ségou, Mali	28.0–33.3	0–100	Takimoto et al. (2008)
Gliricidia sepium (Jacq.) Kunth ex Walp. + maize 10 years-old	Zomba, Malawi	123.0	0–200	Makumba et al. (2007)
Hybrid poplar + crops, 13 year-old	South Canada	125.4	0–40	Oelbermann et al. (2006)
Erythrina poeppigiana + crops, 19 year-old	Costa Rica	162.0	0–40	Oelbermann et al. (2006)
Temperate tree-based intercropping systems	Southern Ontario, Canada	65.0–78.5	0–20	Peichl et al. (2006)
Silvopastoral system				
Silvopastoral system, *Pinus ponderosa*	Chilean Patagonia	193.8	0–40	Duba et al. (2011)
[c]Silvopastoral	Costa Rica	173.0	0–100	Amézquita et al. (2005)
Traditional homegarden systems				
Traditional agroforests	Ipetí-Emberá, Panama	45.0	0–40	Kirby & Potvin (2007)
Homegardens	Kerala, India	101.5−127.4	0−100	Saha et al. (2009)
Multistrata agroforestry, cocoa plantations 2−25 year-old	Western Region, Ghana	17.6−22.6	0−15	Isaac et al. (2005)

Woodlots				
Poplar agroforestry system, 1−6 year-old	Central Punjab , India	23.2–29.1	0–30	Gupta et al. (2009)
Woodlots for 5 *Leucaena* spp. 7 year-old	Eastern Zambia	115.0–186.0	0–200	Kaonga & Bayliss-Smith(2012)
Coppicing fallow10 years-old	Msekera, eastern Zambia	184.0	0–200	Kaonga & Bayliss-Smith (2009)
Rotational woodlot of *Acacia* spp., 5 year-old	Mkundi village, Tanzania	21.6–25.6	0–15	Kimaro et al. (2011)
Others				
Various agroforestry systems	Chiapas, Mexico	98.3−151.0	0–30	Soto-Pinto et al. (2010)
Robinia pseudoacacia L., 2−14 year-old	Lusatian, northeast Germany	22.2 −106.0	0–60	Quinkenstein et al. (2011)

[a] *Coffea canephora* var. *robusta* (L. Linden) A. Chev.+ *Albizia adianthifolia* (Schumach.) W. Wight

[b] *Erythrina poeppigiana* (Walp.) O.F. Cook

[c] *Acacia mangium* Willd. + *Arachis pintoi* Krapov. & W.C. Greg. 10–16 year-old

Table 4. Global estimates of total area covers (million ha) and potential carbon sequestration (PCS) (Pg C y^{-1}) in agroforestry systems.

Estimate area	PCS	Reference	Remark
1023	34.3−193.6	Nair et al. (2009)	The stocks estimated taking into account biomass carbon sequestration potential ranging from 0.29 to 15.21 Mg C ha^{-1} y^{-1} varies agroforestry practice in the globe, and soil C stocks at 1m depth ranging from 33.3 to 173 Mg C ha^{-1}
1023	1.9	Jose (2009)	Carbon sequestration in aboveground biomass using the median carbon sequestration potential used by Dixon (1995) (94 Mg C ha^{-1})
1480	4	Oelbermann et al. (2004)	Carbon sequestration potential on aboveground biomass 2.1×10^9 Mg C y^{-1} in tropical and 1.9×10^9 Mg C y^{-1} in temperate agroforestry biomes
1000	30.3−315.2	Zomer et al. (2009)	Estimated based on biomass carbon sequestration ranging 0.29 to 15.21 Mg C ha^{-1} y^{-1}, and 30–300 Mg C ha^{-1} up to 1 m depth in the soil (Nair et al. 2010)
1023	34.3−322.2	Jose and Bardhan (2012)	Estimated based on biomass carbon sequestration 0.29 to 15.21 Mg C ha^{-1} y^{-1}, and 30–300 Mg C ha^{-1} up to 1 m depth in the soil (Nair et al. 2010), additionally, 630 Million ha unproductive cropland and grassland get into agroforestry and add 586000 Mg C per year by 2040
93.1	0.53	Udawatta and Jose (2012)	US & temperate North America silvopasture, alley cropping, windbreaks &Riparian buffers

imagery for the base year 2006 (Brown et al. 2012). The figure did not include scattered trees on crop and grazing lands.

Various agroforestry systems are practiced in different parts of the country. One of the oldest indigenous agroforestry systems is the retention of scattered apple-ring Acacia (*Faidherbia albida* (Delile) A. Chev.) on farmlands in the Hararghe highlands of eastern Ethiopia (Poschen 1986). Coffee in agroforestry systems occurs in the same part of the country and is cultivated under the shade of remnant native trees, such as *Albizia gummifera* J.F. (Gmel.) C.A.Sm, *Acacia abyssinica* Hochst. ex Benth., *Millettia ferruginea* (Hochst.) Bak, *Ficus sur* Forssk., *Ficus vasta* Forssk. and *Cordia africana* Lam. (Teketay and Tegineh 1991, Muleta et al. 2008). Farmers in southern Ethiopia retain *Cordia africana* and *Millettia ferruginea* for maintaining soil fertility in enset-coffee based agroforestry (Abebe 2005, Asfaw and Ågren 2007). Homegarden agroforestry systems are practiced in different parts of the country (Asfaw 2002, Mengesha 2010, Fentahun and Hager 2010, Debessa 2011, Haileselasie et al. 2012)

Studies indicate that there are between 17 (fruit tree system) and 429 plant species (various agroforestry systems) grown in agroforestry systems in Ethiopia, where they are not only support local livelihoods but also are important in conserving the native biodiversity (Table 5). Asfaw (2002) found a total of 123 tree, 146 shrub, 25 climber and 135 herbaceous species in various agroforestry systems. The greatest plant species richness occurs in south Ethiopia (50−198), followed by southwest (149), central (27−114) and north Ethiopia (17−40) (Table 5). Abebe et al. (2006) reported a total of 198 plant species (78 cultivated crops and 120 trees) from 144 coffee based homegardens in four districts of Sidama, southern Ethiopia. The woody species in this agroforestry system were mainly *Cordia africana*, *Eucalyptus camaldulensis* Dehnh., *Millettia ferruginea* and *Euphorbia candelabrum* Trem and Kotschy. Mengesha (2010) reported that 90 woody species in south-eastern Ethiopia including native tree species such as *Juniperus procera* Hochst. ex Endl**.**, *Olea europaea subsp. Cuspidate* (Wall. ex G. Don) Cif., *Podocarpus falcatus* (*Afrocurps falcatus*) (Thunb.) R. Br. ex Mirb., *Acacia tortilis* (Forssk.) Hayne, *Acacia etbaica* Schweinf. and *Hagenia abyssinica* J.F. Gmel.. Another study in the same part of the country by Debessa (2011) recorded a total of 165 plant species comprising 31% tree, 18% shrub and 45% herbaceous plants growing in homesteads, farms and pasturelands. Kebede (2010) identified 114 plant species in south-western Ethiopia comprising respectively 30%, 23%, 40% and 7% of trees, shrubs, herbs and climbers. Woldeyes (2011) identified 149 species in the same part of the country comprising 30–32% tree, 23–25% shrub, 39–42% herbs and 3–6% climber plants. In north Ethiopia, Fentahun and Hager (2010) recorded a total of 17 fruit tree species growing scattered trees on the farms while Haileselasie and Hiwot (2012) identified 40 plant species in homegarden, mainly vegetables (44%), and fruit trees including coffee, fodder trees, coffee, stimulants (*Catha edulis* Forssk.) and cereals.

Tesemma (2007) identified nine types of agroforestry practices in various parts of Ethiopia having various ecological and socioeconomic services. These are banana-based multi-storey gardens, tef and acacia integrated agroforestry, boundary eucalyptus and cereal crops in agroforestry, conservation based agroforestry, vertically and horizontally packed agroforestry, multistrata perennial crop agroforestry, enset-coffee-tree-spice-based agroforestry, poem fruit trees-bamboo cum-enset-vegetable farming and bamboo cum-cereal farming. These agroforestry systems are primarily aimed at meeting household food needs (Negash 2007) although the Enset-coffee agroforestry systems in southern Ethiopia are also aimed at generating income (Kanshie 2002, Asfaw 2003).

Table 5. Floristic diversity reported in agroforestry systems at different parts of Ethiopia, the value in the parenthesis shows that percentage of tree species recorded of the total number of species.

Agroforestry system	Place	Vegetation type	No. species	Reference
North				
Fruit trees farms	Adiarkay, Debark, Dejen	Edible indigenous fruit trees	17	Fentahun & Hager (2010)
Homegraden	Hintalo Wejerat of Tigray	Fruits & fodder trees, vegetables, herbs	40(66)	Haileselasie & Hiwot (2012)
South				
Coffee-enset system	Four districts, Sidama zone	Woody species + cultivated crops	198 (61)	Abebe et al. (2006)
Traditional homegardens	Around Gate Uduma, Gedeo	Trees, shrubs, herbs	165(31)	Debessa (2011)
Indigenous agroforestry	Aleta wondo district, Gedeo	Trees, shrubs, vegetable crops	50(40)	Negash & Achalu (2008)
Various homegardens	Wolayta and Gurage zones	*All floristic species	60	Asfaw & Woldu (1997)
Southwest				
Homegardens	Basketo, Kafa zone	Trees, shrubs, climbers, spices	149-192 (30-32)	Woldeyes (2011)
Central				
Trees on farms	Three districts, Arsi zone	Woody species	90	Mengesha (2010)
Homegardens	Sebeta-Hawas district	Trees, shrubs, herbs, climbers	114(30)	Kebede (2010)
Trees on farms	Welmera & Alemgana	Tree species	27	Duguma & Hager (2010)
Homegardens	Beseku, Arsi Negelle district	Woody species	64	Tolera et al. (2008)
Country level				
Agroforestry systems	West, north and south Ethiopia	Trees + shrubs + climbers + herbs	429(27)	Asfaw (2002)
Homegardens	Central, eastern, western, south Ethiopia	*All floristic species	162	Asfaw & Nigatu (1995)

*the share of tree species could not be traced in the report.

Enset (*Ensete ventricosum*) based agroforestry systems are common in central, south-west and south Ethiopia (Asfaw 2003, Abebe 2005, Tesemma 2007). Enset, also known as the false banana, belongs to the family Musaceae and is domesticated and used as food only in Ethiopia. The plant produces a pseudostem and a starchy underground corm used for food, fodder and fibre. The plant can grow monocrop as a plantation or mixed with other crops. The rotation period ranges from 3 to 15 years (Brandt et al. 1997, Zewdie et al. 2008) and usually takes 9 or more years to produce flowers and set seed (Tesfaye 2008). Although the exact age of enset domestication is not known, it has been used in the Ethiopian highlands for more than 5000 years (Brandt et al. 1997). The area in which enset is grown covers approximately 300000 ha, yielding 4.4 million metric tons per annum and supporting the livelihood of 20 % of the total population of the country (Shank and Ertiro 1996, Negash and Niehof 2004).

Fruit crops are also a major component in agroforestry systems in the country, serving as major sources of nutrition and income (Negash 2007). Recent decades have witnessed the expansion of exotic species into agroforestry systems (Negash et al. 2005). Fast growing exotic species, such as *Eucalyptus* spp., are increasingly grown and mainly used for pole and fuelwood purposes, though the species not preferred by the farmers for agroforestry (Negash et al. 2005, Asfaw and Ågren 2007). Nevertheless, caution needs to be taken with species planted outside their native habitat (Teketay and Tegineh 1991).

The Federal Government of Ethiopia has included an agroforestry extension package in the rural development strategy for the country (MoARDE 2005). The package is targeted at maximizing and sustaining the natural resources, diversifying sources of income and reducing the risk of production failure, and at improving land productivity on sustainable basis. In 2011, the country formulated a strategy focusing on forestry and agroforestry development and on improving agricultural productivity and energy efficiency (Bishaw et al. 2013). However, the attention given to the ecosystem services provided by agroforestry in both these strategies is limited. There is also a lack of scientific knowledge about the function and structure of these systems, and their exact extent.

1.6 Aims of the study

The overall objective of this study was to determine, and compare the floristic diversity, the C stocks in the biomass and soil, and litterfall production of three indigenous agroforestry systems in the southern-eastern Rift Valley escarpment of Ethiopia.

The specific objectives of this study were to:

- Determine and compare the floristic composition, diversity and stand structure of the three agroforestry systems, and evaluate the role they play in the conservation of native trees and shrubs (Study I);
- Derive allometric biomass equations for coffee and enset growing in the agroforestry systems (Study II & III) in order to determine biomass C stocks (Study IV);
- Determine and compare the C stocks of the woody and non-woody (enset and herbs) biomass, litter and soil in the three agroforestry systems (Study IV); and
- Determine the litterfall production and associated C and N fluxes of seven woody species grown in the agroforestry systems (Study V).

It is envisaged that this study will contribute to the conservation of these unique agroforestry systems and to the recognition of the ecosystems services they provide to the local communities (food production, security and income, soil and water protection, maintenance of soil fertility) and beyond (C sequestration and climate change mitigation, and conservation of biodiversity). The development of national policy concerning the conservation of biodiversity, the mitigation of climate change, and the implementation of international mechanisms such as REDD (Reducing Emission from Deforestation and Forest Degradation) and CDM (Clean Development Mechanism) (IPCC 2007, Verchot et al. 2007) requires science-based information about all land-use types. At present, such science-based information about the biodiversity and C stocks of the indigenous agroforestry systems in the southern-eastern Rift Valley escarpment is limited.

2. MATERIALS AND METHODS

2.1 Study area and sites

The study was carried out in the south-eastern Rift Valley escarpment in the Gedeo zone of the Southern Nations', Nationalities' and Peoples' Regional State (SNNPRs) of Ethiopia, (5° 50' 26"– 6° 12' 48" N, 38° 03' 02"–38° 18' 59" E). The total area of the Gedeo zone is 134700 ha, comprising agricultural land (agroforestry- perennial and annual crops land) (94.5%), grassland (1.4%), wetland (0.8%), natural forest (0.5%), plantations (0.1%) and others (2.7%) (Mebrate 2007). Elevation in the study area ranges between 1300 and 3064 m, rainfall between 800–1800 mm per year and the mean annual temperature between 13 and 25 °C. The climate between 1300 and 1500 m is classified as hot tropical (locally known as 'Kolla'), between 1500 and 2300 m is classified as sub-tropical ('Weynadega'), and between 2300 and 3100 m is classified as mid-altitude ('Dega'). The Gedeo zone is one of the most densely populated administrative districts in Ethiopia, averaging 627 persons km^{-2} with a range of 122 to 1300 persons km^{-2} (Negash 2007, Mebrate 2007, Bishaw et al. 2013).

The three main agroforestry systems in the study area are (Figure 2a-c): 1) Enset based agroforestry system located at elevations of 2100–2400 m and rainfall 800−1200 mm y^{-1} (hereafter termed as Enset system), 2) Enset-coffee based agroforestry system (1900–2200 m and 800−1200 mm y^{-1}) (Enset-coffee system) and 3) Fruit-coffee based agroforestry system (1500–1900 m and 800−1000 mm y^{-1}) (Fruit-coffee system) (Figure 2). The soils in all three agroforestry systems are mainly developed from volcanic rock and classified as Nitosols (FAO 1998).

In the Enset system (Figure 2a), the upper-story tree species include *Erythrina* spp., *Millettia ferruginea* and *Polyscias ferruginea* (*Polyscias fuluva*) and the understory is dominated by root and herbaceous plants, including *Dioscorea alata* L. and *Capsicum* spp. In the Enset-coffee system (Figure 2b), *Erythrina* spp., *Millettia ferruginea* and *Cordia africana* trees shade the coffee and enset. The understory consists of herbaceous crops, including *Disocoria alata*, *Colocasia esculenta* (L.) Schott and *Musa* spp. In Fruit-coffee system (Figure 2c), coffee and fruit trees (e.g. *Persea americana* Mill., *Mangifera indica* L. and *Casimiroa edulis* Lal Llave & Lex.) are shaded by tree species such as *Cordia africana*, *Millettia ferruginea* and *Ficus* spp. The understory consists of herbaceous crops, including *Zea mays* L., *Musa* spp., *Brassica oleracea* L. and *Ipomoea batatas* (L.) Lam..

The agroforestry systems in the Gedeo zone are considered to be among the oldest agricultural systems known, dating back to Neolithic times (Edmond et al. 2000, Kanshie 2002). They developed through the domestication of natural forest and intensification of agriculture (Negash and Achalu 2008). Originally, the vegetation was dominated by native woody species, such as *Syzygium guineense* (Willd.) DC., *Podocarpus falcatus* (Thunb.) Mirb., *Millettia ferruginea*, *Cordia africana*, *Croton macrostachyus* Del., *Aningeria adolfi-friedericii* Rob and Gilb. and *Erythrina* spp. Farmers settled in the forest and selectively felled trees and practised cereal-crop production, and introduced enset and coffee as respectively food and cash crops. Missionaries introduced the fruit trees. According to local knowledge, the existing agroforestry systems formed about 2 to 3 centuries ago (Negash and Achalu 2008).

Enset, which grown on about 86000 ha in Gedeo zone, is grown in association with coffee and cereals in agroforestry systems (Mebrate 2007). Besides serving as a food plant, enset provides economic, cultural and environmental services, including construction material (mainly roof thatching), rope and string, animal fodder, medicine, mulching, and maintenance of soil fertility and moisture (Brandt et al. 1997). Enset is resilient to seasonal drought, is harvestable all year-round.

Figure 2. Vertical and horizontal structures of indigenous agroforestry systems in south-western Rift Valley escarpments, Gedeo, Ethiopian: From top to bottom: (a) Enset system, (b) Enset-coffee system, and (c) Fruit-coffee system. Photos by M. Negash (2006).

Coffea arabica, which is native to Ethiopia, is the dominant coffee species in the study area. The coffee grown under over-storey trees in these traditional agroforestry systems is internationally recognised (known by the name Yiregachefe Coffee), considered organic and prized for its high quality. The area of coffee in the study site is estimated to 63000 ha and supports the livelihoods of 644000 people (GRDAO 2010). In the whole of Ethiopia, coffee is grown on about 662000 ha and is estimated to produce 350000 tons of coffee beans per annum. The production of coffee accounting for more than 60% of Ethiopia's export earnings, and directly and indirectly supports the livelihoods of 15 million people (Muleta et al. 2007, Labouisse et al. 2008). More than 95% of the total volume of coffee beans produced in Ethiopia comes from smallholders in agroforestry systems such as those in the Gedeo zone (Kufa et al. 2011).

2.2 Methods

2.2.1 Sampling design

For this study, areas of the three agroforestry systems were identified using satellite imagery and aerial photographs, and ground observations carried out to validate identification. Two areas of each agroforestry type were then randomly selected along altitudinal gradients and 20 farms representative of each agroforestry system randomly selected (Figure 3). The altitude, slope, aspect and agroforestry type of each farm were recorded.

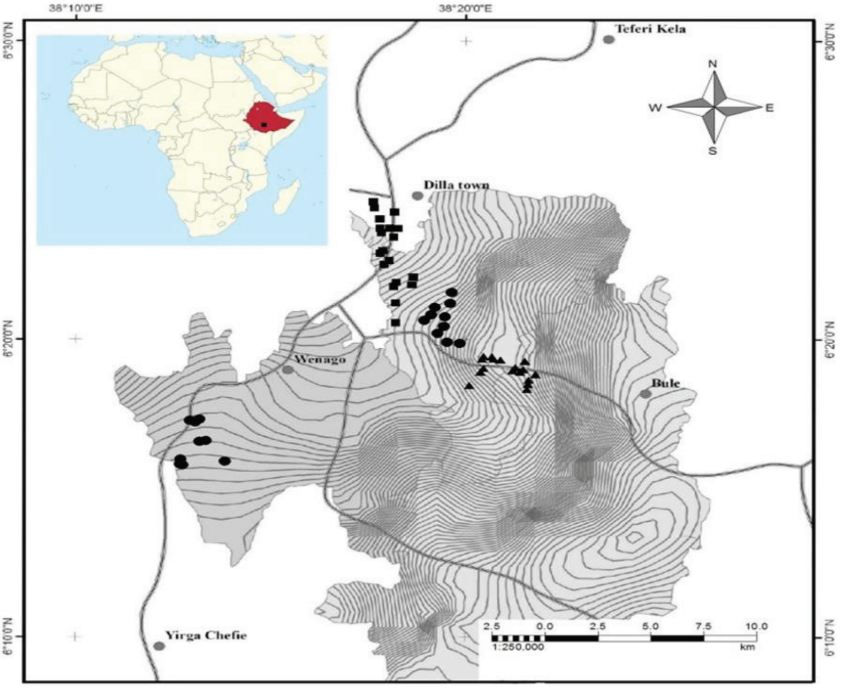

Figure 3. Map showing the location of the 60 farms in the study area (mainly in the administrative district of Wenago and Dila Zuria; symbols: black triangle=Enset system,

black circle=Enset-coffee system, black square=Fruit-coffee system). Inset map shows the location of the study area (Black Square) within Ethiopia (red shaded area) and Africa.

At each farm a 10 × 10 m plot with three 1 × 1 m plots was established (Figure 4). In a few cases, the plot occupied the whole farm. To locate the central position of a plot on the farm, ocular estimation was first used to divide the farm into ten equal parts. Second, a number was assigned to each part. Third, a data collection part was selected by generating random numbers.

