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FROM CARBON SOURCE TO SINK – MANAGING AGRICULTURE FOR CLIMATE CHANGE MITIGATION AND FOOD PRODUCTION IN ETHIOPIA

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ACADEMIC DISSERTATION

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CONTRIBUTIONS

Article I The study was designed by Karoliina Rimhanen and Helena Kahiluoto. Belay Tseganeh contributed to developing the questionnaire and conducted the pilot interviews and Reimund Rötter contributed to developing the questionnaire and the writing-up of specific sections. Karoliina Rimhanen performed the individual in-depth interviews and participated and trained two Ethiopian socio-economic researchers to conduct the focus group discussions in Amharic and Oromiffa with support by Karoliina Rimhanen. Karoliina Rimhanen and Helena Kahiluoto performed the analysis and interpreted the results. Helena Kahiluoto wrote the manuscript with a contribution by Karoliina Rimhanen. Helena Kahiluoto was the corresponding author.

Article II The study was designed by Karoliina Rimhanen and Helena Kahiluoto. Karoliina Rimhanen conducted the data collection and analyses with the help of Ethiopian assistants. Karoliina Rimhanen and Helena Kahiluoto interpreted the results and Karoliina Rimhanen wrote the manuscript with support by Helena Kahiluoto. Karoliina Rimhanen was the corresponding author.

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ABSTRACT

Sub-Saharan Africa is one of the world´s most vulnerable regions to climate change. Even a 1–2 °C increase in the atmospheric global temperature can, together with soil degradation, cause yield losses that, taken with the rapid growth in population, critically reduce food security. Even though the proportion of greenhouse gas (GHG) emissions produced in Sub-Saharan Africa is low relative to the global total, the agricultural sector has an enormous potential for climate change mitigation. Carbon sequestration in agricultural soil represents the highest potential. Promoting adaptation in agriculture, improving productivity and building climate resilience could increase crop yields, exploit the mitigation potential and enable carbon payments. The aim here is to increase understanding of the potential of climate change mitigation in agriculture to enhance food security. The focus of the study is 1) to identify the determinants of this potential, 2) to estimate the possibilities to increase the proportion of carbon ending up in soil on Ethiopian smallholder farms and 3) to quantify the soil carbon sequestration potential of alternative agroecological practices in Ethiopia. Both qualitative and quantitative approaches were utilized in the study.

Identification of the determinants of the potential of climate change mitigation to enhance food security was based on in-depth interviews conducted at the global and national levels in Ethiopia and Finland and focus group discussions at the local level in Ethiopia. An explanatory case-study approach was utilized in the analysis to generate an analytical framework. Knowledge gaps highlighted from the results served as the starting points for the following studies. The assessment of carbon flows harvested in and imported to the farming system and use of carbon flows was based on interviews and sampling on Ethiopian smallholder farms, complemented by statistics and published literature. Material flow analysis and carbon balance counting was used for tracking the carbon flows to food and soil and for estimating the carbon losses. Quantification of the carbon sequestration potential of the agroecological practices agroforestry, restrained grazing and terracing was based on comparison of the existing seven to eight plot pairs, including a plot with an alternative, hypothetically improved agroecological practice and an adjacent plot with a traditional practice in Ethiopia. Previously published estimates have not relied on a similar rigorous comparison of soil carbon stocks between practices.

Our investigation resulted in new empirical knowledge of the socioeconomic and agroecological determinants of the potential of climate change mitigation for enhancing food security. Soil carbon sequestration in eroded agricultural soil was considered as the most important means to promote climate change mitigation and to enhance food security. The primary factors enhancing food security were perceived to be increasing

agricultural productivity and incomes from marketed crops. Contributing to the operability of internal markets was considered important for enhancing access to food at the household, regional and national levels. Carbon payments were considered to be required mainly for monitoring, reporting, verification and advisory services and as compensation for agricultural development activities, such as fencing land and reduction in cattle numbers while soil production recovers. Implementation of mitigation practices was dependent mostly on socioeconomic determinants and feasibility on local agroecological determinants.