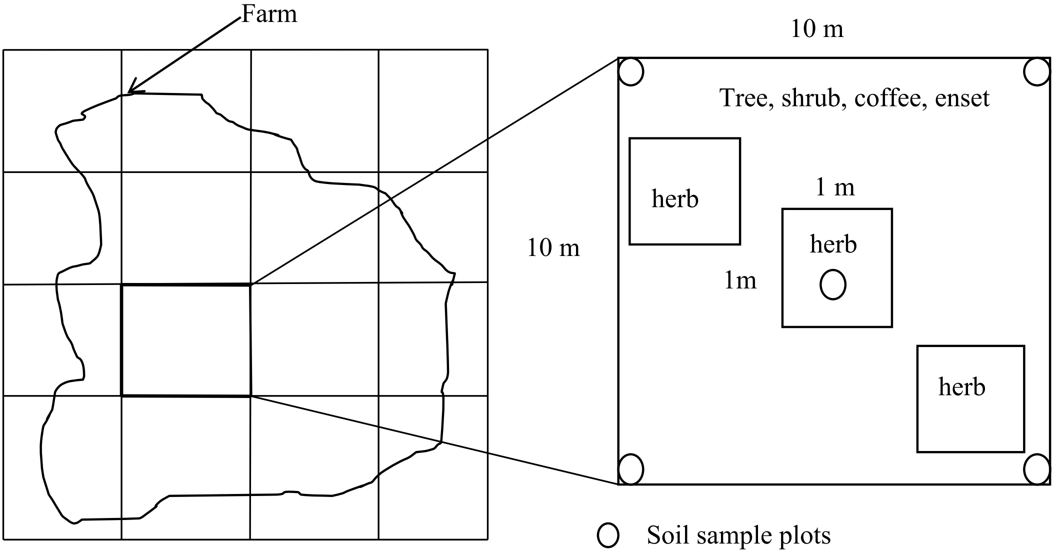

Figure 4. Sample plot layout for inventory of trees, shrubs, coffee and enset plants (10 × 10 m), herbs (three 1 × 1m plots) and soil sample points (circular points).

2.2.2 Species inventory (Study I, II, III, IV, V)

An inventory of the floristic composition and structure of each plot was carried out on the 10 × 10 m plots. The following measurements of all trees and shrubs (single and multi-stemmed) having a breast height diameter ≥ 2.5 cm and height ≥ 1.5 m were made: diameter at breast height (d, cm ±0.1), total height (h, m ±0.1), and crown width (cw, m±0.1) in two directions (the widest diameter, l, and in the perpendicular direction, w). For coffee plants (in Enset-coffee and Fruit-coffee systems), the stem diameter at stump height (40 cm), d_{40}, was also measured. For enset (in Enset and Enset-coffee systems), the basal diameter of the pseudostem (height of 10 cm, d_{10}) of plants one year old or older was measured. The dominant height of three enset plants per farm was also recorded. Stem diameter measurements (d and d_{40}) were taken in two perpendicular directions and the average value used in subsequent calculations. In the case of multi-stemmed plants (2 to11 stems per plant), each stem was measured and the equivalent diameter of the plant calculated as the square root of the sum of diameters of all stems per plant (Snowdon et al. 2002):

$$\text{d or } d_{40} = \sqrt{\sum_{i}^{n} d_i^{2}} \qquad \text{(Eq.1)}$$

where d (cm) = diameter equivalent at breast height, d_{40} (cm) =diameter equivalent at 40 cm height, d_i= diameter of the i^{th} stem at breast height or 40 cm height.

The crown edges were identified using clinometers and the length and width of the crown diameters measured with measuring tape. Crown area (ca, m^2/plant) was calculated as follows, assuming circular crown shape:

$$ca = \pi \times (\frac{l+w}{2})^2 \quad \text{(Eq.2)}$$

where l = crown length, m, w = crown width, m.

For biodiversity analysis, all woody species above 20 cm height were identified and counted using identification keys and local informants. For those species that could not be identified in the field, a sample was taken to the national herbarium for identification. The use values of identified woody species were obtained from key informants. In total (all 60 farms), 286 individual trees and shrubs, 491 coffee plants (1049 stems) and 1333 enset plants were inventoried. On average there were 16 trees/shrubs, five enset and nine coffee plants (1–11 stems per plant) within a single plot. The vertical structure consisted of 3–4 strata, the upper strata being dominated by native trees, the middle strata by fruit trees, lower strata by enset and coffee, and the ground cover being herbaceous plants such as *Crassula alsinoides* (Hook. f.) Engl**.** and *Dioscorea alata*.

The identity and ground cover percentage of the dominant herbs and grasses in the three 1 × 1 m plots located across the diagonal of the tree/shrub plot were recorded using a 10 × 10 cm wooden-frame (Figure 4).

2.2.3 Coffee and enset biomass harvesting for allometric equations (Study II & III)

For the determination of an allometric equation for 31 coffee plants (54 stems) were harvested from four of the 50 farms growing coffee in the Enset and Enset-coffee agroforestry systems. The particular four farms for sample plant harvesting were determined by the farmers' willingness to allow sample plants to be harvested. After measuring the biometric parameters (d, d_{40}, h, dominant height (h_{dom}), ca, crown height (ch), cw) of all the coffee plants in the plot, 1 or 2 of the plants from each the four plots within each farm were randomly selected for harvesting and derivation of the allometric equation. The selected coffee plants covered the range in size and age of the coffee plants found in the study area, and were in good condition. The d_{40} of the felled plants ranged from 3.8 to 22.8 cm, d ranged from 3.0 to 18.3 cm, and h ranged from 4.1 to 7 m. The fresh weight of each biomass component (stem, branch, foliage) was measured on site using a spring balance (± 0.1 kg) and subsamples taken for determination of dry weight and C content.

In case of enset, a total of 40 plants from 20 farms two plants from each of 10 farms from Enset and Enset-coffee systems were selected and harvested. The 40 plants covered the variability of enset biomass in the study area and were either 3 or 5 years of age (harvesting is mainly carried out at 3−5 years of age). Before felling, all individuals of 3 and 5 years of age were identified and one plant of each age in each plot was then randomly selected. The diameter of the pseudostem was measured at a height of 10 cm (basal diameter, d_{10}), at 30 cm (stump diameter, d_{30}), at 130 cm (diameter at breast height, d_{130}) and at 200 cm (bole height diameter, d_{200}) with a diameter tape measure (±0.1cm). Pseudostem height (h_p) and total height (h) were measured (±0.1m) and crown height (h_c) calculated by subtracting hp from h.

The sample plants were dug up and separated into three components: corm (+attached proximal roots), pseudostem and foliage. As enset is shallow rooted plant, the belowground biomass was uprooted with around 50 cm radius and 50 cm deep in the soil. The fresh weight of each component was measured on site using a spring balance (±0.1 kg) and subsamples taken for determination of dry weight and C content.

The subsamples of coffee and enset biomass components were sun-dried for 3 to 5 days and then oven-dried at 70 ºC for 24 hours. The fresh to oven-dry mass ratios were then used to convert the fresh weights of each biomass component measured in the field into oven-dry weights.

2.2.4 Biomass and soil C stocks (Study IV)

The above- and belowground biomass (Mg ha^{-1}) of trees and shrubs, enset and coffee plants for 60 farms (20 farms from each of the three agroforestry systems) was estimated. For the determination of biomass and soil C stocks (Mg C ha^{-1}), 18 of the farms (6 farms from each of the three agroforestry systems) were randomly selected. The C stocks of the tree and shrub, enset, coffee, herbs, fine roots and litter biomass and soil to 60 cm depth were determined.

To estimate the aboveground biomass of the trees and shrubs, four allometric equations were evaluated; that of Brown (1997), Chave et al. (2005), Henry et al. (2009) and Kuyah et al. (2012a). No significant difference in aboveground biomass estimation was found among the equations. However, the equation by Kuyah et al. (2012a) was selected for this study to estimate aboveground biomass. This was because the equation had the highest R^2 and lowest error of prediction values, used only breast height diameter, and developed for trees grown in agroforestry systems in western Kenya. Besides, the study site was having similar environmental conditions (climate and soils) to our study sites. The equation is as follows

$$AGB = 0.091 \times d^{2.472}; \quad R^2 = 0.98, n = 72 \qquad \text{(Eq.3)}$$

where AGB (kg dry matter /plant) = aboveground biomass, d (cm) = diameter at breast height.

To estimate the aboveground biomass (AGB, kg dry matter/plant) of the coffee and enset plants, the equations developed from the harvesting biomass data the same farms as in this study were used (Study II and III).

$$AGB_{coffee} = 0.147 \times d_{40}^2; \quad R^2 = 0.80, n = 31 \qquad \text{(Eq.4)}$$

$$\ln(AGB_{enset}) = - 6.57 + 2.316\ln(d_{10}) + 0.124\ln(h); R^2 = 0.91, n = 40 \qquad \text{(Eq.5)}$$

where d_{40} (cm) = stem diameter of the coffee plant at 40 cm height, d_{10} (cm) = the basal diameter of the enset pseudostem at 10 cm height, h (m) = total height.

The belowground biomass (stump plus coarse roots (>2 cm)) for trees and shrubs, including coffee, were estimated using an allometric equation developed for agroforestry systems by Kuyah et al. (2012b) in western Kenya.

$$BGB = 0.048 \times d^{2.303}; \quad R^2 = 0.96, n = 72 \qquad \text{(Eq.6)}$$

where BGB (kg dry matter/plant) = belowground biomass, d (cm) = diameter at breast height.

For calculating the belowground biomass of enset (corm plus attached proximal roots), the allometric equation developed in Study III was used.

$$BGB_{enset} = 7\times10^{-6} \times d_{10}^{4.083}; \quad R^2 = 0.68, n = 40 \qquad \text{(Eq. 7)}$$

where BGB_{enset} (kg dry matter/plant) = Enset belowground biomass, d_{10} (cm) = the basal diameter of the enset pseudostem at 10 cm height.

Total belowground biomass is defined as the sum of BGB and fine roots (<2 mm) biomasses. Fine roots biomass in the 0–30 and 30–60 cm layers was determined from soil samples taken from the four corners and centre of each 10 × 10 m plot. The biomasses of herbaceous plants and litter were determined from harvested samples taken from the three 1 × 1m and 50 × 50 cm plots, respectively, in the 10 × 10 m plot (Figure 4).

The C stock (Mg C ha^{-1}) of the trees and shrubs were calculated assuming a biomass C content of 48% determined by Kuyah et al. (2012a). The C stock of coffee, enset, herbaceous plants, litter, and fine roots were calculated from their organic matter contents determined by loss-on-ignition (LOI) (ignition at 550 °C for 2 hours) and calculated C content of 44% of the organic matter (Kozlowski and Pallardy 1996) yet actual determinations of plant C content vary (Das and Das 2010, Martin and Thomas 2011, Thomas and. Martin 2012). The value of 44% was used according to the following rationale. The general molecular formula for a unit of a carbohydrate chain is CH_2O and that of glucose C_66H_2O. In the polymerisation of glucose to form cellulose, a water molecule is dehydrated from each glucose chain resulting in a basic molecular formula for plant biomass organic matter of C_65H_2O, which has a molecular weight of 162. The proportion of C in this organic matter molecule on a molar basis, i.e. 0.44 (=72/162), therefore gives the proportion of C in plant organic matter. As the mean LOI contents of the coffee, enset, herbaceous plants, litter, and fine root biomass components were respectively 97.7, 93.3, 72.7, 65.9 and 97.7%, the following C contents were used to convert biomass values into C stocks: 43% for coffee, 41% for enset, 32% for herbaceous plants, 29% for litter, and 43% for fine roots.

Total aboveground biomass C stocks are defined as the sum of tree, shrub, coffee, enset, herb and litter biomass, and total belowground biomass C stocks as the sum of the C stocks associated with tree, shrub and coffee stumps and coarse roots, enset corm (+ attached proximal roots), and fine root biomasses. Total biomass C stocks are defined as the sum of total aboveground and belowground biomass C stocks.

Soil samples of 0–30 cm and 30–60 cm layers for determination of C and N contents were taken from the four corners and centre of each 10 × 10 m plot and composited by layer (Figure 4). Volumetric samples were also taken at the same locations for determination of bulk density separately. The soil C stocks (Mg C ha^{-1}) were calculated as the product of C content (%), bulk density (g cm^{-3}) and layer thickness (cm), and then corrected for coarse (>2mm) fraction content by multiplying by ((100% - volumetric content of coarse fraction, %)/100%). C content in soil determined by the Walkey-Black method. The volumetric content of the coarse fraction was calculated from the gravimetric contents of >2mm material in the soil samples and an assumed density of solids value of 2.65 g cm^{-3}. The C stock values for the two layers (0–30 cm and 30–60 cm) were summed to give the C stock for the 0−60 cm layer. Total C stocks for the agroforestry system are defined as sum of the total biomass C and SOC (0−60 cm) stocks.

2.2.5 Litterfall and associated C and N fluxes (Study V)

Seven dominant woody species (5 native and 2 exotic) were selected to determine litterfall and associated C and N fluxes. The species were the most frequent species in the agroforestry systems (Study I), and accounted for >72% of basal area, stem number and crown area in the Enset system, >86% in the Enset-coffee system and >84% in the Fruit-coffee system. Two trees in each of 17 farms were selected, the 17 farms being those where the farmer was willing to have the litterfall traps set out. Altogether 34 trees were selected for study. The selected trees were isolated individuals and the litterfall traps were placed fully under the canopy. This ensured that the litterfall of the selected species in the trap only came from that individual tree. All the sample trees were of good form and health.

The litterfall traps consisted of four 1.5 m tall wooden poles forming a 1 × 1 m square over which nylon netting (1 mm mesh diameter) was draped and stone placed in the centre to weigh the netting down. Litterfall samples were collected at the end of each month (January 2010–December 2010). Before installing the litterfall traps, the following measurements of the target trees were determined: diameter at breast height, crown area (projected from crown width and length), crown height, total height and age.

The litterfall samples were air-dried for a day and the litterfall of the target tree separated. These samples were then oven-dried for 24 hours at 65°C and weighed (± 0.01g). The oven-dried litterfall samples were then combined by species to make a composite sample of each species for chemical analysis. The composited samples were ground to a fine powder in a rotary grinding machine and four subsamples taken for determination of organic matter and N contents. Organic matter content was determined as LOI (ignition at 550 °C for 2 hours) and values converted to a C content assuming a C content of 44%. N contents were determined by the Kjeldahl method.

2.3 Data analysis

2.3.1 Ordination and diversity analysis of vegetation data (Study I)

Non-metric multidimensional scaling (NMDS) (McCune et al. 2002, after Kruskal 1964, Mather 1974) was used for graphically representing the dissimilarity/similarity of each plot using the Sørensen (Bray-Curtis) distance measure, which is based on species composition and abundance data. The data matrix encompassed 44 (43 woody species and one non-woody – enset). A Monte Carlo test was run to correlate the stronger axes explaining the composition and abundance of species. Spearman rank correlation was used to test the influence of environmental variables (altitude and aspect) and stand characteristics (basal area and stem density) on species composition and abundance on NMDS axes (Arets et al. 2006).

The Shannon diversity index (H′), Simpson’s evenness index (E1/D) and Margalef’s diversity index (D_{mg}) (Magurran, 2004) were calculated for each plot. Sørensen’s quantitative index (CN) was used to determine the similarity/dissimilarity between agroforestry systems. Differences between the three agroforestry systems in terms of stand structure (diameter at breast height, total height, basal area and stem density) were analysed using ANOVA, followed by LSD multiple test (Fisher LSD test). Kruskal–Wallis ANOVA was conducted to evaluate differences among the three agroforestry systems in terms of species diversity, species richness and abundance followed by Mann–Whitney U test for multiple comparisons.

Species of “conservation concern” (rare, threatened, vulnerable, least concern) were identified using IUCN Red Lists (Edwards and Kelbessa 1999, Vivero et al. 2005), 25% of species that have the least occurrence in each agroforestry system (Magurran 2004), and published and unpublished local criteria (Bekele et al. 1999, Gebremariam et al. 2009). List of species formed using local criteria where the total number of individuals for the species accounted for below 100000 individuals in the country (Bekele et al. 1999, Gebremariam et al. 2009). This was done to identify native species needing conservation priority in the agroforestry systems.

2.3.2 Biomass equations for coffee and enset (Study II & III)

In the case of coffee, power equations were fitted to the relationship between aboveground biomass (stem, branch and foliage) and stem diameter (d, d_{40} or both) and h, and both square and fractional powers tested. For total aboveground biomass we compared our best performing equation which uses d_{40}, with the equations for *Coffea arabica* presented by Hairiah et al. (2001, see van Noordwijk et al. 2002) and by Segura et al. (equation presented in Pearson et al. 2005). For plants with multiple stems, the equivalent diameter value was used (see Eq. 1).

For the enset, linear (using untransformed and log-transformed data) and non-linear regression equations were determined for each biomass component separately (corm plus attached proximal roots, pseudostem, and foliage), for aboveground (pseudostem + foliage) biomass, and for total biomass (sum of all three components). R software version 2.11.1 (R Development Core Team 2010) was used to parameterize the biomass data for both coffee and enset.

For both coffee and enset, Spearman rank correlation was carried out between plant biomass and the measured biometric parameters. This helped to identify the best biomass predicator variables. Equation performance analysis was carried out using various goodness-of-fit statistics, namely, the coefficient of determination (R^2), standard error of estimate (SEE), index of agreement (D), bias (B), mean absolute bias (MAB) and prediction residuals sum of squares (PRESS) (Kozak and Kozak 2003, Harmel and Smith 2007, Walpole et al. 2007, Berhe and Arnoldsson 2008, Sampaio et al. 2010).

$$D = 1 - \frac{\sum_{i=1}^{N}(e_i)^2}{\sum_{i=1}^{N}(|\hat{Y}_i - \bar{Y}| + |Y_i - \bar{Y}_i|)^2} \qquad \text{(Eq. 8)}$$

$$B = \frac{\sum_{i=1}^{n} e_i}{n} \qquad \text{(Eq. 9)}$$

$$MAB = \frac{\sum_{i=1}^{n} |e_i|}{n} \qquad \text{(Eq. 10)}$$

$$PRESS = \sum_{i=1}^{n} \delta_i^{\,2} \qquad \text{(Eq. 11)}$$

where $e_i = \hat{Y}_i - Y_i$; $\delta_i = Y_i - \hat{Y}_{i,-i}$; $i = 1, 2, \ldots, n$; n is the number of observations, Y_i the observations of the response variables, $\hat{Y}_i$ is the predicted value of the Y_i, $\bar{Y}$ is the average of the Y_i, δ_i is i_{th} prediction error, $\hat{Y}_{i,-i}$ is the prediction of the i_{th} data point by an equation did not make use of the i_{th} point in the estimation of the parameters.

The best equation should have the highest R^2 and D values and lowest bias, SEE, MAB and PRESS values. The equations were ranked according to each goodness-of-fit statistic, the ranks summed and sums ranked to give an overall equation performance rank.

2.3.3 Differences in biomass C and SOC stock (Study IV)

The biomass of the trees and shrubs, including coffee and enset, were calculated for all 60 farms (plots) while the C stocks were calculated only for the 18 farms (plots) at which the C stocks of the ground herbaceous plants, litter, fine root and soil had also been calculated.
The biomass and soil C stocks for each agroforestry system were described using the mean, minimum, maximum and standard deviation statistics. To test for differences in the biomass of the tree and shrubs, including coffee and enset, between the three agroforestry systems, a one-way ANOVA followed by post-hoc testing (Fisher's LSD test) was used (n=60). To test for differences in C stocks between the three agroforestry systems a non-parametric one-way ANOVA (Kruskal-Wallis test) followed by post-hoc multiple comparison testing (Mann-Whitney U test) was performed (n=18). Non-parametric statistics were used because of the non-normal distribution of the data. All statistical analyses was done using SPSS software version 18 (SPSS Inc. 2010).

2.4.4 Litterfall and associated C and N fluxes (Study V)

Monthly litterfall production per unit area of the crown (g m^{-2}) for each of the seven studied species was calculated by dividing the combined litterfall mass by the combined surface area of the traps. The annual litter production per unit area of the crown (g m^{-2}) was calculated by summing up the monthly litterfall production values.

To calculate the litterfall production per unit area of land (kg ha^{-1} y^{-1}) of each of the seven species, i.e. the flux to the soil, we multiplied the annual litterfall production per unit crown area values (as described above) by the mean crown area per ha as calculated from the data form the 20 farms in each agroforestry system (Study I). The annual litterfall fluxes of C and N (kg ha^{-1} y^{-1}) for each species in the agroforestry systems were calculated by multiplying the annual litterfall production (kg ha^{-1} y^{-1}) by the C and N contents (%) and the appropriate coefficient for unit correction.

The monthly and annual litterfall production, C and N contents and associated fluxes for each species and agroforestry system were described using standard descriptive statistics. The inter-monthly variation of litterfall production per unit crown area for each species was calculated following Silva et al. (2011).

$$\text{Inter-monthly variation (\%)} = (\max - \min/\max) \times 100 \qquad \text{(Eq.12)}$$

where max = maximum monthly litterfall production, min = minimum monthly litterfall production.

Differences between species and agroforestry systems were tested for using non-parametric statistics (Kruskal-Wallis ANOVA and Dunn's or Mann-Whitney tests for multiple comparisons). All statistical analysis were done using SPSS software version 18 (SPSS Inc. 2010).

3. RESULTS

3.1 Floristic diversity of agroforestry systems (Study I)

A total of 58 woody species, belonging to 49 genera and 30 families, was recorded in the three agroforestry systems (Table 6). Additionally, 24 herbaceous species, belonging to 22 genera and 14 families, were identified (Table 7). Among the woody species, trees constituted 84% (49 species), shrubs 9% (5 species) and tree/shrubs 7% (4 species). Native tree and shrub species accounted for 86% (50 out of 58 woody species recorded). The highest proportion of woody native species was recorded in the Enset system (92%), followed by Enset-coffee system (89%) and Fruit-coffee system (82%). *Millettia ferruginea*, *Brucea antidysente* J.F. Mill., *Cordia africana*, and *Croton macrostachyus* were the four most frequently found native tree species in the Enset system. *Cordia africana*, *Vernonia amygdalina* Del. and *Ficus gnaphalocarpa* (Mig.) steud.ex A. Rich were the most abundant species, after *Millettia ferruginea* and *Coffea arabica* in the Enset-coffee system. *Persea americana*, *Mangifera indica* and *Casimiroa edulis* were the most frequent species in the Fruit-coffee system.

The number of woody species listed as being of “conservation concern” according to the IUCN Red Lists and local criteria were 22 species (Table 8). The Enset-coffee system contained the highest number of these species (13), followed by the Enset system and the Fruit-coffee system (9 species each). *Vepris dainellii* (Pichi-Serm.) Kokwaro is identified as both IUCN Red List and a locally rare species, and *Rhus glutinosa* Hochst. Ex A. Richand and *Pygeum africanum* Hook. F. are recorded as vulnerable species in IUCN Red Lists.

The mean basal area and stem density of woody species significantly differed ($P < 0.001$) between agroforestry systems (Table 9). The mean basal area decreased in the order: Fruit-coffee system > Enset-coffee system > Enset system. The mean number of stems in the Fruit-coffee system was by 59% and 18% higher than that in Enset system and Enset-coffee system, respectively. Native woody species accounted for 88% (23 m^2 ha^{-1}) of total basal area on average across all farms (n=60). The mean value for canopy cover was 83%. Among all farms, the most dominant native tree species were *Millettia ferruginea* (mean basal area 1.9 m^2 ha^{-1}) and *Cordia africana* (0.8 m^2 ha^{-1}), and the least dominant species were *Diospyros abyssinica* (Hiern) F. White, *Vepris dainellii* and *Dracaena steudneri* Schweinf. ex Engl.(0.03 m^2 ha^{-1} each).

The NMDS ordination showed that farms in the same agroforestry system maintained similar species composition and abundance. However, there were clear differences among the agroforestry systems (Figure 5). NMDS axes 1 and 2 explained 71.5% and 15.8% of the total data variation, respectively (cumulative $R^2 = 0.873$). The Monte Carlo test showed that axis 1 was most significantly correlated to altitude ($r = -0.84$, $p<0.01$), species richness ($r = 0.37$, $p<0.001$) and aspect ($r = -0.33$, $p<0.05$); while axis 2 was most significantly correlated with stem density ($r = 0.74$, $p<0.01$), basal area ($r = 0.67$, $p<0.01$) and species abundance ($r = 0.41$, $p<0.01$).

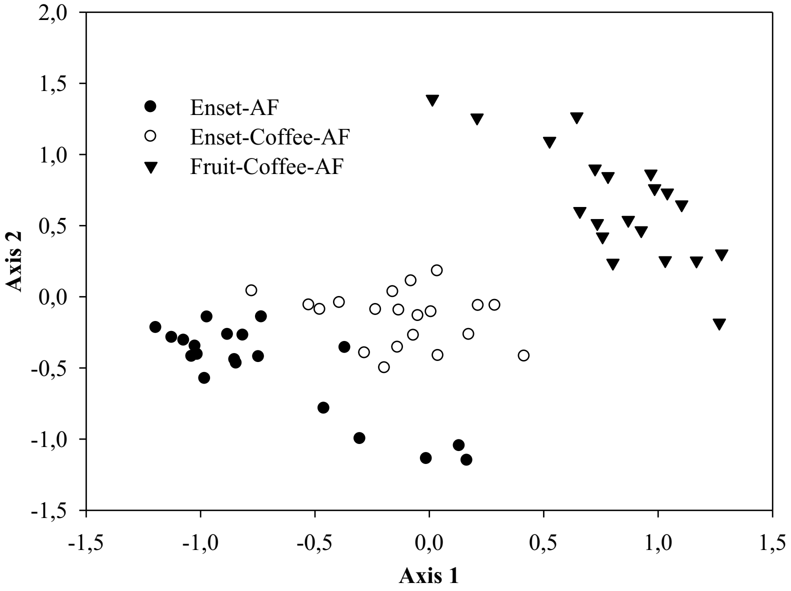

Figure 5. Nonmetric multidimensional scaling (NMDS) ordination of 60 plots samples in 3 agroforestry systems in south Rift Valley escarpment, Ethiopia. Sample plots labeled accroding to three agroforestry groups produced by cluste species analysis; AF = Agroforestry.

Table 6. Woody species frequency, relative abundance, life-forms, nature of establishment and uses of trees and shrubs in agroforestry systems in south-eastern of Rift valley escarpment, Ethiopia (n=20 for each agroforestry system).

Woody species	Local name	Family	Plots (%)	RA (%)	Plots (%)	RA (%)	Plots (%)	RA (%)	LF	W/P	N/ Non	Uses
			E	E	E-C	E-C	F-C	F-C				
Albizia grandibracteata Taub.	Denbele-Kuche	Fabaceae					5	2.5	T	W	N	2,4,9
Albizia gummifera (J.F. Gmel.) C.A.Sm	Gorbe	Fabaceae			5	0.3	5	0.3	T	W	N	1,2,9
Aningeria adolfi-friedericii Rob & Gilb.	Gudubo	Sapotaceae	5	0.9					T	W	N	1,2
Annona chrysophylla Bojer	Geshita	Annonaceae			10	0.6	15	1.1	T	W	Non	12
Bersama abyssinica Fresen	Tibero/Sessa	Melianthaceae	10	2.7	5	0.3			T	W	N	2,11
Brucea antidysente J.F. Mill.	Lafa	Simaroubaceae	35	4.9	5	0.3			T	W	N	9
Casimiroa edulis Lal Llave & Lex.	Abukere	Rutaceae					40	3.6	T	W	Non	12
Cassipourea malosana (Baker) Alston	Tilo	Rhizophoraceae					10	0.5	T	W	N	ns
Catha edulis Forssk.	Chate	Celastraceae					5	0.5	S/T	P	N	2,13,15
Celtis africana Burm.F.	Motokomo	Ulmaceae					10	0.5	T	W	N	2,5,6
Celtis gomphophylla Baker.	Wolaba	Ulmaceae					5	0.3	T	W	N	9
Citrus sinensis (L.) Osbeck	Birtukan	Rutaceae			10	0.6			S/T	P	Non	12,15
Clausena anisata (Willd.) Hook. f. ex Benth	Godere	Rutaceae			15	0.9			T	W	N	16
Coffea arabica L.	Buno	Rubiaceae	30	6.6	100	50.7	100	49.7	S/T	W/P	N	13,15
Cordia africana Lam.	Wedesa	Boraginaceae	30	7.5	45	5.2	10	0.5	T	W	N	1,2,4,7,10
Croton macrostachyus Hochst. ex Delile.	Mokonisa	Euphorbiacee	30	1	10	14	10	0.5	T	W	N	2,7,9,10
Diospyros abyssinica (Hiern) F. White	Lokko	Ebenaceae			10	0.9	5	0.3	T	W	N	1,2,8
Dracaena steudneri Schweinf. Ex Engl.	Cho'e	Dracaenaceae	5	0.4	5	0.3			T	W	N	3,10
Ehretia cymosa Thonn.	Uraga	Boraginaceae			5	0.3			T	W	N	1,2,7,9
Ekebergia capensis Sparrm.	Onono	Meliaceae	10	0.9	5	0.3			T	W	N	1,2,7
Erythrina brucei Schweinf.	Welena	Fabaceae	15	1.8	15	0.9			T	W	N	1,3,4,5,7
Euphorbia candelabrum Tremaut ex Kotschy	Adame	Euphorbiaceae	5	0.9	5	0.3			T	W	N	1,2
Fagaropsis angolensis (Engl.) Dale	Antitenhe	Rutaceae			5	0.3			T	W	N	2,3,6
Ficus elastica Roxb. ex Hornem.	Kilto	Moraceae			5	0.3			T	W	Non	4
Ficus gnaphalocarpa Miq.) Steud. ex Miq.	Odh'e	Moraceae	5	0.9	15	1.4			T	W	N	2,4,7,10
Ficus vasta Forssk.	Kilto	Moraceae			5	0.3	5	0.3	T	W	N	4,6,9,12
Galiniera coffeoides Delile	Abaye	Rubiaceae	5	0.4					T	W	N	1,2
Mangifera indica L.	Mango	Anacardiaceae					65	16.7	T	P	Non	12,15
Millettia ferruginea (Hochst.) Baker	Tatato	Fabaceae	100	47.3	100	26.4	75	10.1	T	W	N	1,2,3,4,7,8,10
Olea welwitschii (Knobl.) Gilg &	Dega/Setamo	Oleaceae			5	0.3	10	0.5	T	W	N	1,3,9

Schellenb.												
Persea americana Mill.	Avocato	Lauraceae	5	0.4	10	0.6	85	8.5	T	P	Non	12,15
Pittosporum viridiflorum Sims	Hangare	Pittosporaceae			5	2.0			T	W	N	1,8
Polyscias ferruginea (Polyscias fuluva) (Hiern) Harms	Tele'a	Araliaceae	10	0.9	10	0.6			T	W	N	5,6
Prunus persica (L.) Batsch	Koke	Rosaceae	5	0.4					T	P	Non	12,15
Psidium guajava L.	Sholla	Myrtaceae					15	0.8	T	P	Non	12,15
Pygeum africanum Hook. f.	Gerebe	Rosaceae	15	2.7	10	0.9	5	0.3	T	W	N	1,2,5,6,8,9
Rhamnus prinoides L'Hér.	Gesho	Rhamnaceae	5	0.4	5	0.3	5	0.5	S	W	N	9,14,15
Sapium ellipticum (Hochst.) Pax	Wagisa	Euphorbiaceae					5	0.8	T	W	N	2,8
Solanecio gigas (Vatke) C. Jeffrey	Dimbola	Asteraceae	5	3.5					S	W	N	9
Trema orientalis (L.) Blume	Walo	Ulmaceae					5	0.3	T	W	N	9
Vepris dainellii (Pic. Serm.) Mziray	Halesa	Rutaceae	10	0.9					T	W	N	1,2
Vernonia amygdalina Delile	Hebicha	Asteraceae	10	2.2	15	3.7	10	0.8	T	W	N	2,3,9,10
Vernonia auriculifera Hiern	Reji	Asteraceae	20	10.2					T	W	N	2,11
Species recorded out of sample plots for richness												
Bridelia micrantha (Hochst.) Baill.	Yebelo	Euphorbiaceae						x	T	W	N	2,3,9,12
Bridelia scleroneura Muell.Arg.	Jembebelo	Euphorbiaceae						x	T	W	N	2,3
Combretum sp.	-	Combretaceae						x	T	W	N	2,3
Deinbollia kilimandscharica Taub	Gorono	Sapinadaceae	x						T	W	N	8,11
Discopodium penninervium Hochst.	Chosika	Solanaceae			x				S/T	W	N	2
Dracaena fragrans (L.) Ker.-Gawl.	Lete	Dracaenaceae						x	S	W	N	3,10
Ficus thonningii Blume.	Denbe	Moraceae			x				T	W	N	4,10
Pavetta abyssinica Fresen.	Kurema	Rubiaceae	x						T	W	N	2
Podocarpus falcatus (*Afrocurps falcatus*) (Thunb.) R. Br. ex Mirb.	Birbrisa	Podocarpaceae			x				T	W	N	1
Ficus sur Forssk.	Wagela	Rosaceae			x				T	W	N	1,2,4,7,10
Pycnostachys abyssinica Fresen.	Tontona	Lamiaceae	x						S	W	N	9
Rhus glutinosa Hochst. Ex A. Rich	Halessa	Anacardiaceae			x			x	T	W	N	2,8
Rothmannia urcelliformis (Hiern) Robyns	Rhetike Buno	Rubicaceae			x				T	W	N	ns
Senna sp.	Cheketa	Fabaceae			x				S	W	N	ns
Syzygium guineense (Willd.) DC.	Badessa	Myrtaceae	x		x				T	W	N	1,3,7,9

Agroforestry systems: E Enset system, E-C Enset-coffee system, F-C Fruit-coffee system; RA Relative abundance; LF Life form: T Tree, S Shrub; Establishment methods: W Wild, P planted; State of the species: N Native species, Non Non-native species; Use types: 1 timber/pole, 2 fuelwood, 3 fodder, 4 shade, 5 beehives construction, 6 beehives hanging, 7 household's utensils, 8 farm tools, 9 medicine, 10 soil fertility, 11 live fences, 12 fruit, 13 stimulus, 14 flavouring drink, 15 cash, 16 bee forage; ns not specified use.

Table 7**.** Species frequency and ground cover of herbaceous plants for agroforestry systems in south-eastern escarpment of Rift Valley, Ethiopia (n=20 for each agroforestry system).

Herbaceous species	Local name	Family	Plot (%)	GC (%)	Plot (%)	GC (%)	Plot (%)	GC (%)	W/P
			E	E	E-C	E-C	F-C	F-C	
Achyranthes aspera L.	Shere	Amaranthaceae	60	13.9	15	6.1	5	0.2	W
Acmella caulirhiza Delile	Baticho	Asteraceae	20	4.3	20	8.1			W
Ageratum conyzoides L.	Bekelecha	Asteraceae	25	7.6	25	14.5	10	1.4	W
Arthraxon sp.	Foge	Poaceae			20	15.6	20	2.9	W
Bidens pilosa L.	Tugeno	Asteraceae	15	2.4	30	16.5	35	16.6	W
Bidens sp.	Ade'Ha	Asteraceae	5	0.8					W
Commelina benghalensis L.	Lalunte	Commelinaceae	50	6.6	30	1.1	25	5.4	W
Dioscorea sp.	Bure	Dioscoraceae	20	0.5	5	0.2			W
Droguetia iners (Forssk.) Schweinf.	Arshoko	Urticaceae	10	1.2	20	8.8	5	0.2	W
Geranium arabicum Forssk.	Derkosha	Geraniaceae	5	0.2					W
Hydrocotyle mannii Hook.f	Shefete	Apiaceae			10	0.6	5	2.9	W
Impatiens ethiopica Grey-Wilson	Leche	Balsaminaceae	70	19.5	50	4.9	10	0.6	W
Impatiens rothii Hoo. F.	Leche	Balsaminaceae	5	0.4					W
Kalanchoe sp.	Hanchule	Crassulaceae	5	0.2			5	0.4	W
Leucas sp.	Boffe	Lamiaceae			5	0.1	5	1.0	W
Poecilostachys oplismenoides (Hack.) Clayton	Daffa	Poaceae	30	16.6	20	11.2	20	63.5	W
Polygonum nepalense Meisn.	Eshedie	Polygonaceae	35	12.2	40	7.0			W
Rumex nepalensis Spreng.	Belekeni	Polygonaceae	15	2.2	5	0.1			W
Sida sp.	Fokene	Malvaceae			5	0.1			W
Snow denia C.E. Hubb.	Muja	Poaceae	15	0.5	10	0.7	5	0.4	W
Sonchus sp.	Guree	Asteraceae	15	0.6	5	0.1			W
Stellaria sennii Chiov.	Rorico	Caryophyllaceae	5	2.8					W
#*Ensete ventricosum* (Welw.) Cheesman	Wassa	Musaceae	100	65	100	35			P
#*Musa sapientum* L.	Muze	Musaceae	10	21	20	21	10	50	P

Agroforestry systems: E Enset system, E-C Enset-coffee system, F-C Fruit-coffee system; GC Ground cover; #*Ensete ventricosum and Musa sapientum* are giant perennial herb, their relative abundance calculated separately; Establishment method: W Wild, P planted.

Table 8. Native woody species recorded for their conservation concern as per IUCN and local criteria in agroforestry systems of south-eastern Rift Valley escarpment, Ethiopia (n=20 for each agroforestry system).

		Agroforestry			Status		
Species	Family	E	E-C	F-C	IUCN[a]	Magurran[b]	Local[c]
Albizia gummifera	Fabaceae			x		R	
Bridelia scleroneura	Euphorbiaceae			x			Ln
Brucea antidysente	Simaroubaceae	x	x				Ln
Celtis gomphophylla	Ulmaceae			x		R	
Diospyros abyssinica	Ebenaceae			x		R	
Discopodium penninervium	Solanaceae		x				Ln
Dracaena steudneri	Dracaenaceae	x				R	
Ekebergia capensis	Meliaceae		x			R	
Erythrina brucei	Leguminosae	x	x		LC		
Euphorbia candelabrum	Euphorbiaceae		x			R	Ln
Fagaropsis angolensis	Rutaceae		x			R	
Ficus gnaphalocarpa	Moraceae		x				Ln
Ficus vasta	Moraceae		x	x		R	
Galiniera coffeoides	Rubiaceae					R	
Millettia ferruginea	Leguminosae		x	x	LC		
Olea welwitschii	Oleaceae		x			R	
Pygeum africanum	Rosaceae			x	V	R	
Rhamnus prinoides	Rhamnaceae		x	x		R	Ln
Rhus glutinosa	Anacardiaceae		x	x	V		
Solanecio gigas	Asteraceae				LC		
Trema orientalis	Ulmaceae		x				
Vepris dainellii	Rutaceae				LC	R	Ln

Agroforestry systems: E Enset system, E-C Enset-coffee system, F-C Fruit-coffee system; x donates agroforestry type where the species is found; LC least concern, V vulnerable, R rare, Ln least number of individuals.

[a] According to IUCN RED lists (Vivero et al. 2005).

[b] Designated as rare for 25% of species that least occurred (Magurran 2004).

[c] Least number of individuals (100000 individuals in the country) as per local criteria (Bekele et al. 1999).

Table 9. Mean altitude, dbh, height, basal area and stem numbers for each agroforestry system in south-eastern Rift Valley escarpment, Ethiopia, followed by standard error of the mean (SE) in parenthesis.

Agroforestry system	n	altitude (m.a.s.l)	dbh (cm)	height (m)	basal area (m^2 ha^{-1})	stem number (ha^{-1})
Enset	20	2273 (18.1)^{a}	13.2 (1.8)^{a}	9.5 (0.9)^{a}	5.4 (0.5)^{a}	625 (84)^{a}
Enset-coffee	20	1868 (35.8)^{b}	10.7 (0.8)^{a}	7.9 (0.4)^{a}	9.3 (0.8)^{b}	1240 (111)^{b}
Fruit-coffee	20	1612 (11.7)^{c}	11.0 (0.6)^{a}	7.8 (0.2)^{a}	11.7 (1.0)^{c}	1505 (142)^{c}
p-value		<0.001	ns	ns	<0.001	<0.001

Differences between agroforestry systems were analysed using ANOVA, followed by LSD multiple test (Fisher LSD test); Similar letter shows not significant difference and different letters indicate significance differences between groups according to LSD multiple test (Fisher LSD test) at P <0.05; ns not significant.

Species richness and stem number did not differ between the Enset-coffee and Fruit-coffee systems but both significantly differed from the Enset system (Table 10). The Shannon diversity index did not significantly differ among the agroforestry systems, but Margalef's diversity index of species richness did. Simpson's evenness index for the Enset system was significantly different from that of the Enset-coffee and Fruit-coffee systems ($p < 0.05$).

Table 10. Mean woody species abundance, richness, Shannon index (H'), Simpson's evenness (E1/D) and Margalef's index (D_{mg}) of 10 × 10 m sample plot of agroforestry systems in south-eastern Rift Valley escarpment, Ethiopia. SE is shown in parenthesis.

Agroforestry system	n	Abundance	Richness	H'	E1/D	D_{mg}
Enset	20	11 (1.5)^a	3.55 (0.4)^a	0.93 (0.1)^a	0.74 (0.04)^a	37.48 (7.7)^a
Enset-coffee	20	17.45 (1.5)^b	4.35(0.4)^b	1.07 (0.1)^a	0.60(0.04)^b	35.38 (1.2)^b
Fruit-coffee	20	17.70 (1.6)^b	4.90(0.3)^b	1.16 (0.1)^a	0.54(0.03)^b	35.24 (1.2)^b
P-value		<0.05	<0.05	ns	<0.01	<0.05

Kruskal Wallis Test ANOVA was conducted to evaluate mean differences between groups and followed by Mann-Whitney U test for multiple comparisons. Similar letter shows not significant difference and different letters indicate significance differences between groups at $p < 0.05$; ns not significant.

The Sørensen quantitative index showed species similarity between the Enset and Enset-coffee systems was calculated to 53% (27 of 51 species recorded in both systems). The highest species similarity was observed between Enset-coffee and Fruit-coffee systems, i.e. 64% (32 of 50 species). The lowest species similarity was recorded between Enset and Fruit-coffee systems, i.e. 17% (7 out of 45 species).

3.2 Biomass allometric equations for coffee and enset (Study II & III)

The mean biomass of each biomass component for coffee is presented in Table 11. Stem biomass accounted for 56% of aboveground biomass on average, branch 39% and twigs plus foliage 5%. The organic matter content of the total biomass was determined by LOI, calculated by weighting the contribution of each biomass component to total biomass, averaged 98%.

Table 11. Summary statistics of dry mass (kg/plant) of total aboveground and biomass components of harvested coffee (*Coffea arabica*) plant samples (n=31); SD standard deviation.

Components	Mean	Minimum	Maximum	SD
Twigs + Foliage	1.1	0.2	3.7	0.7
Branches	8.9	0.3	25.0	6.9
Stem	12.9	0.6	36.9	8.6
Total aboveground	22.9	1.1	65.6	15.8

For enset, the pseudostem component accounted for 64% of total plant biomass, the corm for 24% and foliage for 12% (Table 12). The aboveground biomass (pseudostem plus foliage) thus accounted for 76% of total plant biomass. The organic matter content of the total biomass of enset averaged 94%.