On the Ethiopian farms, 8–12% of the total harvested carbon was used for soil and 9–16% for food. Of the carbon imported to a farm, usually from other farms, e.g. as feed and bioenergy, 3–11% was used for soil and 3–35% for food. The largest carbon losses were due to biomass burning and livestock metabolism. Residues, apart from the negligible quantities of offal and human excreta, were carefully utilized in the farming system. Consequently, the proportion of carbon used for soil could mainly be increased by reducing gaseous losses. Such development could also lead to increase in the proportion of carbon used for food. Biomass burning could even be totally avoided by introducing alternative energy sources for manure and straw.

Agroforestry for 6–20 years led to 11.4 t ha^{-1}, restrained grazing for 6–17 years to 9.6 t ha^{-1} and terracing for 5–10 years to 1.7 t ha^{-1} greater soil carbon stock than did their adjacent, traditionally managed control plots. The gains resulting from agroecological management were dependent on the carbon stock levels in the traditionally managed plots and the durations of the agroecological practices. The empirical estimates presented here are higher than those based on process-modelling studies. The difference probably resulted from the development and validation of process models under such conditions and in farming systems that differ from those in East-Africa. The greater carbon sequestration than previously modelled may also be explained by the severely eroded Ethiopian soils that are still far from the carbon equilibrium typical for recently introduced agroecological practices.

From the results it can be concluded that the most important means perceived as enhancing food security through climate change mitigation is improving food availability for food-insecure communities through soil carbon sequestration by agricultural practices. Development of the infrastructure of internal food markets is required to enhance access to food at the household, regional and national levels.

Financial compensation for carbon sequestration enables and promotes smallholders to adopt carbon-sequestering practices. Income from the increased amount of marketed crops, a result of increased agricultural productivity, is also needed to enhance access to food at the household level. Socio-economic determinants, such as policy coherence for promoting mitigation and food security, supporting governance, clear land tenure, early access to financial incentives and knowledge of the carbon market, play the most important roles in the potential of mitigation for enhancing food security.

The major losses of carbon from farming systems are gaseous, originating mainly from biomass burning and from livestock metabolism. The proportion of carbon used for energy determines the proportion ending up in soil. Energy sources alternative to manure and straw are needed to increase the flow of carbon to soil and to reduce emissions. Material flow analysis is a useful tool for tracking flows and losses of harvested and imported carbon when measurement of gaseous carbon losses is not feasible.

The soil carbon sequestration potential in Ethiopian agriculture is greater than previously estimated. The adjacent plot in traditional farming represents a useful control to assess the carbon-sequestering potential of a novel agricultural practice. The size of the soil carbon stock in the traditionally managed control plot defines the difference in soil carbon stocks between agroecological practices and controls. Climate conditions, intercropping treatment and assessment of the distance of the soil carbon stock to the new equilibrium should be incorporated into process models to improve their adequacy for farming systems in East Africa. Agroecological practices provide the technological potential to compensate for the current total GHG emissions in Ethiopia.

TIIVISTELMÄ

Saharan eteläpuolinen Afrikka on yksi maapallon haavoittuvimpia alueita ilmastonmuutoksen vaikutuksille. Jo 1–2 °C:n nousu ilmakehän keskilämpötilassa yhdessä maaperän erodoitumisen kanssa voi aiheuttaa huomattavia sadonmenetyksiä ja voimakkaan väestönkasvun myötä heikentää väestön ruokaturvaa. Vaikka Saharan eteläpuolisen Afrikan osuus kasvihuonekaasujen tuottajana on maailmanlaajuisesti pieni, sisältää alueen maataloussektori huomattavan suuren ilmastonmuutoksen hillintäpotentiaalin. Suurin osa potentiaalista muodostuu hiilensidonnasta maatalousmaahan. Maatalouden ilmastonmuutokseen sopeutumisen edistäminen sekä tuottavuuden ja resilienssin parantaminen voisivat kasvattaa viljelykasvien satotasoja, hyödyntää olemassa olevan hillintäpotentiaalin ja tuottaa viljelijöille tuloja hiilensidonnasta. Tämän väitöskirjan päämäärä on lisätä ymmärrystä ilmastonmuutoksen hillinnän mahdollisuuksista edistää ruokaturvaa. Tutkimuksen tavoitteet ovat 1) tunnistaa tekijät, jotka vaikuttavat ilmastonmuutoksen hillinnän mahdollisuuksiin edistää ruokaturvaa, 2) arvioida mahdollisuuksia lisätä maahan päätyvän hiilen osuutta etiopialaisilla pientiloilla, sekä 3) arvioida empiirisesti vaihtoehtoisten agroekologisten menetelmien maaperän hiilensidontapotentiaalia Etiopiassa. Tutkimuksessa hyödynnetään laadullisen ja määrällisen lähestymistavan tutkimusotteita.