The biomass of all components for coffee were correlated with stem diameter ($p < 0.01$), particularly stump diameter (d_{40}), but not with height (Table 13). The highest correlation was with stem biomass, followed by total aboveground, branch, and twig plus foliage biomass.

Table 12. Summary statistics of dry mass (kg/plant) of total and biomass components of harvested enset Plant samples (n=40).

Component	Mean	Minimum	Maximum	SD
[a]Foliage	1.1	0.4	2.0	0.5
Pseudostem	6.0	0.9	15.7	3.7
[b] Pseudostem plus foliage	7.1	1.6	17.3	4.0
[c]Corm (+ proximal roots)	2.2	0.3	8.0	1.8
Total	9.4	2.2	24.6	5.3

[a]Foliage includes leaf lamina + leaf midrib + petiole, [b]aboveground biomass, [c]belowground biomass.

Table 13. Spearman correlations between biomass components and coffee plant biometric parameters (n = 31).

Biomass component	d, cm	d_{40}, cm	h, m	h_{dom}, m	cw, m	ch, m	ca, m^2
Twigs + foliage	0.47^{**}	0.72^{**}	0.08^{ns}	0.11^{ns}	0.26^{ns}	0.22^{ns}	0.30^{ns}
Branches	0.79^{**}	0.84^{**}	-0.02^{ns}	0.06^{ns}	0.48^{**}	0.38^{*}	0.55^{**}
Stem	0.83^{**}	0.90^{**}	-0.02^{ns}	0.12^{ns}	0.40^{*}	0.41^{*}	0.46^{**}
Total aboveground	0.82^{**}	0.89^{**}	-0.01^{ns}	0.10^{ns}	0.45^{*}	0.43^{*}	0.52^{**}

d diameter at breast height, d_{40} stump diameter at 40 cm height, h total height, h_{dom} dominant height, cw crown width, ch crown height, ca crown area; $^{*}p < 0.05$; $^{**}p < 0.01$,ns not significant

For enset, total and component biomasses were significantly ($p < 0.05$) correlated to all diameter measurements and, except for the corm component, also with height measurements (Table 14). The highest correlation was between total biomass and d_{10} and the weakest correlation between corm plus proximal roots (belowground biomass) and total height.

Table 14. Spearman correlations between diameter and height variables and biomass for each biomass component for enset plants (n = 40).

Biomass component	d_{10}	d_{30}	d_{130}	d_{200}	h_p	h_c	h
Foliage	0.76^{**}	0.70^{**}	0.70^{**}	0.67^{**}	0.36^{*}	0.32^{*}	0.34^{*}
Pseudostem	0.94^{**}	0.89^{**}	0.69^{**}	0.65^{**}	0.60^{**}	0.45^{**}	0.50^{**}
[a]Pseudostem plus foliage	0.96^{**}	0.90^{**}	0.74^{**}	0.70^{**}	0.59^{**}	0.44^{**}	0.49^{**}
[b]Corm (+ proximal roots)	0.74^{**}	0.63^{**}	0.55^{**}	0.53^{**}	0.27^{ns}	0.26^{ns}	0.23^{ns}
Total	0.98^{**}	0.90^{**}	0.75^{**}	0.70^{**}	0.55^{**}	0.42^{**}	0.45^{**}

[a]aboveground biomass, [b]belowground biomass, h_p pseudostem height, h_c crown height, h total height; $^{*}p < 0.05$, $^{**}p < 0.01$, ns not significant.

Overall, the results show that stump diameter (d_{40}) is a better predictor of total aboveground and biomass components for coffee (Figure 6) while basal diameter (d_{10}) is the best biomass predictor for enset (Figure 7). The residuals (estimated minus measured biomass values) for total and components biomasses for both coffee and enset increased with stem and pseudostem diameter, respectively. Stump diameter had a stronger effect on the variation in coffee branch, stem and total aboveground biomasses than on foliage biomass (Figure 6). For enset, the variability in corm and foliage biomasses increased with basal diameter (d_{10}) while the effect on pseudostem and total biomass variability was less (Figure 7).

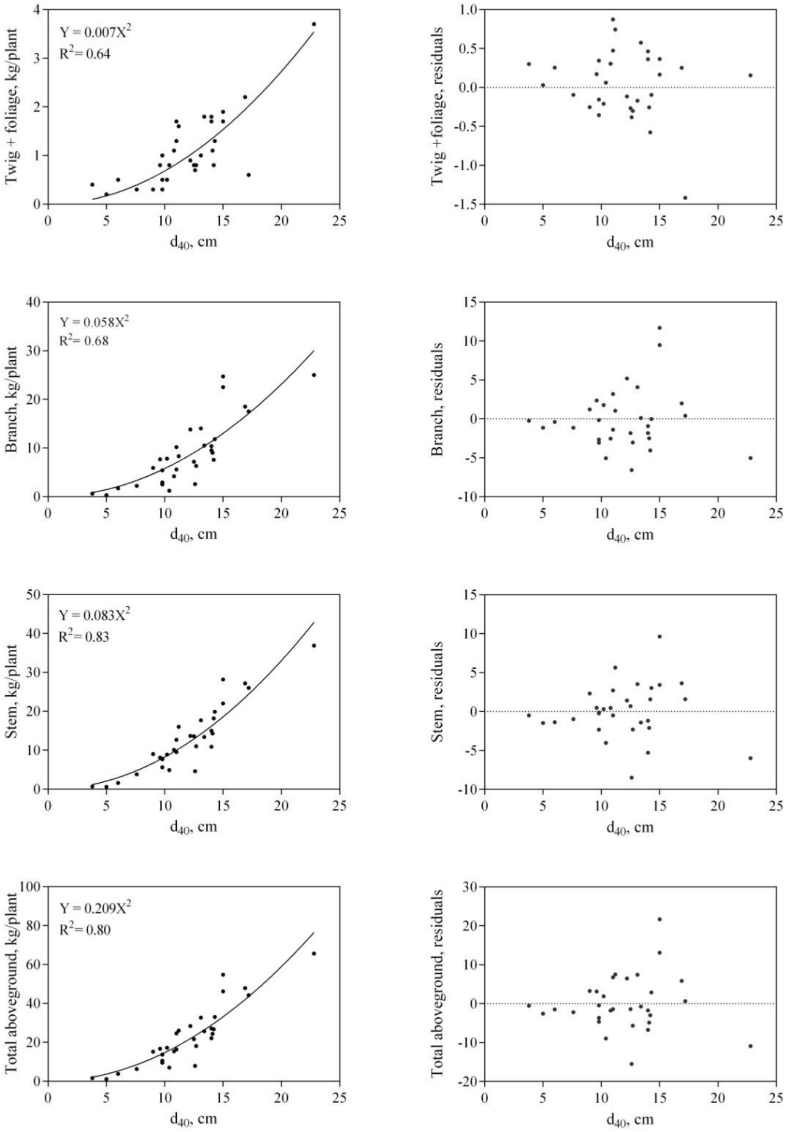

Figure 6. Relationship between biomass components of *Coffea arabica* and stump diameter at 40 cm (d_{40}) (left) and corresponding residual plots (right).

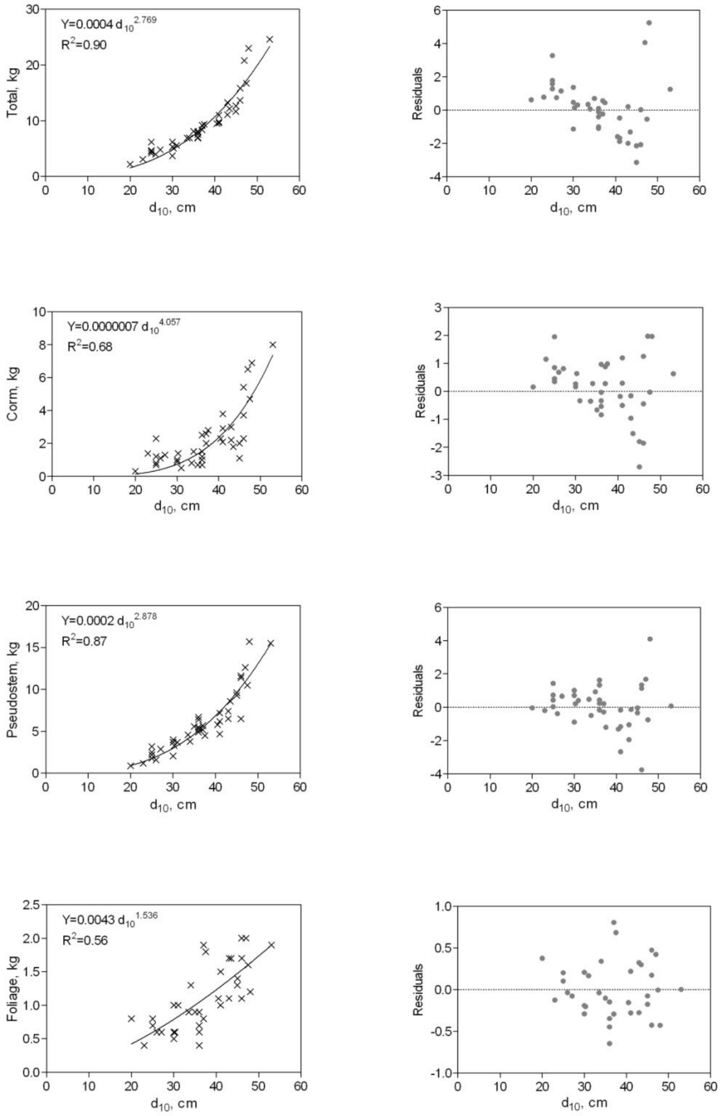

Figure 7. Relationships between the biomass of each component and stump basal diameter at 10 cm (d_{10}) for the harvested enset plants (n = 40) (left) and corresponding plots of residuals (estimated minus measured biomass values) (right), corm=corm plus proximal roots.

Several biomass equations were tested, but the best for coffee was equation M6 ($Y=b_1d_{40}^2$), which explained 80% of the variance in total aboveground biomass (Table 15).The reliability of the prediction decreased in the order: stem > branches > twigs plus foliage. While for enset, equation M9 ($Y=b_1d_{10}^{b2}H^{b3}$) was the best, which explained 91% in total biomass. The bias for biomass prediction decreased in the order: total biomass > corm plus proximal roots (belowground) > pseudostem > foliage. Other equations tested but not shown in the summary include Equations no. 1, 2, 3,4 and 5 in study II and Equations no. 1, 14, 15, 16, 21 and 23 in study III.

Table 15. The best equations and goodness-of-fit performance statistics for estimating biomass (kg dry mass/plant) of coffee and enset grown in agroforestry systems.

Plant	Biomass Components	Equation no.	Equation	Coefficient				Performance statistics					
				b_1	b_2	b_3	b_4	R^2	SEE	Bias	MAB	PRESS	D
Coffee	Twigs + foliage	6 in study II	$Y=b_1d_{40}^2$	0.007^{***}	–	–	–	0.63	0.45	-0.013	0.34	6.50	0.90
	Branches	6 in study II	$Y=b_1d_{40}^2$	0.058^{***}	–	–	–	0.68	3.91	0.061	2.78	512.71	0.89
	Stem	6 in study II	$Y=b_1d_{40}^2$	0.083^{***}	–	–	–	0.83	3.51	0.002	2.53	422.99	0.95
	[a]Total	6 in study II	$Y=b_1d_{40}^2$	0.147^{***}	–	–	–	0.80	7.11	-0.115	5.12	1723.46	0.94
Enset	Foliage	17 in study III	$Y=b_1(d_{10}^{b2}d_{30}^{b3}d_{130}^{b4})$	$3.4\text{x}10^{-3ns}$	1.982^{***}	1.154^{*}	0.863^{**}	0.67	0.28	-0.002	0.22	3.91	0.97
	Pseudostem	24 in study III	$\ln(Y)=\ln(d_{10})+\ln(h)$	-7.827^{***}	2.607^{***}	0.079^{ns}	–	0.88	1.32	0.022	0.90	73.72	0.97
	[b]Corm (+ proximal roots)	17 in study III	$Y=b_1(d_{10}^{b2}d_{30}^{b3}d_{130}^{b4})$	$8\text{x}10^{-7ns}$	5.576^{***}	2.221^{**}	0.709^{ns}	0.75	0.95	-0.129	0.72	51.00	0.93
	[c]Total	9 in study III	$Y=b_1d_{10}^{b2}h^{b3}$	$7\text{x}10^{-4ns}$	2.571^{***}	0.102^{ns}	–	0.91	1.67	-0.106	1.10	122.67	0.98

SEE, Bias, MAB are in kg per plant, n=31 for coffee, n=40 for enset, d_{10} diameter at 10cm height, d_{30} diameter at 30cm height, d_{40} stump diameter at 40 cm height, d_{130} diameter at breast height, h total height, b_1, b_2, b_3 and b_4 are parameters; $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$, ns not significant.

[a]Total aboveground biomass = Stem + Branches + Foliage plus twigs

[b] Belowground biomass

[c] Total biomass = Foliage + Pseudostem + Corm plus attached proximal roots

The aboveground biomass of coffee estimated with equations M2 ($Y=b_1d_{40}^{b2}$) and M6, and the equations presented by Hairiah et al. (2001) and Segura et al. (2006) plotted against the measured biomass values are presented in Figure 8. While the Hairiah et al. (2001) equation overestimated total aboveground biomass, the Segura et al. (2006) equation substantially underestimated total aboveground biomass of our coffee plants. This emphasizes the need to parameterize allometric equations with site-specific data when possible.

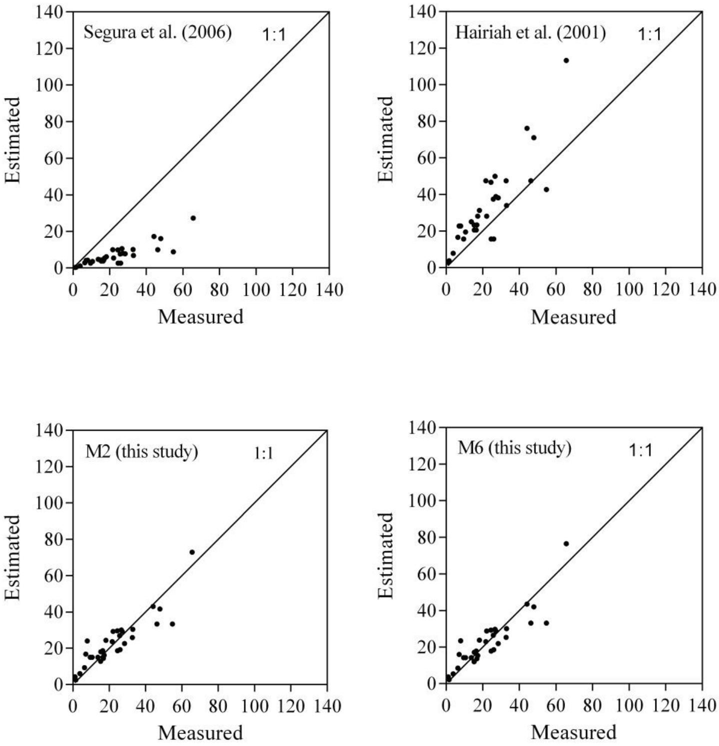

Figure 8**.** Relationship between estimated and measured total aboveground biomass of coffee sample plants (n = 31). Equations used were: M2 ($Y = 0.209 \times d_{40}^{1.872}$), M6 ($Y = 0.147 \times d_{40}^{2}$) (both this study), Segura et al. (2006), $Y = \exp(-2.719 + 1.991(\ln(d)))(\log_{10}d)$, and Hairiah et al. (2001), $Y = 0.281\times d^{2.06}$.

3.3 Carbon stocks of the indigenous agroforestry systems (Study IV)

The mean aboveground woody species biomass, including coffee and enset, ranged from 81.6 Mg ha^{-1} (Enset system) to 135.6 (Enset-coffee) and for belowground biomass from 23.1 Mg ha^{-1} (Enset system) to 37.6 (Enset-coffee) (Table 16). The mean total (above- plus belowground) biomass of the Enset-coffee and Fruit-coffee systems were not significantly different but both were significantly different ($p<0.05$) from that of the Enset system. The total biomass for the Enset-coffee system was respectively 11 and 40% higher than the Fruit-coffee and Enset systems. Trees other than coffee and enset contributed the most (83–92%) to the total biomass in all three agroforestry systems. In the two agroforestry systems that included coffee, the coffee accounted for 9% (Enset-coffee) and 17% (Fruit-coffee) of total biomass. For the two agroforestry systems that included enset, the total biomass of enset contributed 4% (Enset-coffee system) and 8% (Enset system) to total biomass.

The mean C stock of total biomass (above- and belowground, and including herbaceous plants and litter) was the highest for the Enset-coffee system (115.6±65.1 Mg C ha^{-1}, mean ±SD), followed by the Fruit-coffee system (78.6±23.9) and the lowest for the Enset system (48.9±43.8) (Figure 9 and 10). The proportion of aboveground biomass to the total biomass C stocks was similar for the Enset and Fruit-coffee systems (76% each) but slightly high for the Enset-coffee system (85%). Trees and shrubs contributed 89% to the total biomass C stock of the Enset-coffee system, 81% in the Enset system and 80% in the Fruit-coffee system (Figure 9 and 10). Fruit trees alone accounted for 68% of the total biomass C stock in the case of the Fruit-coffee system. Enset and coffee together contributed nearly 7% to the total biomass C stock of the Enset-coffee system while enset contributed 9% to the Enset system and coffee 12% to the Fruit-coffee system.

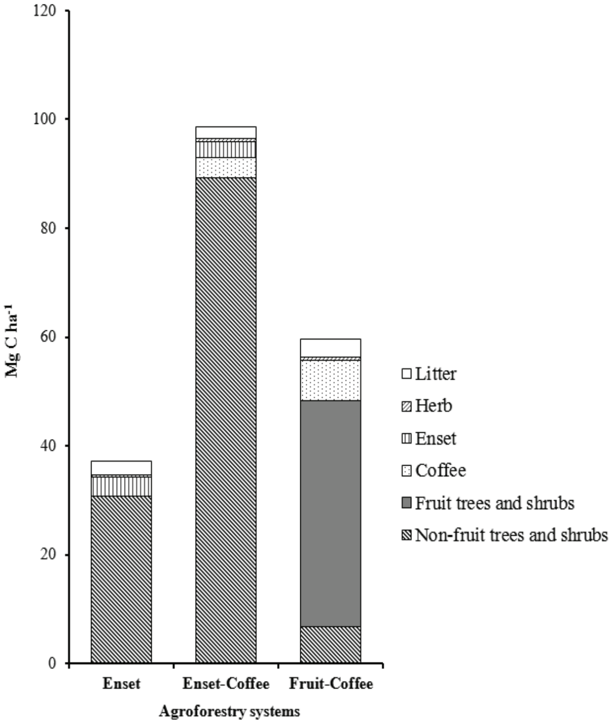

Figure 9. Aboveground biomass carbon stocks of the three agroforestry systems (Enset = Enset based agroforestry system) by biomass component.

Table 16. Mean (± SD) above- (AG), belowground (BG) and total biomass (Mg ha^{-1}) of woody and enset components grown in three agroforestry systems. Within each biomass component, agroforestry systems having the same letter are not significantly ($p < 0.05$) different from each other (Fisher LSD test; n=20 for each agroforestry system).

Biomass component	Agroforestry system	Woody			Coffee	Enset	Total
		Fruit	Non-fruit	Total			
AG biomass	Enset	1.7 ± 7.7^{a}	72.5 ± 72.1^{a}	74.2 ± 71.7^{a}	–	7.4 ± 3.4^{a}	81.6 ± 69.8^{a}
	Enset-coffee	1.2 ± 3.8^{a}	115.7 ± 106.4^{ab}	116.9 ± 105.8^{a}	12.6 ± 8.2^{a}	6.1 ± 3.2^{a}	135.6 ± 102.7^{b}
	Fruit-coffee	50.0 ± 47.8^{b}	$42.3+80.1^{ac}$	98.3 ± 86.4^{a}	20.7 ± 8.2^{a}	–	119.0 ± 87.9^{b}
BG biomass	Enset	0.5 ± 2.3^{a}	21.7 ± 19.9^{a}	22.3 ± 19.7^{a}	–	0.8 ± 0.4^{a}	23.1 ± 19.5^{a}
	Enset-coffee	0.7 ± 2.0^{a}	32.4 ± 27.3^{ab}	33.1 ± 27.2^{a}	3.2 ± 2.7^{a}	1.2 ± 1.0^{b}	37.6 ± 27.1^{b}
	Fruit-coffee	17.8 ± 13.9^{b}	10.9 ± 20.6^{ac}	28.8 ± 22.6^{a}	5.7 ± 3.0^{b}	–	34.4 ± 22.3^{b}
Total biomass	Enset	2.2 ± 10.0^{a}	94.2 ± 91.9^{a}	96.4 ± 91.3^{a}	–	8.2 ± 3.7^{a}	104.7 ± 89.2^{a}
	Enset-coffee	1.9 ± 5.3^{a}	148.1 ± 133.6^{ab}	150.0 ± 132.8^{a}	15.9 ± 9.1^{a}	7.3 ± 4.2^{a}	173.1 ± 129.6^{b}
	Fruit-coffee	73.8 ± 61.3^{b}	53.2 ± 100.5^{ac}	127.0 ± 108.9^{a}	26.4 ± 10.5^{b}	–	153.4 ± 109.7^{b}

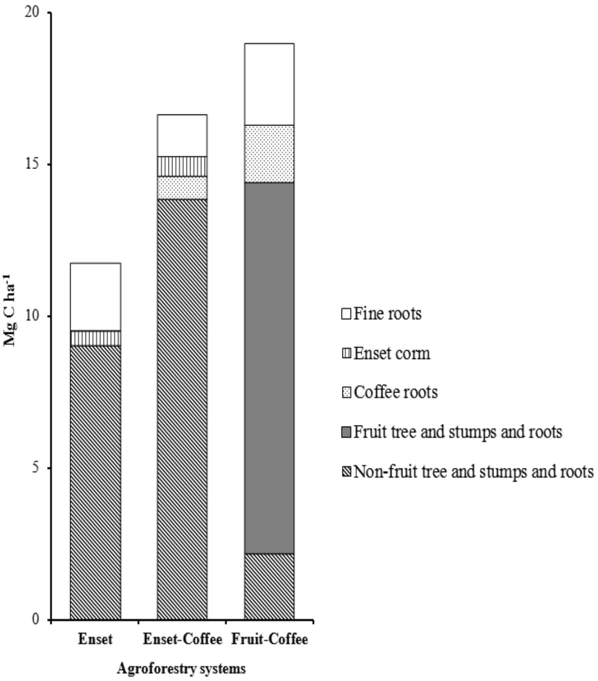

Figure 10. Belowground biomass carbon stocks of the three agroforestry systems (belowground part of stump and coarse roots >2 cm diameter) (Enset = Enset based agroforestry system) by biomass component. Fine roots (all roots <2 mm diameter) and Enset corm (+ proximal roots) values are based on measured data; coffee roots and woody roots (fruit and non-fruit) are estimates using equation developed by Kuyah et al. (2012b).

The soil C stocks (Mg C ha^{-1}) to 60 cm depth did not significantly differ among the three agroforestry systems, although the stock for the Enset system was slightly higher than that of the other two systems (Table 17). The surface layer (0–30cm) contributed 66% to the total (0–60 cm) SOC stock for the Enset system, 67% for the Enset-coffee system and 64% for the Fruit-coffee system. The SOC stocks of the subsurface (30-60 cm) layer were similar for the Enset and Fruit-coffee systems but slightly low for the Enset-coffee system.

Table 17. Mean (±SD) soil carbon stock (Mg C ha^{-1}) of each agroforestry system. Within each soil layer, agroforestry systems having the same letter are not significantly ($p < 0.05$) different from each other (Mann-Whitney U test; n= 6 for each agroforestry system).

Soil depth	Enset system	Enset-Coffee	Fruit-Coffee
0-30 (cm)	122±18^{a}	120±43^{a}	115±45^{a}
30-60 (cm)	64±11^{a}	58±18^{a}	64±11^{a}
Total (0-60 cm)	186±27^{a}	178±45^{a}	179±51^{a}

The total ecosystem (all biomass components plus soil) C stocks did not significantly differ among the three agroforestry systems, but the Enset-coffee system had the highest mean stock (293.4±39.3 Mg C ha$^{-1,}$ mean ±SD), followed by the Fruit-coffee system (257.0±70.9) and the lowest for the Enset system (235.0±59.0) (Figure 11). The highest variation in ecosystem C stocks was associated with the Fruit-coffee system (181.0–377.4 Mg C ha^{-1}), followed by Enset system (171.7–339.6), and the least for the Enset-coffee system (236.8–348.3). The SOC stock accounted for 79%, 61% and 70% of the total ecosystem C stock of the Enset, Enset-coffee and Fruit-coffee systems, respectively.

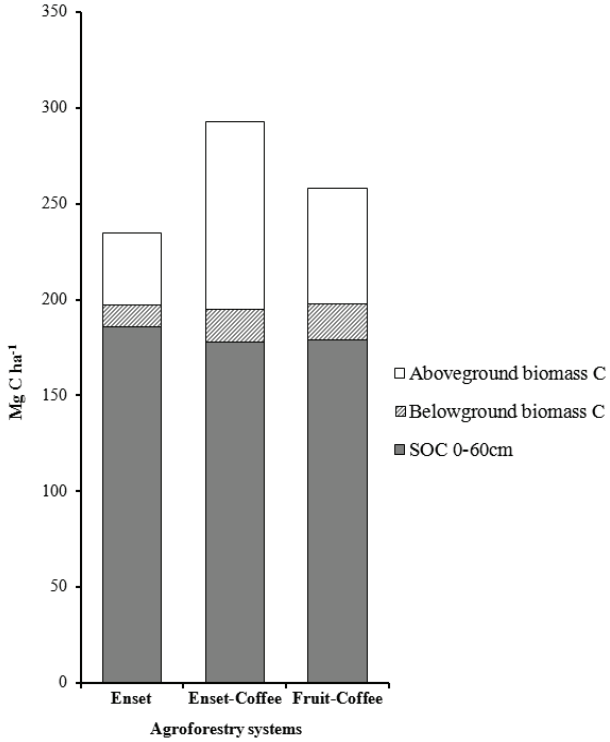

Figure 11. Agroforestry total carbon stocks (including trees, shrubs, coffee, enset, ground herbaceous pants, litter, stumps and large roots, fine roots and SOC) by agroforestry system.

3.4 Litterfall and associated C and N fluxes (Study V)

March was the month with the highest litterfall for *Cordia africana* and *Croton macrostachyus*, and December the month with the highest litterfall for *Coffea arabica*, *Millettia ferruginea*, *Mangifera indica*, and *Persea americana* (Figure 12). The month with the highest litterfall for *Erythrina brucei* was July, when rainfall was low. The month having the lowest litterfall differed more among the species more than the month having the highest litterfall.

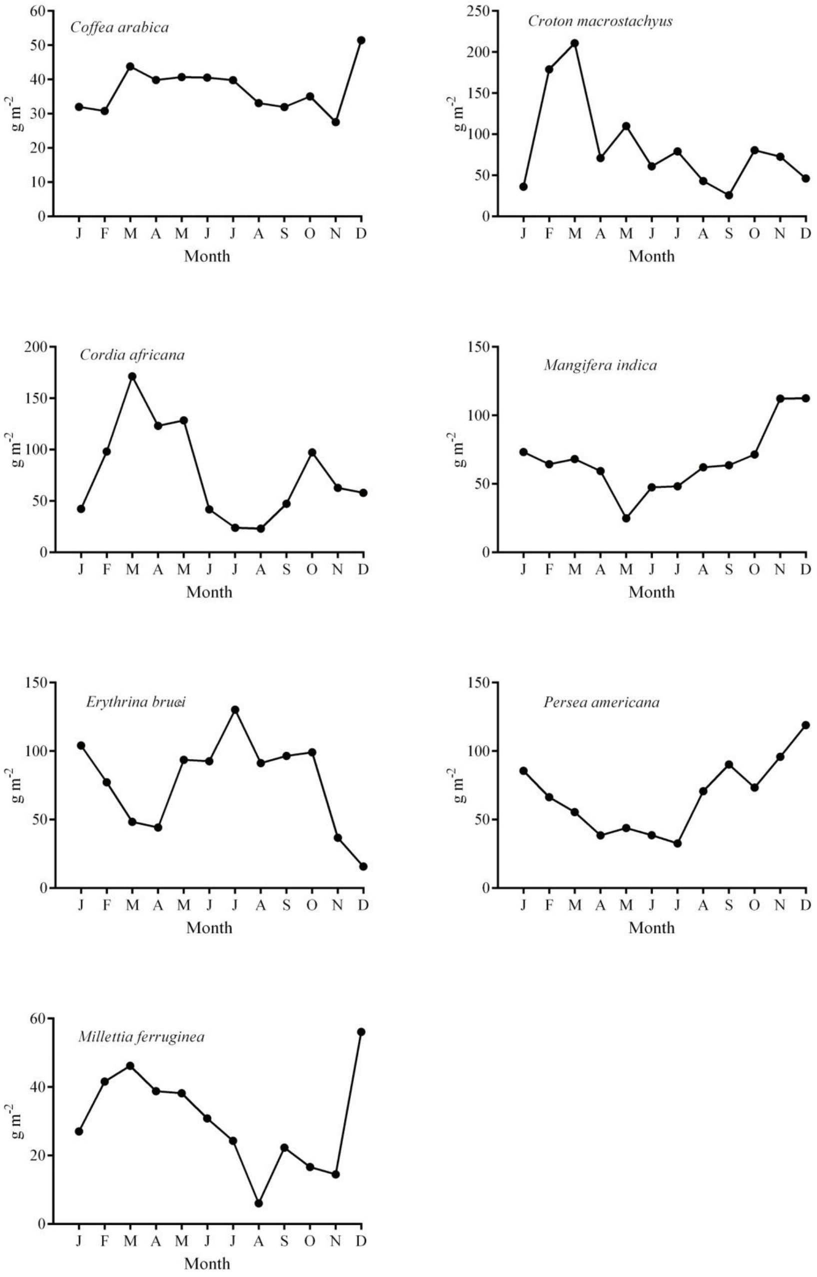

Figure 12. Mean monthly litterfall production per unit area of crown of seven woody species studied.

Coffea arabica clearly showed the least inter-monthly variation (46%) while the inter-monthly variation of the other species ranged between 73 and 89% (Table 18). The annual litterfall production per unit area of crown decreased in the order: *Croton macrostachyus* > *Erythrina brucei* > *Cordia africana* > *Persea americana* > *Mangifera indica* > *Coffea arabica*

> *Millettia ferruginea*. Litterfall production for *Croton macrostachyus* was 2 and 3 times higher than that of *Coffea arabica* and *Millettia ferruginea*, respectively. The litterfall production of *Coffea arabica* and *Millettia ferruginea* did not differ significantly from each other but both had significantly ($p < 0.05$) lower litterfall production values than the other five species (Table 18).

Table 18. Inter-monthly variation and annual litterfall production (g m^{-2} of crown area, mean ± SD) for the seven woody species. Non-significant differences in annual litterfall between species are indicated by the same letter (Kruskal-Wallis test followed by Mann-Whitney U test, $p < 0.05$).

Species	n	Inter-monthly variation (%)	Annual g m^{-2}
Coffea arabica	4	46.4	446.3 ± 80.3^a
Cordia africana	6	86.5	917.1 ± 561.8^b
Croton macrostachyus	4	87.7	1014.0 ± 680.4^b
Erythrina brucei	4	88.0	929.1 ± 403.5^b
Mangifera indica	6	77.9	806.9 ± 298.1^b
Millettia ferruginea	4	89.3	362.3 ± 174.1^a
Persea americana	6	72.6	809.3 ± 322.3^b

The C content of the litterfall decreased in the order: *Coffea arabica* > *Persea americana* > *Millettia ferruginea* > *Croton macrostachyus* > *Erythrina brucei* > *Mangifera indica* > *Cordia africana* (Table 19). The N content decreased in the order: *Coffea arabica* = *Croton macrostachyus* = *Erythrina brucei* > *Millettia ferruginea* > *Cordia africana* > *Mangifera indica* > *Persea americana*. The C:N ratio of the litterfall varied from 12 for *Croton macrostachyus* and *Erythrina brucei* to 29 for *Persea americana*.

Table 19. C and N contents (mean ± SD) and C:N ratio of litterfall for each of the seven studied woody species. For each variable, values having the same letter are not significantly ($p < 0.05$) different from each other (Mann-Whitney U test; n= 4 for each species).

Species	Carbon,%	Nitrogen,%	C:N
Coffea arabica	40.5 ± 0.1^a	3.0 ± 0.3^a	13.4 ± 1.1^a
Cordia africana	36.6 ± 0.8^b	2.1 ± 0.1^b	17.1 ± 0.4^b
Croton macrostachyus	37.6 ± 0.9^{bc}	3.0 ± 0.1^a	12.6 ± 0.3^a
Erythrina brucei	37.4 ± 3.6^b	3.0 ± 0.0^a	12.4 ± 1.5^a
Mangifera indica	36.7 ± 1.0^b	1.7 ± 0.1^c	21.8 ± 1.0^c
Millettia ferruginea	39.8 ± 0.5^{ac}	2.7 ± 0.1^d	14.5 ± 0.3^d
Persea americana	40.3 ± 0.6^a	1.4 ± 0.1^e	29.0 ± 1.9^e

The annual litterfall production (sum of seven species) was the highest for the Fruit-coffee system (average = 12938 kg ha^{-1} land), followed by the Enset-coffee system (10187) and Enset system (7430). The associated annual C fluxes (kg ha^{-1}) were 5145, 3928 and 2803, respectively and the corresponding N fluxes were: 278 kg ha^{-1}, 257 and 190 (Table 20).

Table 20. Mean (±SE) annual litterfall production and associated C and N (kg ha^{-1} yr^{-1}) fluxes for each of the seven studied woody species and total (sum of species) by agroforestry system. Non-significant differences between agroforestry systems total values are indicated by the same lower case letter (Kruskal-Wallis test followed by Dunn's multiple comparison tests; n= 20; $p < 0.05$).

Species	Litterfall			C			N		
	Enset system	Enset-Coffee	Fruit-Coffee	Enset system	Enset-Coffee	Fruit-Coffee	Enset system	Enset-Coffee	Fruit-Coffee
Coffea arabica	126.7±101.7	2845.6±424.2	4945.5±394.6	51.3±41.2	1151.2±171.6	2000.8±159.6	3.8±3.1	85.9±12.8	149.4±11.9
Cordia africana	2932.4±1264.0	4327.8±1783.7	253.0±225.1	1074.4±463.1	1585.6±653.5	92.7±82.5	62.2±26.8	91.7±37.8	5.4±4.8
Croton macrostachyus	1962.6±875.0	n.p.	29.0±29.0	738.6±329.3	n.p.	10.9±10.9	58.3±26.0	n.p.	0.9±0.9
Erythrina brucei	863.3±706.1	464.5±464.5	n.p.	322.9±264.1	173.8±173.8	n.p.	25.7±21.0	13.8±13.8	n.p.
Mangifera indica	n.p.	n.p.	1683.1±625.5	n.p.	n.p.	617.0±229.3	n.p.	n.p.	28.0±10.4
Millettia ferruginea	1373.1±364.8	2224.2±577.7	762.8±201.7	547.1±145.4	886.2±230.2	304.0±80.4	37.4±9.9	60.5±15.7	20.8±5.5
Persea americana	171.7±171.7	325.0±223.7	5264.0±1110.3	69.1±69.1	130.8±90.1	2119.3±447.0	2.4±2.4	4.6±3.1	73.7±15.5
Total	7429.91±444.3^{a}	10187.1±1795.7^{ab}	12937.5±1477.3^{a}	2803.4±535.2^{a}	3927.6±664.2^{ab}	5144.6±586.0^{b}	189.7±36.6^{a}	256.6±39.3^{ab}	278.1±25.5^{b}

SE standard error, n.p. not present

3.5 Relationship between species composition and carbon stocks (Study I, IV & V)

The total above and belowground biomass C stocks (Total AGC and BGC) were significantly correlated to species abundance and richness (Spearman r = 0.47–0.57, $p < 0.05$) but none of the biomass components were significantly correlated to the Shannon diversity index (Table 21). The strongest significant correlation was found between C stock of the total belowground biomass carbon (Total BGC) with species abundance (r = 0.57; $p < 0.05$) and the weakest correlation was between total belowground biomass and soil C stocks (Total BG-BSC) with species richness. Litterfall correlated more strongly (r = 0.52, $p < 0.05$) with species abundance than richness.

Table 21. Spearman correlations between biomass and soil carbon stocks, and woody species composition (n=18)

Carbon stock components	Richness	Abundance	Shannon diversity index
Woody AGC	0.51*	0.54*	0.27
Woody BGC, >2cm	0.51*	0.54*	0.27
Soil,0-60cm	-0.08	-0.02	-0.24
Fine root carbon (<2mm), 0-60cm	0.24	0.12	0.08
Litterfall	0.36	0.52*	0.16
Total AGC	0.47*	0.53*	0.35
Total BGC	0.53*	0.57*	0.38
Total ABG-BC	0.51*	0.55*	0.33
Total BG-BSC	0.01	0.08	-0.12
Total AFC	0.42	0.41	0.24

Woody AGC = Aboveground carbon stock for woody species
Woody BGC = Belowground carbon stock for woody species
Total AGC = Total aboveground carbon (= woody + coffee + enset + litter + herb)
Total BGC = Total belowground carbon (= woody + coffee + enset + Fine roots)
Total ABG-BC = Total above- and belowground biomass carbon (=above + belowground biomass C)
Total BG-BSC = Total belowground biomass and soil carbon (= belowground biomass C + SOC)
Total AFC = Total agroforestry carbon stock (total biomass + soil C stocks)
*$p < 0.05$

4. DISCUSSION

4.1 Review of the study approach

Biodiversity conservation and climate change mitigation and adaptation have become current issues globally. The impact of climate change is highly manifested in developing countries particularly in agriculture in which considerable numbers of people depend for their livelihoods. Thus, most studies focus on climate change adaptation as it affects adaptive capacity of local communities (Kalame 2011). However, the roles of agricultural landscapes in conservation of biodiversity and mitigation of climate have been little studied in Ethiopia. It is in this view that the study was initiated. The initial idea was to compare the indigenous agroforestry system with natural forest in respect to the above two issues, but no natural forest was found in the nearby area to compare with. Therefore, the study was limited to compare the different indigenous agroforestry systems, accounting the main indicator plant in each systems, particularly enset, coffee and fruit.

In Study I, the role of the indigenous agroforestry systems to maintain native woody species was determined. Species area curve was used to evaluate if sufficient numbers of farms were taken (Magurran 2004). A sample size (10×10 m) was used because of the agroforestry system in the study area is horizontally and vertically well-packed (Tesemma 2007), and land holding size is too small (in few cases 0.01ha). Since no allometric equations formed to estimate the biomass of native coffee and enset plants in the study area, biomass was harvested and allometric equations parameterized (study II and III). Ideally, the equations should be cross validated using an independent dataset; however, such data for coffee and enset are unavailable in the research area. For the cross validation of coffee plant instead it was used a split-sample approach in which the harvested plants were partitioned into two sets, ‘‘training’’ (i.e. deriving equations) and ‘‘testing’’ (i.e. testing the equations) (Arlot and Celisse 2010). Besides, the performance of the best equation in this study was compared to other previous equation developed for coffee, i.e. Hairiah et al. 2001; Segura et al. 2006. However, for enset plant no other allometric equations found to compare with, implying that the need to do further research to validate the performance of equations developed in this study. As this study was conducted on farms, it was unable to harvest trees/shrubs to develop site specific allometric equations for trees and shrubs. Instead, equations already developed for trees and shrubs grown in agroforestry system in similar agroecosystems were used (Kuyah et al. 2012 a & b).

The carbon content of coffee, enset, herbaceous plant, litter and fine roots in the present study were determined based on loss-on-ignition (LOI). Studies showed that carbon content was estimated from 50% of the ash free mass (Das and Das 2010). This default value would result in over estimation of the C stock. Most studies neglect volatile C constituents that make up on average 1.3–2.5% of total C in living wood (Thomas and Martin 2012). Thus, in this study the carbon content was determined to 44% of the organic matter (ash free mass). The 44% of C out of organic mass (i.e. after LOI) is theoretical number based on the structure of carbohydrates that form most of the plant structures (Kozlowski & Pallardy 1996) (see detail in sub-section 2.2.4). For instance, using 50% of the ash free mass to estimate the carbon stock in Enset-Coffee system had increased the carbon stock estimate by 2% compared to 44% value.

Uncertainty of C stock estimation also occurs using various proportion of carbon content. Several studies estimated the C stock half of the biomass; assuming that 50% of the biomass is carbon (Schroeder 1994, Chave et al. 2009, Soto-Pinto et al. 2010). However, recent studies indicate that this assumption is not accurate, with substantial variation in C content among tree species as well as among tissue types. Systematic error introduce in accounting C content may range from 1.6 to 5.8% of carbon stocks assessment (Martin and Thomas 2011, Thomas and Martin 2012). C content of 48% was used in this study for trees and shrubs determined by Kuyah et al. (2012a) in agroforestry system. This would minimize the over-estimation of biomass and carbon in this study.

4.2 Management of agroforestry for floristic diversity conservation (Study I)

The indigenous agroforestry systems in the south-eastern Rift Valley escarpment of Ethiopia were shown to maintain a high proportion of native tree species (86%). This is considerably higher than reported for traditional tree-crop and Enset-coffee agroforestry systems in the eastern and southern parts of Ethiopia (Teketay and Tegineh 1991, Abebe 2005, Asfaw and Ågren 2007). The number of native tree species in the three agroforestry systems varied, however, which probably reflects differences in altitude, species adaptability, and farmer management practices (Hervé and Vidal, 2008). The Fruit-coffee and Enset-coffee systems had higher total species richness but a lower number of native species than the Enset system. This is because farmers in the Fruit-coffee and Enset-coffee systems plant cash crops such as fruit trees (mainly *Mangifera indica* and *Persea americana*) and coffee. Native tree species under the Fruit-coffee system are mostly intended for shading coffee. In the Enset system, farmers manage enset with native woody species. The number of woody species recorded in coffee growing agroforestry systems in the current study is high compared to Coffee-shade tree system (Méndez et al. 2009) and in rustic coffee plantations (Bandeira et al. 2005).

The combined basal area of woody species in this study was higher than that reported for Enset-coffee systems in southern Ethiopia by Asfaw (2003) and that of other agroforestry systems in the tropics (Asase and Tetteh 2010); but lower than that reported for coffee-based agroforests in Guinea (Correia et al. 2010) and cocoa forest gardens in southern Cameroon (Hervé and Vidal 2008). The difference can be attributed to differences in farmer management practices, including species selection, spacing and tending practices. For example, woody species stem densities in agroforestry systems of this study were high and diameters small in comparison. However, the differences between the basal area of the various agroforestry systems is probably also related to differences in environmental (climate and soil) conditions.