Ilmastonmuutoksen hillinnän ruokaturvaan vaikuttavien tekijöiden tunnistaminen perustui kansainvälisellä sekä Etiopian ja Suomen kansallisilla tasoilla tehtyihin syvähaastatteluihin ja Etiopian paikallistasolla tehtyihin fokusryhmäkeskusteluihin. Selittävän tapaustutkimuksen analyysiä hyödynnettiin analyyttisen viitekehyksen luomisessa. Tämän osion tuloksista nostetut tietoaukot toimivat lähtökohtana kahdelle seuraavalle tutkimusosiolle. Viljelyjärjestelmistä korjattujen ja järjestelmiin tuotujen hiilivirtojen suuruuden ja käytön arviointi perustui haastatteluihin ja näytteenottoon etiopialaisilla pientiloilla. Aineistoa täydennettiin tilastoihin ja kirjallisuuteen perustuvilla tiedoilla. Ruoaksi korjattujen ja maahan päätyvien hiilivirtojen jäljittämiseksi sekä hiilen hävikkien arviointiin hyödynnettiin materiaalivirta-analyysiä ja hiilitaselaskentaa. Arviot agroekologisten menetelmien hiilensidontapotentiaalista perustuivat olemassa olevien, vierekkäisten, agroekologisin ja perinteisin menetelmin viljeltyjen lohkoparien hiilivarastojen koon vertailuun 7–8 kerranteella Etiopiassa. Aikaisemmin julkaistut arviot perustuvat mallinnuksiin, eivät eri tuotantotavoilla saavutettujen hiilikertymien täsmälliseen vertailuun.

Tutkimus tuotti uutta empiiristä tietoa sosioekonomisista ja agroekologisista tekijöistä, jotka vaikuttavat ilmastonmuutoksen hillinnän mahdollisuuksiin edistää ruokaturvaa. Tärkeimpänä ilmastonmuutoksen hillintää ja ruokaturvaa edistävänä keinona pidettiin hiilensidontaa

eroosiosta kärsivään maatalousmaahan. Ensisijaisina ruokaturvaa edistävinä tekijöinä pidettiin maatalouden tuottavuuden kasvattamista ja markkinoitavasta sadosta saatavia tuloja. Hiilen sidonnasta saatavia mahdollisia lisätuloja pidettiin tarpeellisina valvonta-, raportointi-, varmentamis- ja neuvontapalveluista koituvien kulujen sekä maatalouden kehittämistoimista, kuten aitojen rakentamisesta ja karjan määrän vähentämisestä koituvien kulujen kattamiseen. Hillintätoimien toteutettavuuteen koettiin vaikuttavan eniten sosioekonomiset tekijät ja toimien soveltuvuuteen ensisijaisesti paikalliset agroekologiset tekijät.