The number of species of "conservation concern" was the highest in the Enset-coffee system (13 native woody species). Enset-coffee and Enset systems are still serving more than Fruit-coffee system as refuges for many native woody species. Fruit-coffee system accommodates *Rhus glutinosa* and *Pygeum africanum* (also known as in *Prunus africanum*), which are IUCN Red-Listed species and are marked as 'vulnerable' species (Edwards and Kelbessa 1999, Vivero et al. 2005). These species are facing a high risk of disappearance in the wild (Edwards and Kelbessa 1999) and hence, agroforestry system can provide potential sites for maintaining both species outside forest land use. *Prunus africanum* is an evergreen tree that is mainly demanded for medicine (bark and leaves) and it has declined in the wild by at least 20% during the last 10 years (Edwards and Kelbessa 1999).

It is also reported that *Cordia africana* and *Podocarpus falcatus* are locally endangered and are not allowed to be felled in state and private forests in Ethiopia (Gebremariam et al. 2009). *Vepris dainellii* is also one of the rarest native woody species in the country (Bekele et al. 1999). *Vepris dainellii* in agroforestry system may help to conserve the species. Native tree species such as *Albizia gummifera*, *Bersama abyssinica* Fresen, *Dracaena steudneri*, *Ekebergia capensis* Sparrm. and *Olea welwitschii* (Knobl.) Gilg & Schellen. are locally rare and need to be given conservation priority in the Gedeo agroforestry systems. Native tree species that once dominated the mid-altitude natural forests, such as *Combretum* sp., *Podocarpus falcatus* and *Syzygium guineense*, were not abundant in our study sites, and need attention for conservation. Management strategies favouring enset and coffee may put other native tree species at risk. Extensive global meta-analysis on biodiversity and ecosystem services on agroforestry systems in the tropics (De Beenhouwer et al. 2013) has also shown that management intensification decreased ecosystem services including species richness.

4.3 Biomass allometric equations for coffee and enset (Study II & III)

The results from this study clearly showed that while stump diameter (d_{40}) was the best predictor of aboveground and component coffee biomasses, basal diameter (d_{10}) was the best for enset total and component biomasses. Total height was found not to be correlated to any of the coffee biomass components. Several studies have also shown that tree height is a poor predictor of biomass and attributable, at least in part, to the inaccuracy of height measurements (Philip 1994, Starr et al. 1998, Chave et al. 2005, Segura et al. 2006). Moreover, height growth of trees is strongly affected by competition. Although the correlation between aboveground biomass and height for enset was significant, the correlation was considerably smaller than those for the diameter measurements. However, studies by Shank and Ertiro (1996) and Tesgaye and Struik (2003) both found a strong correlation between food yield and pseudostem height.

The best preforming equation in this study for coffee, M6, using d_{40} explained 80% of the variation in total aboveground biomass. This is less than reported by Segura et al. (2006) for coffee grown in Nicaragua. Allometric equations with a single predictor, such as M6, are more efficient and increase accuracy and reduce data collection costs (Zianis and Mencuccini 2004, Chave et al. 2005, Segura et al. 2006). However, the square power equation using breast height diameter generally showed the most bias in our study. This is further indication that breast height diameter is not as reliable as using stump diameter for predicting coffee biomass.

For enset, the best performing equation M9 in this study, which uses both d_{10} and total height, explained 91% of total biomass. This value is lower than those reported by Hairiah et al. (2011) for banana (*Musa* spp.), which has a similar growth form to that of enset. However, the inclusion of total height into our equation M9 only slightly improved equation performance compared to the single variable equation M1 ($Y=b_1d_{10}^{b_2}$). Eliminating the need for height measurements and using the principle of parsimony (Crawley, 2005), equation M1, which explained 90% in total biomass variation, would therefore be recommended for use in practice.

4.4 Carbon stocks of the indigenous agroforestry systems (Study IV)

The total biomass (above- plus belowground) values for the three agroforestry systems in this study (105−173 Mg ha^{-1}) are higher than the global average values for forest biomass and for some tropical forest types. The mean total biomass of forests globally averages 149 Mg ha^{-1} (FAO 2010). Brown and Lugo (1984) reported a range in total biomass stocks for undisturbed, broadleaf tropical forests of 61 to 176 Mg ha^{-1} and for dry sub-tropical dry forests of 78 to 90 Mg ha^{-1}. More recent studies give aboveground biomass estimates of 260 Mg ha^{-1} for African tropical moist deciduous forest and of 115 Mg ha^{-1} for African tropical mountain systems (Aaron and Gibbs 2008). The aboveground biomass stocks in this study (82–119 Mg ha^{-1}) were also approximately 2.7−4.7 times higher than reported for agroforestry systems in Western Kenya (Kuyah et al. 2012 a & c). This difference is due to the difference in the amount of trees in the agroforestry systems. In the agroforestry systems studied by Kuyah et al. (2012 a & c) there are few trees whereas in present study, trees form a major part of the agroforestry systems.

The total biomass C stocks of the three agroforestry systems (49–116 Mg C ha^{-1}) are within the range reported for agroforestry systems globally (12−228 Mg C ha^{-1}) (Dixon 1995; Albrecht and Kandji 2003), but substantially higher than the range reported for agroforestry systems in sub-Saharan Africa (4.5–19 Mg C ha^{-1}) (Unruh et al. 1993), agrisilviculture systems in the humid tropical region of Africa (29−53 C Mg ha^{-1}) (Albrecht and Kandji 2003), and other agroforestry systems in the tropics (De Jong et al. 1997; Pandey 2002; Mutuo et al. 2005; Soto-Pinto et al. 2010). However, our values were lower than reported for other traditional agroforestry systems in the tropics (Kirby and Potvin 2007; Roshetko et al. 2007) and Cacao-based agroforestry systems in western and central Africa (Duguma et al. 2001). The total biomass C stocks of the two agroforestry systems in which coffee was grown (Enset-Coffee and Fruit-Coffee) were high compared to other coffee agroforestry systems (Schmitt-Harsh et al. 2012; Häger 2012), but this is due to the high contribution of trees in our agroforestry systems.

Soil organic C plays a vital role in the global carbon cycle, forming large C pools (Schmidt et al. 2011) with long residence times (Post et al. 1982). The SOC stocks in these agroforestry systems are noticeably high compared to the SOC stocks of other ecosystems and soils. Batjes (1996) reported the SOC stocks of Nitosol soils (the dominant soil type in our study area) from around the world to average 41 Mg ha^{-1} for the 0−30 cm layer, Lal (2004) reported SOC stocks in the 0–60 cm layer for tropical forest and tropical savannas to be 121−123 Mg ha^{-1} and 110−117 Mg ha^{-1}, respectively. Lemenh and Fisseha (2004) reported SOC stocks for semi-arid *Acacia etabica* woodland in southern Ethiopia to be 43 t C ha^{-1} and Swamy and Puri (2005) reported SOC stocks for agroforestry systems in Central India to be 27 Mg ha^{-1}, in both studies for the 0-60 cm soil layer. Our SOC stocks were also greater than those reported for cropland and grazing land in nine East and West African countries, including Ethiopia (Brown et al. 2012) and for parkland agroforestry practiced in southern Ethiopia (Demessie et al. 2013). The high SOC stocks in our agroforestry systems can be attributed to the high proportion of tree and shrubs in these systems. For example, the tree density in agroforestry systems in the present study site was much higher than that in the study by Demessie et al. (2013).

Of the three agroforestry systems in our study, the Enset system had the highest SOC stocks. This is due to the practice of cutting-off of old enset leaves that are left on site to mulch, the slower decomposition of enset litter compared to the litter of other agroforestry tree species (unpublished data), and lower mineralization rates due to the higher elevation (lower temperature) of the Enset system. The 0–30 cm SOC stocks in the two coffee agroforestry systems were 16–32% higher than reported for other coffee agroforestry systems in other parts of the tropics (Dossa et al. 2008; van Noordwijk et al. 2002). The 0–30 cm SOC stock of the Fruit-Coffee system in this study was by 6% higher than reported for polyculture-shade organic coffee systems and by 13% and 26% lower than reported for polyculture-shade non-organic coffee systems and Inga-shade organic coffee systems, respectively (Soto-Pinto et al. 2010).

The ecosystem C stocks (biomass plus soil) in our study (235−293 Mg C ha^{-1}) were higher than reported for low latitude (0−25°) forest ecosystems (mean 244 Mg C ha^{-1}; Dixon et al. 1994). This suggests that our agroforestry systems sequester considerably more C than do tropical forest ecosystems. The distribution of C stocks between biomass and soil differs among ecosystems and varies with latitude. Dixon et al. (1994) reported the biomass and SOC (1 m) stocks of forest ecosystems from around the world. In general the highest SOC (mean 343 Mg C ha^{-1}, ranging 181–484) stocks were in high latitudes and the lowest (mean 121 Mg C ha^{-1}, ranging 120–139) biomass C stocks were in low latitudes, and the proportion of forest ecosystem C stock in biomass increases towards the tropics, from 16% in high latitudes to 50% in low latitudes. Brown and Lugo (1982) reported that 58% of the organic matter storage in tropical forests resides in the biomass, 41% in the soil and 1% in the litter.

A high proportion of the ecosystem C stock in agroforestry systems in the present study is in the soil. The SOC (0−60 cm) to total biomass C ratio for the Enset system was 4:1, 2:1 for the Fruit-coffee system, and 1.5:1 for the Enset-coffee system. Several factors affect the SOC to biomass C ratio in agroforestry systems, including how long the agroforestry system has been practiced, tree species and rotation age (Montagnini and Nair 2004), elevation and climate (Soto-Pinto et al. 2010), soil type (Lal 2004), silvicultural management (e.g. planting density, pruning, thinning), and land-use history (Nair et al. 2009).

4.5 Litterfall and associated C and N fluxes (Study V)

The highest monthly and annual litterfall production per unit area of crown for *Croton macrostachyus, Erythrina brucei* and *Cordia africana* may be related to the deciduous nature of the species (Bekele, 1993). This could be a strategy for the species to adapt seasonal rainfall and temperature variation. The seasonal pattern of litterfall of *Erythrina brucei* clearly differed from that of the other species; litterfall peaking in January and July, the months when rainfall was the lowest, while the litterfall of the other species showing a strong inter-monthly variation peaked in March and December. This seasonal difference in litterfall production among the studied species undoubtedly reflects a difference in the response to rainfall and moisture conditions. Coffee has leaf longevity, leaf thickness and is well adapted to dry periods (Vaast et al. 2006). The nitrogen-rich and steady supply of coffee litterfall and the difference in the seasonality of litterfall of the other species may partly explain the productiveness of these traditional agroforestry systems.

The annual litterfall productions per unit area of crown varied considerably among the seven studied species (446–1014 g m^{-2} y^{-1}), but were all considerably higher than reported for woody species in other agroforestry systems. Das and Das (2010) reported average litterfall production values for five woody species grown in traditional homegarden systems ranging from 38 to 105 g m^{-2} y^{-1}, and Benjamin et al. (2001) reported values of between 0.2 and 30.1 g m^{-2} y^{-1} for ten woody species grown in Maya homegardens in Mexico. The values in this study are also higher than reported for nine woody species (104−343 g m^{-2} y^{-1}) grown in exclosures in northern Ethiopia (Descheemaeker et al. 2006). These differences are likely to be due to the different species, age, management practice, site and soil factors among the studies.

Besides high and continuous litterfall production, the C:N ratio of the litterfall of different species also helps to explain the high productivity and other ecosystem services of these indigenous agroforestry systems. Litterfall C:N ratios differed considerably among the seven species in present study (from 12 to 29), indicating a wide range in litter decomposition rates. Having species with a range in C:N ratios (decomposition rates) may be expected to be beneficial, helping to ensure a continuous supply of nutrients and organic matter to the soil.

Even though our annual total litterfall values do not include all the tree species present and are therefore underestimates of the true total litterfall production, the values in this study were higher than reported for Asian tropical and sub-tropical coniferous and broadleaved forests (Liu et al. 2004), home gardens in India (Issac and Nair 2006, Das and Das 2010) and in Mexico (Benjamin et al. 2001), and in exclosures in northern Ethiopia (Descheemaeker et al. 2006). The high litterfall production of the traditional agroforestry systems in the Rift Valley escarpment of south-eastern Ethiopia found in this study would account for the high productivity of these systems.

4.6 Biodiversity conservation and climate change mitigation (Study I, IV & V)

Currently, conservation of biodiversity and mitigation of climate change are the most important global environmental challenges, particularly in the tropics. Biodiversity regulates ecosystem functions, including the carbon and biogeochemical cycling (Srivastava et al. 2012). The general trend is that ecosystem with high biodiversity sequester more carbon in the soil than those which have lower diversity (Lal and Akinremi 1983). Biodiversity particularly native woody species play important roles in the rate of carbon gain or loss, the amount and stability of carbon pools (Díaz et al. 2009). However, studies show inconsistent effects of biodiversity on the carbon storage. Zhang et al. (2011) found a negative relation between plant diversity and aboveground C storage in subalpine coniferous forest. While Potvin et al. (2011) reported plant diversity positively influenced the carbon pools and fluxes following establishment of tree plantation on a former pasture. Species richness and abundance in agroforestry systems in the present study positively correlated with above and belowground carbon stocks. However, the Shannon diversity index, which combines richness and abundance, did not significantly correlated to biomass C stocks. This may partly be due to index sensitivity to low sample size and the weight it gives to rare species. Henry et al. (2009) found similar results for agroforestry system in western Kenya. The authors found that species richness directly related to the aboveground carbon stock but not with species diversity. Saha et al. (2009) found that species richness correlated to SOC in homegarden of Kerala, India. Thus, biodiversity can be seen as an independent agro-ecosystem function that may not directly correlated to carbon storage. The effect of species diversity on biomass storage depends on management practices, species, age and site factors.

5. CONCLUSIONS AND RECOMMENDATIONS

The indigenous agroforestry systems of the south-eastern Rift Valley escarpment of Ethiopia are not only productive, providing food and supporting livelihoods, and protecting soil and watershed, but are also important for conservation of native floristic diversity and for serving as C sinks to help in climate change mitigation.

The indigenous agroforestry systems have a higher proportion of native woody species compared to Enset-coffee and Cereal based agroforestry systems in some other parts of Ethiopia and in the tropics in general. The Enset and Enset-coffee systems had higher numbers of native woody species than the Fruit-coffee system. The introduction of exotic fruit tree species explains the lower number of native woody species in the Fruit-coffee system. A total 22 woody species of "special interest for conservation" according to IUCN Red lists and local criteria were identified. Current agroforestry management practices that favour enset and coffee may put native tree species at risk and result in a loss of biodiversity. It is important to inform the local community about the detrimental effects of loss of biodiversity and encourage them to maintain native species and taxa.

Coffee and fruit are the most important cash crops and enset an important source of food in these indigenous agroforestry systems. The allometric equations developed in this study now enable to estimate the biomass and associated C sequestration of coffee and enset. The aboveground biomass of *Coffea arabica* was found to be strongly correlated with stump diameter (d_{40}), explaining 80% of the variance in biomass. In the case of enset (3−5 year-old), total biomass was also found to be strongly correlated with basal diameter (d_{10}), and except in the case of the corm, was also with total height, explaining 91 % of the variation. However, the power equation using d_{10} alone could explain 90% of the variation in total biomass.

The C stocks of the indigenous agroforestry systems were found to be substantially higher than those tropical forests and other agroforestry systems. The high C stocks can be attributed to the high proportion of trees in the agroforestry systems and results in high litterfall production. The monthly and annual litterfall production and associated C and N fluxes of seven dominant woody species (*Coffea arabica*, *Cordia africana*, *Croton macrostachyus*, *Erythrina brucei*, *Millettia ferruginea*, *Mangifera indica*, *Persea americana*) in the indigenous agroforestry systems were substantially higher than those reported for some tropical forests and other tropical agroforestry systems. The high litterfall production explains why more than 61% of the agroforestry ecosystem C stocks are in the soil (0-60 cm). SOC not only maintains soil quality and site productivity, but is also a more permanent store of C than biomass, helping to mitigate climate change. The high litterfall production of the woody species in these agroforestry systems can also be expected to result high levels of nutrient cycling.

Thus, the indigenous agroforestry systems of south-eastern Rift Valley escarpment of Ethiopia were found to be important for biodiversity conservation and C sequestration – both important ecosystem services. However, these ecosystem services need to be acknowledged and consideration given as to how they can benefit the local smallholders. Increasing population and the incentive of simplifying the system to favour cash crop may result in detrimental effects, including loss of soil fertility and soil erosion. Further research is needed on how to tackle these emerging threats to ensure that these unique traditional agroforestry systems are maintained into the future. The recent inclusion of agroforestry as part of the agricultural climate change mitigation strategy by the IPCC is therefore supported by the results of this study.

REFERENCES

Aaron, R. & Gibbs, H.K. 2008. New IPCC Tier-1 Global Biomass Carbon Map for the Year 2000. Available online from the Carbon Dioxide Information Analysis Centre [http://cdiac.ornl.gov], Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Abebe, T. 2005. Diversity in homegarden agroforestry system of southern Ethiopia. PhD Dissertation, Wageningen Agricultural University. The Netherlands.

Abebe, T., Wiersum, K.F., Bongers, F. & Sterck, F. 2006. Diversity and dynamics in homegardens of southern Ethiopia. In: B.M. Kumar & P.K.R. Nair (Eds.). Tropical homegardens: a time-tested example of sustainable agroforestry, p.123–142.

Aerts, R., Van Overtveld, K., Haile, M., Hermy, M., Deckers, J. & Muys. B. 2006. Species composition and diversity of small Afromontane forest fragments in north Ethiopia. Plant Ecology 187:127−142.

Albrecht, A. & Kandji, S.T. 2003. Carbon sequestration in tropical agroforestry systems: review. Agriculture, Ecosystems and Environment 99:15–27.

Amézquita, M.C., Ibrahim, M., Llanderal, T., Buurman, P., & Amézquita, E. 2005. Carbon sequestration in pastures, silvopastoral systems and forests in four regions of the Latin American tropics. Journal of Sustainable Forestry 21:31–49.

Arlot S, Celisse A (2010) A survey of cross-validation procedures for model selection. Statistics surveys 4:40–79.

Asase, A. & Tetteh, A.D. 2010. The role of complex agroforestry systems in the conservation of forest tree diversity and structure in south-eastern Ghana. Biodiversity and Conservation 14:1225–1240.

Asfaw, Z. & Ågren, G.I. 2007. Farmers' local knowledge and topsoil properties of agroforestry practices in Sidama, southern Ethiopia. Agroforestry Systems 71:35−48.

Asfaw, Z. & Nigatu, A. 1995. Home-gardens in Ethiopia: Characteristics and plant diversity. Ethiopian Journal of Science 18(2):235−266.

Asfaw, Z. & Woldu, Z. 1997. Crop association of home-gardens in Wolayta and Gurage in southern Ethiopia. Ethiopian Journal of Science 20(1):73−90.

Asfaw, Z. 2002. Homegardens in Ethiopia: some observations and generalizations. In: Homegardens and in-situ conservation of plant genetic resources in farming systems. Watson, J.W. & Eyzagurre, P. B., (Eds.). Proceedings of the 2nd international homegardens workshop, 17-19 July 2001. Witzenhausen, Federal Republic of Germany.

Asfaw, Z. 2003. Tree species diversity, topsoil conditions and arbuscular mycorrhizal association in the Sidama traditional agroforestry land use, Southern Ethiopia. PhD Dissertation, Swedish University of Agricultural Sciences.

Att-Krah, K., Kindt, R., Skilton, J.N. & Amaral, W. 2004. Managing biological and genetic diversity in tropical agroforestry. Agroforestry Systems 61:183−194.

Backes, M.M. 2001. The role of indigenous tress for conservation of biocultural diversity in traditional agroforestry land use systems: the Bungoma case study, In situ conservation of indigenous tree species. Agroforestry Systems 52:119−132.

Bandeira, P.F., Martorell, C.J., Meave, A. & Caballero, J. 2005. The role of rustic coffee plantations in the conservation of wild tree diversity in the Chinantec region of Mexico. Biodiversity and Conservation 14:1225–1240.

Bardhan, S., Jose, S., Biswas, S., Kabir, K. & Rogers, W. 2012. Homegarden agroforestry systems: an intermediary for biodiversity conservation in Bangladesh. Agroforestry Systems 85:29–34.

Barreto, P.A.B., Gama-Rodrigues, E.F., Gama-Rodrigues, A.C., Fontes, A.G., Polidoro, J.C., Moço, M.K.S., Machado, R.C.R. & Baligar,V.C. 2011. Distribution of oxidizable organic C fractions in soils under cacao agroforestry systems in Southern Bahia, Brazil. Agroforestry Systems 81:213–220.

Batjes, N.H. 1996. Total carbon and nitrogen in the soils of the world. European Journal of Soil Science 47:151–163.

Beer, J., Muschler, R., Kass, D. & Somarriba, E. 1998. Shade management in coffee and cacao plantations. Agroforestry Systems 38:139–164.

Bekele, A. 1993. Useful trees and shrubs for Ethiopia. RSCU. Nairobi, Kenya.

Bekele, T., Haase, G. & Soromessa, T. 1999. Forest genetic resources of Ethiopia: status and proposed actions. In: Edwards, S., Demissie. A., Bekele, T. & Haase. G. (Eds.). The national forest resources conservations strategy development workshop. Proceedings of national workshop from June 21-22, 1999 held in Addis Ababa, Ethiopia. Institute of Biodiversity Conservation and Research (IBCR), GTZ, Addis Ababa, Ethiopia, pp. 39−48.

Benjamin, T.J., Montanez, P.I., Jimenez, J.J. & Gillespie, A.R. 2001. Carbon, water and nutrient flux in Maya homegardens in the Yucatan peninsula of Mexico. Agroforestry Systems 53:103–111.

Berhe, L. & Arnoldsson, G. 2008. Tree taper models for *Cuppressus lusitanica* plantations in Ethiopia. Southern Forests 70(3):193−203.

Bernholt, H., Kehlenbeck, K., Gebauer, J. & Buerkert, A. 2009. Plant species richness and diversity in urban and peri-urban gardens of Niamey, Niger. Agroforestry Systems 77:159–179.

Bhagwat, S.A., Willis, K.J., Birks, H.J.B. & Whittaker, R.J. 2008. Agroforestry: a refuge for tropical biodiversity? Trends in Ecology and Evolution 23(5): 261−265.

Bishaw, B., Neufeldt, H., Mowo, J., Abdelkadir, A., Muriuki, J., Dalle, G., Assefa, T., Guillozet, K., Kassa, H., Dawson, I.K., Luedeling, E. & Mbow, C. 2013. Farmers' strategies for adapting to and mitigating climate variability and change through agroforestry in Ethiopia and Kenya. In: Davis, C.M., Bernart, B. & Dmitriev, A. (Eds.). Forestry Communications Group, Oregon State University, Corvallis, Oregon.

Boffa, M.J., Turyomurugyendo, L., Barnekow-Lillesø, P.J. & Kindt, R. 2005. Enhancing farm tree diversity as a means of conserving landscape-based biodiversity: insight from the Kigezi highlands, Southwestern Uganda. Mountain Research and Development 25(3):212−217.

Boutin, C., Baril, A. & Martin, P.A. 2008. Plant diversity in crop fields and woody hedgerows of organic and conventional farms in contrasting landscapes. Agriculture, Ecosystems and Environment 123:185–193.

Brakas, S.G. & Aune, J.B. 2011. Biomass and carbon accumulation in land use systems of Claveria, the Philippines. In: Kumar, B.M. & Nair, P.K.R. (Eds.). Carbon sequestration potential of agroforestry Systems: opportunities and challenges, Advances in Agroforestry 8. Springer Dordrecht Heidelberg, London, New York. pp.163–175.

Brandt, A.S. 1984. New perspective on the origins of food production in Ethiopia. In: Clark, J.D. & Brandt, A. (Eds.). From hunters to farmers: the case and consequence of food production in Africa. p. 173−190.

Brandt, A.S., Spring, A., Hiebsch, C., McCabe, J.T, Tabogie, E., Diro, M., Wolde-Michael, G., Yntiso, G., Shigeta, M. & Tesfaye, S. 1997. The "Tree Against Hunger" *Enset*-based agricultural systems in Ethiopia. American Association for the Advancement of Science.

Breymeyer, A.I., Berg, B., Gower, S.T. & Johnson, D. 1996. Carbon budget: Temperate coniferous forests. In: Breymeyer, A.I, Hall, D.O, Melillo, J.M. & Ågren, G. (Eds.). SCOPE56–Global change: Effects on coniferous forests and grasslands. John Wiley & Sons.

Brown, S. & Lugo, A.E. 1982. The storage and production of organic matter in tropical forest and their role in the global carbon cycle. Biotropica 14(3):161−187.

Brown, S. & Lugo, A.E., 1984. Biomass of tropical forests: A new estimate based on forest volumes. Science 223:1290–1293.

Brown, S., 1997. Estimating biomass and biomass change of tropical forests. Forestry paper no. 134. Food and Agriculture Organization of the United Nations. Rome

Brown, S., Grais, A., Ambagis, S. & Pearson, T. 2012. Baseline GHG emissions from the agricultural sector and mitigation potential in countries of East and West Africa. CCAFS Working paper no. 13. CGIAR research program on climate change, agriculture and food security (CCAFS). Copenhagen, Denmark. Available online at: www.ccafs.cgiar.org

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.-P., Nelson, B., Ogawa, H., Puig, H., Riéra, B. & Yamakura, T. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145:87–99.

Chave, J., Coomes, D., Jansen, S., Lewis, S.L., Swenson, N.G. & Zanne, A.E., 2009. Towards a worldwide wood economics spectrum. Ecological Letter 12, 351–366.

Correia, M., Diabaté, M., Beavogu, P., Guilavogui, K., Lamanda, N. & de Foresta, H. 2010. Conserving forest tree diversity in Guinée Forestiére (Guinea, West Africa): the role of coffee-based agroforests. Biodiversity and Conservation 9:1725–1747.

Crawley, M.J. 2005. Statistics: An introduction using R. John Wiley & Sons Ltd. West Sussex, England. p. 327.

Cromwell, E. Cooper, D. & Mulvany, P. 1999. Agriculture, biodiversity and livelihoods: issues and entry points for development agencies. Overseas Development Institute, London. http://nt1.ids.ac.uk/eldis/agbio.htm.

Das, T. & Das, A.K. 2010. Litter production and decomposition in the forested areas of traditional homegardens: A case study from Barak Valley, Assam, northeast India. Agroforestry Systems 79:157–170.

Das, T. & Das, K.A. 2005. Inventorying plant biodiversity in homegardens: A case study in Barak valley, Assam, north-east India. Current Science 89(1):155−163.

Dáttilo, W., Martins, R.L., Uhde, V., Noronha, J.C., Florêncio, F.P. & Izzo, T.J. 2012. Floral resource partitioning by ants and bees in a jambolan *Syzygium jambolanum* (Myrtaceae) agroforestry system in Brazilian Meridional Amazon. Agroforestry Systems 85:105–111.

Dawoe, E.K., Isaac, M.E. & Quashie-Sam, J. 2010. Litterfall and litter nutrient dynamics under cocoa ecosystems in lowland humid Ghana. Plant Soil 330:55–64.

De Beenhouwer, M., Aerts, R. & Honnay, O. 2013. A global meta-analysis of the biodiversity and ecosystem service benefits of coffee and cacao agroforestry: review. Agriculture, Ecosystems and Environment 175:1–7.

De Jong, B.H.J., Tipper, R. & Taylor, J. 1997. A framework for monitoring and evaluating carbon mitigation by farm forestry projects: example of a demonstration project in Chiapas, Mexico. Mitigation and Adaptation Strategies for Global Change 2:231−246.

Debessa, S.T. 2011. Study of useful plants Gedeo homegardens Ethiopia in and around Gate Uduma gardens in Kochere Wereda of Gedeo Zone, Ethiopia: an ethnobotanical approach. M.Sc. thesis Addis Ababa University, Ethiopia. P. 144.

Demessie, A., Singh, B.R. & Lal, R. 2013. Soil carbon and nitrogen stocks under chronosequence of farm and traditional agroforestry land uses in Gambo District, Southern Ethiopia. Nutrient Cycling in Agroecosystem 95:365–375.

Descheemaeker, K., Muys, B., Nyssen, J., Poesen, J., Raes, D., Haile, M. & Deckers, J. 2006. Litter production and organic matter accumulation in exclosures of the Tigray highlands, Ethiopia. Forest Ecology and Management 233:21–35.

Díaz, S., Hector, A. & Wardle, D.A. 2009. Biodiversity in forest carbon sequestration initiatives: not just a side benefit. Current opinion in Environmental Sustainability 1:55−60.

Dixon, R.K. 1995. Agroforestry systems: sources or sinks of greenhouse gases? Agroforestry Systems 31:99−116.

Dixon, R.K. Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C. & Wisniewski, J. 1994. Carbon pools and flux of global forest ecosystems. Science 263:185–190.

Dossa, E.L, Fernands, E.C.M., Reid, W.S, & Ezui, K. 2008. Above- and-belowground biomass, nutrient and carbon stocks contrasting an open-grown and a shaded coffee Plantation. Agroforestry Systems 72:103–115.

Dube, F., Thevathasan, N.V., Zagal, E., Gordon, A.M., Stolpe, N.B. & Espinosa, M. 2011.Carbon sequestration potential of silvopastoral and other land use systems in the Chilean Patagonia. In: Kumar, B.M. & Nair, P.K.R. (Eds.). Carbon sequestration potential of agroforestry systems: opportunities and challenges, Advances in Agroforestry 8. Springer. p. 101−127

Duguma, B., Gockowski, J. & Bakala, J. 2001. Smallholder cacao *(Theobroma cacao* Linn.) cultivation in agroforestry systems of west and central Africa: challenges and opportunities. Agroforestry Systems 51:177–188.

Duguma, L.A. & Hager, H. 2010. Woody plants diversity and possession, and their future prospects in small-scale tree and shrub growing in agricultural landscapes in central highland of Ethiopia. Small-scale Forestry 9:153-174.

Edmond, N., Yakam-Simen, F., Tadesse, K.K. & Romeij, P. 2000. Gedeo Zone Mapping Project. Phase 2. Final Report. Treemail, Heelsum, the Netherlands, Privateers N.V. and the Agricultural Bureau for Gedeo Zone. http://www.treemail.nl/download. Accessed 24 March 2009.

Edwards, S. & Kelbessa, E. 1999. Forest genetic resources of Ethiopia: status and proposed actions. In: Edwards, S., Demissie, A., Bekele, T. & Haase, G. (Eds.). The national forest resources conservations strategy development workshop. Proceedings of national workshop from June 21-22, 1999 held in Addis Ababa, Ethiopia. Institute of Biodiversity Conservation and Research (IBCR), GTZ, Addis Ababa, Ethiopia, p. 101−133.

FAO. 1988. Soil map of the world. Revised legend, by FAO–UNESCO–ISRIC. World Soil Resources Report No. 60. Rome.

FAO. 2010. Global forest resource assessment. Main report no. 163.FAO (Food and Agriculture Organization of the United Nations). Rome.

Faria, D., Paciencia, M.L.B, Dixo, M., Laps, R.R. & Baumgartenzards, J. 2007. Ferns, frogs, lizards, birds and bats in forest fragments and shade cacao plantations in two contrasting landscapes in the Atlantic forest, Brazil. Biodiversity and Conservation 16:2335−2357.

Fentahun, M. & Hager, H. 2010.Integration of indigenous wild woody perennial edible fruit bearing species in the agricultural landscapes of Amhara region, Ethiopia. Agroforestry Systems 78:79–95.

Fisher, B., Turner, R.K. & Morling, P. 2009. Defining and classifying ecosystem services for decision-making. Ecological Economics 68:543−653.

Gama-Rodrigues, A.C. 2011. Soil organic matter, nutrient cycling and biological dinitrogen-fixation in agroforestry systems. Agroforestry Systems 81:191–193.

Garrity, D.P., Akinnifesi, F.K., Ajayi, O.C., Weldesemayat, S.G., Mowo, J.G., Kalinganire, A., Larwanou, M. & Bayala, J. 2010. Evergreen Agriculture: A robust approach to sustainable food security in Africa. Food Security 2:197–214.

Gascon, C., da Fonseca, G.A.B., Sechrest, W., Billmark, K.A. & Sanderson, J. 2004. Biodiversity conservation in deforested and fragmented tropical landscapes: an overview. In: Schroth, G., da Fonseca, G.A.B., Harvey, C.A., Gascon, C., Vasconcelos, H.L. & Izac, A-M.N (Eds.). Agroforestry and biodiversity conservation in tropical landscapes. Island Press Washington, DC p. 15-32.

Gebremariam, A.H., Bekele, M. & Ridgewell, A. 2009. Small and medium forest enterprises in Ethiopia. IIED Small and Medium Forest Enterprise Series No. 26.FARM-Africa and International Institute for Environment and Development, London, UK.

Gedeo Rural Development and Agricultural Office (GRDAO). 2010. Ten years rural development sector performance and future direction report. Amharic version (Unpublished). Gedeo zone, Dilla, Ethiopia.

Getahun, A. 1974. The role of wild plants in the native diet of Ethiopians. Agroecosystems 1:45−56.

Gupta, N., Kukal, S.S., Bawa, S.S. & Dhaliwal, G.S. 2009. Soil organic carbon and aggregation under poplar based agroforestry system in relation to tree age and soil type. Agroforestry Systems 76:27–35.

Häger, A. 2012. The effects of management and plant diversity on carbon storage in coffee agroforestry systems in Costa Rica. Agroforestry Systems 86:159–174.

Haileselasie, T.H. & Hiwot, M.T.G. 2012. Agroforestry practices and flora composition in backyards in Hiwane, Hintalo Wejerat of Tigray, Northern Ethiopia. International Journal of Biodiversity and Conservation 4(7):294–303.

Haileselasie, T.H., Gebrehiwot, M.T., Gebremichael, G.E. & Hiluf, S.A. 2012. Agroforestry practices and biodiversity management in backyards in Hiwane, Hintalo Wejerat of Tigray, Northern Ethiopia. Asian Journal of Agricultural Sciences 4(2): 110−116.

Hairiah, K., Dewi, S., Agus, F., Velarde, S., Ekadinata, A., Rahayu, S. & van Noordwijk, M. 2011. Measuring carbon stocks across land use systems: a manual. Bogor, Indonesia. World Agroforestry Centre (ICRAF), SEA Regional Office, p. 154.

Hairiah, K., Sitompul, S.M., van Noordwijk, M. & Palm, C.A. 2001. Carbon stocks of tropical land use systems as part of the global C balance: effects of forest conversion and options for 'clean development' activities. International Centre for Research in Agroforestry. Bogor, Indonesia.

Harmel, R.D. & Smith, P.K. 2007. Consideration of measurement uncertainty in the evaluation of goodness-of-fit in hydrologic and water quality modelling. Journal of Hydrology 33:326– 336.

Harrington, R., Anton, C., Dawson, T.P, de Bello, F., Feld, C.K, Haslett, J.R, Kluvánkova-Oravská, T., Kontogianni, A., Lavorel, S., Luck, G.W, Rounsevell, M.D.A, Samways, M.J, Settele, J., Skourtos, M., Spangenberg, J.H, Vandewalle, M., Zobel, M. &

Harrison, P.A. 2010. Ecosystem services and biodiversity conservation: concepts and a glossary. Biodiversity and Conservation 19:773−2790.

Harvey, C.A. & Villalobos, G.J.A. 2007. Agroforestry systems conserve species-rich but modified assemblage of tropical birds and bats. Biodiversity and Conservation 16:2257–2292.

Harvey, C.A. Gonzalez, J. & Somarriba, E. 2006. Dung beetle and terrestrial mammal diversity in forests, indigenous agroforestry systems and plantain monocultures in Talamanca, Costa Rica. Biodiversity and Conservation 15: 555−585.

Hemp, A. 2006. The banana forests of Kilimanjaro: Biodiversity and conservation of the Chagga homegardens. Biodiversity and Conservation 15:1193–1217.

Henry, M., Tittonell, P., Manlay, R.J., Bernoux, M., Albrecht, A. & Vanlauwe, B. 2009. Biodiversity, carbon stocks and sequestration potential in aboveground biomass in smallholder farming systems of western Kenya. Agriculture, Ecosystems and Environment 129: 238–252

Hervé, B.D.B. & Vidal, S. 2008. Plant biodiversity and vegetation structure in traditional cacoa forest gardens in southern Cameroon under different management. Biodiversity and Conservation 17:1821−1835.

Hoehn, P., Steffan-Dewenter, I. & Tscharntke, T. 2010. Relative contribution of agroforestry, rainforest and open land to local and regional bee diversity. Biodiversity and Conservation 19:2189–2200.

ICRAF. 2000. Paths to prosperity through agroforestry. ICRAF's corporate strategy, 2001–2010. Nairobi: International Centre for Research in Agroforestry.

IPCC. 1992. The 1992 IPCC supplement scientific assessment. Working Group I. Intergovernmental panel on climate change. Genva.P.1-22. http://www.ipcc.ch/ipccreports. Accessed on 3 June, 2013.

IPCC. 2000. Land use, land-use change, and forestry. A special report of the IPCC. Cambridge University Press, Cambridge, UK, p. 375.

IPCC. 2007. Climate change 2007: Impacts, adaptation and vulnerability. Report of the working Group II. Cambridge University Press, UK, p. 973.

Isaac S.R & Nair M.A. 2006. Litter dynamics of six multipurpose trees in a homegarden in Southern Kerala,India. Agroforestry Systems 67:203–213.

Isaac, M.E., Gordon, A.M., Thevathasan, N., Oppong, S.K. & Quashie-Sam, J. 2005. Temporal changes in soil carbon and nitrogen in west African multistrata agroforestry systems: a chronosequence of pools and fluxes. Agroforestry Systems 65:23–31.

Jose, S. & Bardhan, S. 2012. Agroforestry for biomass production and carbon sequestration: an overview. Agroforestry Systems 86:105–111.

Jose, S. 2009. Agroforestry for ecosystem services and environmental benefits: an overview. Agroforestry Systems 76:1–10.

Kabir, E. & Webb, E.L. 2008. Can homegardens conserve biodiversity in Bangladesh? Biotropica 40(1): 95–103.

Kabir, E. & Webb, E.L. 2009. Household and homegarden characteristics in south-western Bangladesh. Agroforestry Systems 75:129–145.

Kalame, F.B. 2011. Forest governance and climate change adaptation: case studies of four African countries. Doctoral thesis. University of Helsinki.

Kanshie, T.K. 2002. Five thousand years of sustainability? A case study on Gedeo land use (Southern Ethiopia). PhD Dissertation, Wageningen Agricultural University

Kaonga, M. & Bayliss-Smith, T.P. 2009. Carbon pools in tree biomass and the soil in improved fallow in eastern Zambia. Agroforestry Systems 76:37−51.

Kaonga, M.L. & Bayliss-Smith, T.P. 2012. Simulation of carbon pool changes in woodlots in eastern Zambia using the CO2FIX model. Agroforestry Systems 86:213–223.

Kebede, T.M. 2010. Homegardens agrobiodiversity conservation in Sebeta-Hawas Wereda, southwestern Shewa Zone of Oromia Region, Ethiopia. M.Sc. thesis. Addis Ababa University, Ethiopia. p.78.

Kehlenbeck, K., Kindt, R., Sinclair, F.L., Simons, A.J. & Jamnadas, R. 2011. Exotic tree species displace indigenous ones on farms at intermediate altitudes around Mount Kenya. Agroforestry Systems 83:133–147.

Kessler, M., Keßler, P.J.A., Gradstein, S.R., Bach, K., Schmull, M. & Pitopang, R. 2005. Tree diversity in primary forest and different land use systems in Central Sulawesi, Indonesia. Biodiversity and Conservation 14: 547–560.

Kimaro, A.A., Isaac, M.E. & Chamshama, S.A.O. 2011. Carbon pools in tree biomass and soils under rotational woodlot systems in Eastern Tanzania. In: Kumar, B.M. & Nair, P.K.R. (Eds.). Carbon sequestration potential of agroforestry systems: opportunities and challenges, Advances in Agroforestry 8. Springer. p. 129−143.

Kindt, R., Van Damme, P., Simons, A.J. & Beeckman, H. 2006. Planning tree species diversification in Kenya based on differences in tree species composition between farms. I. Analysis of tree uses. Agroforestry Systems 67:215–228.

Kirby, K.R. & Potvin, C. 2007. Variation in carbon storage among tree species: Implications for the management of a small-scale carbon sink project. Forest Ecology and Management 246(2-3): 208−221.

Köhler, L., Hölscher, D. & Leuschner, C. 2008. High litterfall in old-growth and secondary upper montane forest of Costa Rica. Plant Ecology 199:163–173.

Kozak, A & Kozak, R. 2003. Does cross validation provide additional information in the evaluation of regression models? Canadian Journal of Forest Research 33:976-987

Kozlowski, TT, Pallardy SG .1996. Physiology of woody plants, 2nd ed. Academic Press, San Diego, CA, USA. p.411.

Kufa, T., Ayano, A., Yilma, A., Kumela, T. & Tefera, W. 2011. The contribution of coffee research for coffee seed development in Ethiopia. Journal of Agricultural Research and Development 1(1):009–016.

Kumar, B.M. & Nair, P.K.R. 2004.The enigma of tropical homegardens. Agroforestry Systems 61: 135−152.

Kumar, B.M. & Nair, P.K.R. 2011. Carbon sequestration potential of agroforestry systems: opportunities and challenges. Springer, the Netherlands, p. 307.

Kuyah, S., Dietz, J., Catherine, M., Jamnadassa, R., Mwangi, P., Coe, R. & Neufeldt, H. 2012a. Allometric equations for estimating biomass in agricultural landscapes: I. Aboveground biomass. Agriculture, Ecosystems and Environment 158:216–224.

Kuyah, S., Dietz, J., Muthuria, C., Jamnadassa, R., Mwangi, P., Coe, R. & Neufeldta, H. 2012b. Allometric equations for estimating biomass in agricultural landscapes: II. Belowground biomass. Agriculture, Ecosystems and Environment 158:225– 234.

Kuyah, S., Muthuri, C., Jamnadass, R., Mwangi, P., Neufeldt, H., Dietz, J. 2012c. Crown area allometries for estimation of aboveground tree biomass in agricultural landscapes of western Kenya. Agroforestry Systems 86:267–277.

Labouisse, J.P., Bellachew, B., Kotecha, S. & Bertrand, B. 2008. Current status of coffee (*Coffea arabica* L.) genetic resources in Ethiopia: Implications for conservation. Genetic Resources and Crop Evolution 55:1079–1093.

Laird, S.A., Awung, G.L. & Lysinge, R.J. 2007. Cocoa farms in the Mount Cameroon region: Biological and cultural diversity in local livelihoods. Biodiversity and Conservation 16:2401–2427

Lal, R. & Akinremi, O.O. 1983. Physical properties of earthworm cast and surface soil as influenced by management. Soil Science 135:114–122.

Lal, R. 2004. Soil carbon sequestration to mitigate climate change. Geoderma 123:1−22.