Viljelyjärjestelmissä korjatusta hiilestä 8–12 % päätyi maahan ja 9–16 % ruokaan ja viljelyjärjestelmiin tuodusta hiilestä 3–11 % päätyi maahan ja 3–35 % ruokaan. Suurimmat hiilen hävikit syntyivät biomassan poltosta ja kotieläinten aineenvaihdunnasta. Syntyvät jätteet hyödynnettiin tarkkaan, lukuun ottamatta merkityksetöntä määrää teurasjätteitä ja ihmisulostetta. Maanparannukseen käytettävää hiiltä voitaisiin näin ollen lisätä vähentämällä kaasumaisia hiilen hävikkejä järjestelmästä. Tämä voisi johtaa myös ruoaksi korjattavan sadon määrän ja osuuden, ja siten ruokaan päätyvän hiilen määrän ja osuuden lisääntymiseen. Hävikeistä biomassan poltto olisi jopa täysin vältettävissä ottamalla käyttöön vaihtoehtoisia energialähteitä lannalle ja oljelle.

Peltometsäviljelyllä saavutettiin 6–20 vuodessa 11.4 t ha^{-1}, vapaan laidunnuksen rajoittamisella 6–17 vuodessa 9.6 t ha^{-1} ja viljellyillä terasseilla 5–10 vuodessa 1.7 t ha^{-1} suurempi maan hiilivarasto verrattuna vierekkäisiin perinteisesti viljeltyihin lohkoihin. Olosuhteet, joissa agroekologisia menetelmiä harjoitettiin ja parannettujen menetelmien kestoaika vaikuttivat parannettujen ja perinteisesti viljeltyjen lohkojen hiilivarastojen koon eroon. Arviomme agroekologisten maatalouden menetelmien hiilensidontapotentiaalista ovat suuremmat kuin aikaisemmin julkaistut arviot, jotka perustuivat prosessimalleihin. Ero johtunee siitä, että prosessimallit on kehitetty ja validoitu Itä-Afrikan olosuhteisin nähden poikkeavissa olosuhteissa ja viljelyjärjestelmissä. Myös vakava maan eroosio Etiopiassa on saattanut johtaa siihen, että maan nykyinen hiilivarasto on arvioitua kauempana uudesta tasapainotilasta, jonka seurauksena hiilensidonta on todellisuudessa aikaisempia arvioita runsaampaa.

Tulosten perusteella voidaan päätellä, että maatalouden hillintätoimilla voidaan edistää ruokaturvaa, erityisesti parantamalla tuottavuutta ja lisäämällä ruoan saatavuutta sitomalla hiiltä maatalousmaahan. Myös ruoan sisämarkkinoiden kehittäminen on tärkeää ruoan saatavuuden edistämiseksi kotitalouden, alueen ja kansallisella tasolla. Taloudellinen korvaus hiilensidonnasta mahdollistaa ja kannustaa viljelijöitä ottamaan käyttöön hiilensidontamenetelmiä. Markkinoitavista kasveista saatavat lisätulot lisäävät kotitalouksien kykyä hankkia ruokaa tarvittaessa markkinoilta. Sosioekonomiset tekijät, kuten politiikkatoimien koherenssi ilmastonmuutoksen hillinnän ja ruokaturvan edistämiseksi, hallinnon selkeys ja -tuki, selkeät maanhallintaolot, hillintähankkeen toteuttajalle varhaisessa vaiheessa suoritetut taloudelliset korvaukset ja hiilimarkkinatiedon levittäminen edistävät ilmastonmuutoksen hillinnän mahdollisuuksia parantaa ruokaturvaa.

Suurimmat hiilivuodot viljelyjärjestelmästä ovat kaasumaisia ja peräisin biomassan poltosta ja kotieläinten metaboliasta. Viljelyjärjestelmässä energiaksi käytetty hiilen osuus määrittää maahan päätyvän hiilen osuuden: mitä vähemmän biomassan polttoa, sitä enemmän orgaanista hiiltä päätyy maahan. Vaihtoehtoisia energialähteitä lannalle ja oljelle on kehitettävä päästöjen vähentämiseksi ja hiilivirtojen suuntaamiseksi maahan. Materiaalivirta-analyysi on hyödyllinen työkalu hiilivirtojen ja hiilivuotojen jäljittämiseen silloin, kun kaasumaisten päästöjen mittaaminen ei ole mahdollista.

Etiopian maatalouden maan hiilensidontapotentiaali on aikaisempia arvioita suurempi. Maatalouden menetelmien hiilensidontapotentiaalia arvioitaessa on tärkeää sisällyttää koejärjestelyyn perinteisesti viljelty lohko kontrolliksi. Ero agroekologisen ja perinteisen menetelmän hiilivaraston koon suuruudessa eri agroekologisilla menetelmillä selittyy olosuhteilla, joissa agroekologisia menetelmiä harjoitetaan ja joita kontrollilohkojen hiilivaraston koko ilmentää. Ilmasto-olosuhteiden, sekaviljelyn erityispiirteiden ja eroosioasteen huomioiminen parantaisi prosessimallien soveltuvuutta Itä-Afrikassa. Hiilensidontapotentiaalin hyödyntäminen laajasti Etiopian maatalousmaahan voisi kompensoida jopa täysin ihmisen aiheuttamat kasvihuonekaasupäästöt.

ABBREVIATIONS

C	Carbon
CDM	Clean Development Mechanism
CH_4	Methane
CI	Confidence interval
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DM%	Dry matter percentage
GHG	Greenhouse gas
K	Potassium
MFA	Material flow analysis
N	Nitrogen
N_2O	Nitrous oxide
NAMA	Nationally Appropriate Mitigation Action
NGO	Non-governmental organization
P	Phosphorus
ρb	Bulk density
S	Sulphur
SIC	Soil inorganic carbon
SOC	Soil organic carbon
SOM	Soil organic matter
SSA	Sub-Saharan Africa

KEY DEFINITIONS

Agroecological practice: An agricultural practice that is environmentally friendly, socially fair and economically beneficial. These practices aim at increasing the activity of the soil biota and improving soil fertility (Wezel et al. 2014). In this study, an agroecological practice is a method that hypothetically increases the soil carbon stock as a result of increased carbon inputs and reduced soil disturbance.

Agroecosystem: A unit of agricultural activity including the environmental, social, economic, ethical and developmental aspects of agricultural production and food systems (Wezel et al. 2009). Agroecosystem is a research subject to agroecology, a scientific discipline originating from crop production and plant protection in the 1930s. Examination can vary from a narrow soil level to a farming system or even to a global food system level (Francis et al. 2003). In this study, the examination focuses on the soil, farming system and national food system levels.

Adaptation: Refers to coping with or adjustment to fulfilled or expected change by easing the damage or exploiting opportunities from the household to global levels (Smit and Wandel 2006; Field et al. 2014).

Carbon sequestration: Transferring of atmospheric carbon into long-term pools (Lal 2004b).

Carbon dioxide equivalent: A measure used to compare the various greenhouse gases, based on their global-warming potential (Environmental Protection Agency EPA 2013).

Climate-smart agriculture: Agricultural systems that support enhancing food security by increasing productivity and income, building resilience and adaptation to climate change and reducing greenhouse gas emissions (Food and Agriculture Organization FAO 2013).

East-Africa: Includes Burundi, Comoros, Djibouti, Ethiopia, Eritrea, Kenya, Madagascar, Malawi, Mauritius, Mayotte, Mozambique, Réunion, Rwanda, Seychelles, Somalia, Uganda, United Republic of Tanzania, Zambia and Zimbabwe (FAOSTAT 2014).

Exposure: Confrontation with the impacts of climate change (O´Brien et al. 2004).

Food security: “A situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life” (FAO 1996; FAO 2002).

Mitigation in agriculture: Reducing greenhouse gas emissions, enhancing carbon sinks in soil and vegetation or avoiding emissions by substituting residual-based bioenergy for fossil fuel (Smith et al. 2008).

Resilience: “The capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks”
(Walker *et al.* 2004).

Sub-Saharan Africa: Includes all of Africa except Northern Africa (United Nations UN 2013).