Lemenih, M. & Fisseha, I., 2004. Soil carbon stocks and turnovers in various vegetation types and arable lands along an elevation gradient in southern Ethiopia. Geoderma 123:177–188.

Liu, C., Westman, C., Berg, B., Kutsch, W., Wang, G.Z., Man, R. & Ilvesniem, H. 2004. Variation in litterfall-climate relationships between coniferous and broadleaf forests in Eurasia. Global Ecology and Biogeography 13:105–114.

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

Luedeling, E. & Neufeldt, H. 2012. Carbon sequestration potential of parkland agroforestry in the Sahel. Climate Change 115:443–461.

Luedeling, E., Sileshi, G., Beedy, T. & Dietz, J. 2011. Carbon sequestration potential of agroforestry systems in Africa. In: Kumar, B.M. & Nair, P.K.R. (Eds.). Carbon sequestration potential of agroforestry Systems: opportunities and challenges, Advances in Agroforestry 8. Springer. p. 61−83.

Lundgren, B.O. 1982. Cited in Editorial: What is Agroforestry?. Agroforestry Systems 1: 7-12.

Magurran, A.E. 2004. Measuring biological diversity. Blackwell Sciences, Oxford, UK.

Makumba, W., Akinnifesi, F.K., Janssen, B. & Oenema, O. 2007. Long-term impact of a *gliricidia*-maize intercropping system on carbon sequestration in southern Malawi. Agriculture, Ecosystems and Environment 118:237−243.

Martin, A.R. & Thomas, S.C. 2011. A reassessment of carbon content in tropical trees. PLoS ONE 6(8): e23533−e23533

McCune, B. & Mefford, M.J. 2006. Multivariate analysis of ecological data. PC-ORD Version 5. MjM software, Gleneden Beach, Oregon.

McNeely, J.A. & Schroth, G. 2006. Agroforestry and biodiversity conservation- traditional practices, present dynamics, and lessons for the future. Biodiversity and Conservation 15:549−554.

Mebrate, B.T. 2007. Agroforestry practices in Gedeo Zone, Ethiopia: A geographical analysis. PhD dissertation, Panjab University, India. p.188

Méndez, V.E., Shapiro, E.N. & Gilbert, G.S. 2009. Cooperative management and its effects on shade tree diversity, soil properties and ecosystem services of coffee plantations in western El Salvador. Agroforestry Systems 76:111–126.

Mengesha, B. 2010. Alternative technologies for sustainable agricultural production and agroecosystem conservation in Arsi highlands, south-eastern Ethiopia. PhD thesis. Addis Ababa University, Ethiopia. p. 198.

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

Ministry of Agriculture and Rural Development of Ethiopia (MoARDE). 2005. Agroforestry extension package for Pastoral community (Amharic version). Addis Ababa Ethiopia.

Montagnini, F. & Nair, P.K.R., 2004. Carbon sequestration: an under environmental benefits of agroforestry systems. Agroforestry Systems 61:281−295.

Muleta, D., Assefa, F. & Nemomissa, S. 2008. Distribution of arbuscular mycorrhizal fungi spores in soils of smallholder agroforestry and monocultural coffee systems in south-eastern Ethiopia. Biology and Fertility of Soils 44:653−659.

Muleta, D., Assefa, F., Nemomissa, S. & Granhall, U. 2007. Composition of coffee shad tree species and density of indigenous arbuscular mycorrhizal fungi (AMF) spores in Bonga natural coffee forest, southwestern Ethiopia. Forest Ecology and Management 241:145–154.

Murovhi, N.R., Materechera, S.A. & Mulugeta, S.D. 2012. Seasonal changes in litter fall and its quality from three sub-tropical fruit tree species at Nelspruit, South Africa. Agroforestry Systems. doi 10.1007/s10457-012-9508-6.

Mutuo, P.K., Cadisch, G., Albrecht, A., Palm, C.A. & Verchot, L. 2005. Potential of agroforestry for carbon sequestration and mitigation of greenhouse gas emissions from soils in the tropics. Nutrient Cycling in Agroecosystem 71:43−54.

Nair, P.K.R. 1985. Classification of agroforestry systems. Agroforestry Systems 3(2):97−128.

Nair, P.K.R. 1993. An introduction to agroforestry. Kluwer Academic Publishers. Dordrecht, The Netherlands.

Nair, P.K.R. 1998. Directions in tropical agroforestry research: past, present and future. Agroforestry Systems 38:223-245.

Nair, P.K.R. 2011. Methodological challenges in estimating carbon sequestration potential of agroforestry systems. In: Kumar, B.M. & Nair, P.K.R. (Eds.). Carbon sequestration potential of agroforestry systems: Opportunities and challenges, Advances in Agroforestry 8. Springer. p. 3−16.

Nair, P.K.R. 2012. Carbon sequestration studies in agroforestry systems: A reality-check. Agroforestry Systems 86:243–253.

Nair, P.K.R., Kumar, B.M. & Nair, V.D. 2009. Agroforestry as a strategy for carbon sequestration. Journal of Plant Nutrition and Soil Science 172:10–23.

Nair, P.K.R., Nair, V.D., Kumar, B.M. & Showalter, J.M. 2010. Carbon sequestration in agroforestry systems. Advance in Agronomy 108:237–307.

Nair, P.K.R., Tonucci, R.G., Garcia, R. & Nair, V.D. 2011. Silvopasture and carbon sequestration with special reference to the Brazilian Savannah (Cerrado). In: Kumar, B.M. & Nair, P.K.R. (Eds.). Carbon sequestration potential of agroforestry systems: opportunities and challenges, Advances in Agroforestry 8. Springer Dordrecht Heidelberg, London, New York, pp.145–162.

Negash, A. & Niehof, A.2004. The significance of enset culture and biodiversity for rural household food and livelihood security in southwestern Ethiopia. Agriculture and Human Values 21:61–71

Negash, M. & Achalu, N. 2008. History of indigenous agroforestry in Gedeo, southern Ethiopia, Based on local community interviews: vegetation diversity and structure in the land use systems. Ethiopian Journal of Natural Resources 10(1):31−52.

Negash, M. 2007. Trees management and livelihoods in Gedeo's agroforests, Ethiopia. Forests, Trees and livelihoods 17(2):157-168.

Negash, M., Abdulkadir, A. & Hagberg, S. 2005. Farmers' planting practices of Eucalyptus in Enset-Coffee based agroforestry system of Sidama, Ethiopia. Ethiopian Journal of Natural Resources 7(2):239−251.

Nobel, I.R. & Dirzo, R. 1997. Forest as Human-dominated ecosystems. Science 277:522−525.

Nyhus, P. & Tilson, R. 2004. Agroforestry, elephants, and tigers: balancing conservation theory and practice in human-dominated landscapes of South-east Asia. Agriculture, Ecosystems and Environment 104:87−97.

Oelbermann, M., Voroney, R.P. & Gordon, A.M. 2004. Carbon sequestration in tropical and temperate agroforestry systems: a review with examples from Costa Rica and southern Canada. Agriculture, Ecosystems and Environment 104:359–377.

Oelbermann, M., Voroney, R.P., Thevathasan, N.V., Gordon, A.M., Kass, D.C.L. & Schlönvoigt, A.M. 2006. Soil carbon dynamics and residue stabilization in a Costa Rican and southern Canadian alley cropping system. Agroforestry Systems 68:27–36.

Pandey, D.N. 2002.Carbon sequestration in agroforestry systems. Climate policy 2: 367−377.

Pankhurst, R. 1993. Enset as reported by Ethiopian royal chroniclers and early European travellers. International Workshop on Enset, A.A., Ethiopia, December, 1993, p.5.

Pearson, T., Walker, S. & Brown, S. 2005. Sourcebook for land use, land-use change and forestry projects. Winrock International.P.57. http://www.forestcarbonportal.com/resource/sourcebook-land-use-land-use-change-and-forestry-projects. Accessed: November 10, 2012.

Peichl, M., Thevathasan, N.V., Gordon, A.M., Huss, J. & Abohassan, R. 2006. Carbon sequestration potentials in temperate tree-based intercropping systems, southern Ontario, Canada. Agroforestry Systems 66:243–257.

Peters, V.E. & Carroll, C.R. 2012. Temporal variation in coffee flowering may influence the effects of bee species richness and abundance on coffee production. Agroforestry Systems 85:95–103.

Peyre, A., Guidall, A., Wiersum, K.F. & Bongers, F. 2006. Dynamics of homegarden structure and function in Kerala, India. Agroforestry Systems 66:101–115.

Philip, M.S. 1994. Measuring trees and forests. 2nd edition. CAB international. New York, USA and Wallingford, Oxon, UK. p. 310.

Philpott, M.S., Bichier, P., Rice, R.A. & Greenberg, R. 2008. Biodiversity conservation, yield, and alternative products in coffee agroecosystems in Sumatra, Indonesia. Biodiversity and Conservation 17:1805–1820.

Poch, T.J. & Simonetti, J.A. 2013. Ecosystem services in human-dominated landscapes: insectivory in agroforestry systems. Agroforestry Systems. doi. 10.1007/s10457-013-9603-3.

Polzot, C.L. 2004. Carbon storage in coffee agroecosystems of southern Costa Rica: potential applications for the Clean Development Mechanism. M.Sc. thesis York University, Canada. p. 149.

Poschen, P. 1986. An evaluation of the *Acacia albida*-based agroforestry practices in the Hararghe highlands of eastern Ethiopia. Agroforestry Systems 4:129−143.

Potvin, C., Mancilla, L., Buchmann, N *et al.* 2011. An ecosystem approach to biodiversity effects: Carbon pools in a tropical tree plantation. Forest Ecology and Management 261:1614–1624.

Quinkenstein, A., Böhm, C., Matos, E. da S., Freese, D. & Hüttl, R.F.2011. Assessing the carbon sequestration in short rotation coppices of *Robinia pseudoacacia* L. on marginal sites in Northeast Germany. In: Kumar, B.M. & Nair, P.K.R. (Eds.). Carbon sequestration potential of agroforestry systems: opportunities and challenges, Advances in Agroforestry 8, Springer. p. 201-216.

R Development Core Team. 2010. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0.

Roshetko, J.M., Lasco, R.D. & Angeles, M.SD. 2007. Smallholder agroforestry systems for carbon storage. Mitigation and Adaptation Strategies for Global Change 12:219–242.

Saha, S.K., Nair P.K.R., Nair, V.D. & Kumar, B.M. 2009. Soil carbon stock in relation to plant diversity of homegardens in Kerala, India. Agroforestry Systems 76:53–65.

Sampaio, E., Gasson, P., Baracat, A., Cutler, D., Pareyn, F. & Lima, K.C. 2010. Tree biomass estimation in regenerating areas of tropical dry vegetation in northeast Brazil. Forest Ecology and Management 259:1135–1140.

Sauer, J.T, Cambardella, A.C. & Brandle, R.J. 2007. Soil carbon and tree litter dynamics in red cedar-scotch pine shelterbelt. Agroforestry Systems 71:163−174.

Schaffnit-Chatterjee, C. 2011. Mitigating climate change through agriculture: An untapped potential. Current issue. Deutsche Bank Research. Frankfurt. Germany. p. 32

Schmitt-Harsh, M., Evans, T.P., Castellanos, E. & Randolph, J. C. 2012. Carbon stocks in coffee agroforests and mixed dry tropical forests in the western highlands of Guatemala. Agroforestry Systems. doi 10.1007/s10457-012-9549-x.

Schoeneberger, M.M. 2008. Agroforestry: working tress for sequestering carbon on agricultural lands. Agroforestry Systems. doi 10.1007/s10457-008-9123-8.

Schroeder, P. 1994. Carbon storage benefits of agroforestry systems. Agroforestry systems 27: 89−97.

Schroth, G., da Fonseca, G.A.B., Harvey, C.A., Vasconcelos, H.L., Gascon, C. & Izac, A-M N. 2004. Introduction: the role of agroforestry in biodiversity conservation in tropical landscapes. In: Schroth, G., da Fonseca, G.A.B., Harvey, C.A., Gascon, C., Vasconcelos, H.L. & Izac A-MN (Eds.). Agroforestry and biodiversity conservation in tropical landscapes. ISLAND PRESS Washington, DC p. 112.

Schulp, J.E.C., Nabuurs, J.G., Verburg, H.P. & de Waal, W.R. 2008. Effect of tree species on carbon stocks in forest stocks in forest floor and mineral soil and implications for soil carbon inventories. Forest Ecology and Management 256:482−490.

Segura, M., Kanninen, M. & Suárez, D. 2006. Allometric models for estimating aboveground biomass of shad trees and coffee bushes grown together. Agroforestry Systems 68:143-150.

Shank, R. & Ertiro, C. 1996. A linear model for predicting enset plant yield and assessment of Kocho production in Ethiopia. World Food Program, Ministry of Agriculture, Southern Nation Nationalities, People Regional State, UNDP Emergencies Unit for Ethiopia, Addis Ababa, p. 62

Silva, A.K.L., Vasconcelos, S.S., de Carvalho, C.J.R. & Cordeiro, I.M.C. 2010. Litter dynamics and fine root production in *Schizolobium parahyba var. amazonicum* plantations and regrowth forest in Eastern Amazon. Plant and Soil 347:377–386.

Simons, A.J. & Leakey, R.R.B. 2004. Tree domestication in tropical agroforestry. Agroforestry Systems 61: 167-181.

Smiley, G.L. & Kroschel, J. 2008. Temporal change in carbon stocks of cocoa–*gliricidia* agroforests in central Sulawesi, Indonesia. Agroforestry Systems 73:219–231.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B. & Sirotenko, O. 2007. Agriculture. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Metz, B., Davidson, O.R., Bosch, P.R., Dave, R. & Meyer L.A. (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Snowdon, P., Raison, J., Keith, H., Ritson, P., Grierson, P., Adams, M., Montagu, K., Bi H-Q., Burrows, W. & Eamus, D. 2002. Protocol for sampling tree and stand biomass. National Carbon accounting System, Technical report no. 31. Canberra: Australian Greenhouse Office. p 66

Soto-Pinto, L., Anzueto, M., Mendoza, J., Ferrer, G.J. & de Jong, B. 2010. Carbon sequestration through agroforestry in indigenous communities of Chiapas, Mexico. Agroforestry Systems 78:39–51.

Soto-Pinto, L., Villalvazo-López, V., Jiménez-Ferrer, G., Ramírez-Marcial, N., Montoya, G. & Sinclair, F.L. 2007. The role of local knowledge in determining shade composition of multistrata coffee systems in Chiapas, Mexico. Biodiversity and Conservation 16:419−436.

SPSS version 18 .2010. SPSS Inc. Headquarter 233.5. Waker Drive, 11th floor Chicago, Illinois.

Srivastava, P., Kumar, A., Behera, S.K., Sharma, Y.K. & Singh N. 2012. Soil carbon sequestration: an innovative strategy for reducing atmospheric carbon dioxide concentration. Biodiversity and Conservation 21:1343–1358.

Starr, M., Hartman, & Kinnunen, T.1998. Biomass functions for mountain birch in the Vuoskojärvi Integrated Monitoring area. Borial Environment Research 3:297-303

Starr, M., Saarsalmi, A., Hokkanen, T., Merilä, P. & Helmisaari, H-S. 2005. Models of litterfall production for Scots pine (*Pinus sylvestris* L.) in Finland using stand, site and climate factors. Forest Ecology and Management 205:215–225.

Swamy, S.L. & Puri, S. 2005. Biomass production and C-sequestration of *Gmelina arborea* in planation and agroforestry system in India. Agroforestry Systems 64:181−195.

Takimoto, A., Nair, V.D. & Nair, P.K.R. 2008. Contribution of trees to soil carbon sequsetration under agroforestry systems in the west African Sahel. Agroforestry Systems. doi 10.1007/s10457-008-9179-5.

Teketay, D. & Tegineh, A. 1991. Traditional tree crop based agroforestry in coffee producing areas of Harerge, Eastern Ethiopia. Agroforestry Systems 16: 257−267.

Tesemma, B.A. (Ed.). 2007. Profitable agroforestry innovations for eastern Africa: experience from 10 agroclimatic zones of Ethiopia, India, Kenya, Tanzania and Uganda. World Agroforestry Centre (ICRAF), Eastern African Region.

Tesfaye, B. 2008. On Sidama folk identification, naming, and classification of cultivated Enset (*Ensete ventricosum*) varieties. Genetic Resources and Crop Evolution 55:1359–1370.

Thomas, S.C. & Martin, A.R. 2012. Carbon content of tree tissues: a synthesis. Forests 3:332−352

Tolera, M., Asfaw, Z., Lemenih, M. & Karltun, E. 2008. Woody species diversity in a changing landscape in the south-central highland of Ethiopia. Agricultural, Ecosystems and Environment 128:52−58.

Torquebiau, E.F. 2000. A renewed perspective on agroforestry concepts and classification. Life Sciences 323:1009−1017.

Tsegaye, A. & Struik, P.C. 2003. Growth, radiation use efficiency and yield potential of Enset (*Ensete ventricosum*) at different sites in southern Ethiopia. Annals Applied Biology 142:71-81.

Udawatta, R.P. & Jose, S. 2011. Carbon sequestration potential of agroforestry Practices in temperate North America. In: Kumar, B.M. & Nair, P.K.R. (Eds.). Carbon sequestration potential of agroforestry Systems: opportunities and challenges, Advances in Agroforestry 8. Springer Dordrecht Heidelberg, London, New York. pp.17−42.

Uezu, A., Beyer, D.D. & Metzger, J.P. 2008. Can agroforest woodlots work as stepping stones for birds in the Atlantic forest region? Biodiversity and Conservation 17:1907−1922.

Ulrich, B., Benecke, P., Harris, W.F. & Khanna, P.K. 1981. Soil process. In: Reichle, D.E: (Ed.). Dynamic properties of forest ecosystems. Cambridge University Press, International Biological Programme 23, pp. 265–339.

Unruh, J.D., Houghton, R.A. & Lefebvre, P.A. 1993. Carbon storage in agroforestry: an estimate for sub-Saharan Africa. Climate Research 3:39−52.

Upadhyay, T.P, Sankhayan, P.L. & Solberg, S. 2005. A review of carbon sequestration dynamics in the Himalayan region as a function of land use change and forest/soil degradation with special reference to Nepal. Agriculture, Ecosystems and Environment 114:69−85.

Vaast, P., Bertrand, B., Perriot, J.J, Guyot, B. & Génard, M. 2006. Fruit thinning and shade improve bean characteristics and beverage quality of coffee (*Coffea arabica* L.) under optimal conditions. Journal of Science of Food and Agriculture 86:197–204.

van Noordwijk M., Rahayu S., Hairiah K., Wulan Y.C., Farida A. & Verbist, B. 2002. Carbon stock assessment for a forest-to-coffee conversion landscape in Sumber-Jaya (Lampung, Indonesia): from allometric equations to land use change analysis. Science in China C 45:75-86. http://www.globalcarbonproject.org. Accessed: November 5, 2012.

Vaughan, M. & Black, S.H. 2006. Agroforestry: Sustaining native bee habitat for crop pollination. Agroforestry notes. USDA National agroforestry center.UNL-East Campus, Lincoin, Nebraska. p. 4.

Verchot, L.V., Noordwijk, M.V., Kandji, S., Tomich, T., Ong, C., Albrecht, A., Mackensen, J., Bantilan, C., Anupama, K.V. & Palm, C. 2007. Climate change: linking adaptation and mitigation through agroforestry. Mitigation and Adaptation Strategies for Global Change 12:901–918.

Vivero, L.J, Kelbessa, E. & Demissew, S. 2005. The Red list of endemic trees and shrubs of Ethiopia and Eritrea. Fauna and Flora international, Cambridge, UK. p. 23.

Walpole, R.E., Myers, R.H., Myers, S.L. & Ye, K. 2007. Probability and statistics for engineering and scientists. 8th edition. Pearson Education International Inc. New Jersey, USA. P. 445−509.

Wilkie, D.S. & Lee, R. J. 2004. Hunting in agroforestry systems and landscapes: conservation implications in west-central Africa and south-east Asia. In: Schroth, G., da Fonseca, G.A.B., Harvey, C.A, Gascon, C., Vasconcelos, H.L. & Izac, A-M.N (Eds.). Agroforestry and biodiversity conservation in tropical landscapes. ISLAND PRESS Washington, DC p. 346–370.

Woldeyes, F. 2011. Homegardens and spices of Basketo and Kafa (Southwest Ethiopia): Plant diversity, product valorization and implications to biodiversity conservation. PhD thesis. Addis Ababa University, Ethiopia.

Young, A. 1983. An environmental data base for agroforestry. ICRAF Working Paper 5, Nairobi.

Zeide, B. 1997. Assessing biodiversity. Environmental monitoring and assessment 48: 249−260.

Zewdie, S., Fetene, M. & Olsson, M. 2008. Fine root vertical distribution and temporal dynamics in mature stands of two enset (*Enset ventricosum* Welw Cheesman) clones. Plant and Soil 305:227–236.

Zhang, Y., Duan, B., Xian, J., Korpelainen, H. & Li, C. 2011. Links between plant diversity, carbon stocks and environmental factors along a successional gradient in a subalpine coniferous forest in Southwest China. Forest Ecology and Management 262: 361–369

Zianis, D. & Mencuccini, M. 2004. On simplifying allometric analysis of forest biomass. Forest Ecology and Management 187:311–332.

Zomer, R.J, Trabucco, A., Coe, R. & Place, F. 2009. Trees on Farm: analysis of global extent and geographical patterns of agroforestry. ICRAF Working Paper no. 89. Nairobi, Kenya: World Agroforestry Centre.

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ISBN 978-952-10-9414-9 (pbk.)
ISBN 978-952-10-9415-6 (PDF)
ISSN 0786-8170
Helsinki 2013
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