1 INTRODUCTION

1.1 CONTRIBUTION OF AGRICULTURE TO CLIMATE CHANGE

Greenhouse gas (GHG) emissions originate mainly from the industrialized countries (Climate Analysis Indicator Tool CAIT 2014; World Resources Institute, Washington DC, USA), but the impacts wreak disarray in agricultural systems in the developing countries, with serious impacts on the livelihoods of poor smallholders (Cooper et al. 2008). Changes directly and indirectly caused by climate are already shaking up agroecosystems in Africa. In the coming decades, smallholders will need to adapt increasingly to the multifold negative impacts of climate change, such as increasing water stress, the increasing rate of agricultural land becoming unsuitable for cultivation, declining crop yields, fluctuating food prices, increasing pests, crop diseases and weeds and climate-related human and livestock diseases, such as malaria (Niang et al. 2014). The global and irreversible impacts of climate change challenge all aspects of food security: availability, access, utilization and stability (Niang et al. 2014). There is a need for greater understanding of the opportunities and challenges in enhancing food security in situation in which agriculture is, on the one hand, under pressure to increase production and, on the other, to cut emissions.

Since 1850, after the Industrial Revolution, terrestrial ecosystems have contributed 136 Gt to carbon emissions, about half of that from fossil-fuel combustion (Lal 2004b). Estimates for the historic loss of soil organic carbon (SOC) range between 55 and 78 Gt, of which one third is caused through soil erosion and two thirds through mineralization of organic matter (Lal 2004b). Since the Green Revolution, population and economic growth have increasingly put pressure on agriculture to increase production. While succeeding in reducing hunger in places, growth has occured at the expense of exacerbating environmental problems and depleting natural resources (Tilman et al. 2001). Currently, agriculture releases 13% of the world´s total global GHG emissions, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases, when emissions from land-use change and the forestry sector are taken into account (CAIT 2014), and is responsible for 75% of the deforestation (Vermeulen et al. 2013). The main threats identified in Europe to soil are erosion, decline in organic matter, soil contamination, soil sealing, soil compaction, decline in soil biodiversity, salinization and floods and landslides, being to a large extent the same in Sub-Saharan Africa (SSA) (European Commission 2002).

During 15 years in Africa, the carbon stock in living biomass has been reduced by 18 Mt CO_2, due to deforestation (Nabuurs et al. 2007). The proportion of SSA in the global total GHG emissions is currently 7%

(including land-use change and forestry) (CAIT 2014). Emissions from the closely linked agriculture and land-use change and forestry sectors account for 67% of the total emissions in SSA (CAIT 2014). In Eastern Africa, the agricultural area has increased over 20% since 1961 to the current 342 million ha, whereas the forested area has been reduced by 19% during the last 20 years (FAO Corporate Statistical Database FAOSTAT 2014). By 2020, SSA emissions are projected to increase by as much as 86%, compared with the 1990 level (De Pinto et al. 2010), due to economic growth and increasing demand for meat and dairy products. Such development may trigger further conversion from forests to agricultural land (Rosegrant and Cline 2003; Smith et al. 2007), which will deplete the SOC stock by as much as 50–75% in the tropics (Post and Kwon 2000; Lal 2004b).

1.2 RESPONSE OF AGRICULTURE IN AFRICA TO CLIMATE CHANGE

With the highest proportion of undernourished people in the world and an economy heavily reliant on agriculture, SSA is considered as one of the world´s most vulnerable regions to climate change (Boko et al. 2007). Climate change is expected to cause declining rainfall and increasing evaporation, resulting in widespread water shortages (Niang et al. 2014). The length of the growing season may become shorter in most places (Thornton et al. 2011), and the likelihood of crop failures will increase, which can shift the production from mixed crop-livestock- to livestock-based production (Thornton et al. 2009).

The impacts on major cereal yields were estimated to be negative, with strong regional variability (Niang et al. 2014). Nelson et al. (2010) suggested yield losses of 2–35% in cereals by 2050 and Thornton et al. (2011) losses of 2–71% by the end of the century in Africa. The risk of losing livestock due to prolonged droughts is also high. The impact of droughts on crop production may be reflected in livestock production through the lower availability of crop residues per livestock head (Niang et al. 2014).

In addition to climate variability, increases in world food prices since 2007–2008 have caused market instability, undermining food security in Africa (Wodon and Zaman 2010). A group particularly vulnerable to price peaks are female-headed households with low incomes (Kumar and Quisumbing 2013). These impacts will have a broad effect on all aspects of food security. There is a substantial need to develop food production towards what is known as ‘climate-smart agriculture’ which will increase agricultural productivity and income sustainably, adjust agriculture and build resilience to climate change and decrease emissions from agriculture (FAO 2013; Wheeler and von Braun 2013).

1.3 SYNERGIES BETWEEN FOOD SECURITY AND CLIMATE CHANGE MITIGATION

1.3.1 ASPECTS OF FOOD SECURITY

The FAO defines food security as “a situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life” (FAO 1996; FAO 2002). The definition covers the major features of food security: availability, access, stability and utilization. Of these features, food availability refers to a situation in which the quantity and quality of food meets the demand of the population. Access to food stands for the people’s ability to obtain resources, such as economic or political means, to supply or purchase food. Stability refers to the systems’ capacities to maintain food security under perturbation, and, utilization refers to food safety, quality and health issues (Schmidhuber and Tubiello 2007; Ericksen 2008; Pinstrup-Andersen 2009; Wheeler and von Braun 2013). Food insecurity can be both a consequence of conflict as well as a cause, accelerating the conflict fuelled by key drivers such as poverty (Blattman and Miguel 2010), inequality in access to resources (Macours 2011), population pressure (Østby et al. 2011) and poor governance (Fearon 2010).

Despite rapid and strong economic growth, Ethiopia is still one of the poorest countries in the world (World Bank 2014a). The proportion of the undernourished population has declined from 75% in 1990–1992 to 35% in 2012–2014 (FAO, International Fund for Agricultural Development IFAD and World Food Programme WFP 2014), but both chronic and acute food insecurity still occurs, particularly among smallholders and rural dwellers. About 33 million people suffer from malnutrition in Ethiopia (FAO, IFAD and WFP 2014), causing suffering and irrevocable cognitive and physical developmental disorders (Galler et al. 2012; Huang et al. 2013). In January 2014, 2.7 million people in Ethiopia experienced acute food insecurity, demanding food aid or cash to satisfy their food needs (U.S. Agency for International Development USAID 2014).

In countries where agriculture directly supports the livelihood of most people, such as in Ethiopia (85% of the population) (Central Intelligence Agency CIA 2012), food security and poverty reduction are dependent mainly on the agricultural sector, which is highly exposed to climate variability and extremes. In Ethiopia, agricultural production is mainly rain-fed, characterized by the use of low inputs and production of low outputs (World Bank 2007). Droughts may result in notable yield losses and, at worst, famine such as in 1984–1985 and the early 1970s, causing extensive loss of lives (Rahmato 1991). Efforts to satisfy the need of the growing population for food and fuel have intensified agriculture and expanded cultivation into mountain slopes, even mountain tops. Forested areas have declined from

40% of the land area in the early 1900s (Nyssen et al. 2004) to the current 4% (Pohjonen and Pukkala 1990; Berhanu 2005; Bationo et al. 2007). About 60% of farms have cultivation area less than 0.9 ha and 40% less than 0.5 ha (Taffesse et al. 2011). The shortage of firewood has increased the use of dried cow dung as fuel and reduced its use for soil amendment. Furthermore, fields are cleared after harvesting of crop residues for fodder and fuel (Corbeels et al. 2000). These developments have reduced the return of residue carbon into the soil, depleted SOC stocks and weakened soil infiltration and nutrient supply (Elias et al. 1998; Haileslassie et al. 2005; Bationo et al. 2007).

1.3.2 RESTORATION OF ERODED SOILS

Soil degradation refers to soil erosion, nutrient depletion, salinization and vegetation degradation, all of which lower soil resources and productive capacity (Young 1994; Girmay et al. 2008). Soil erosion is the most widely distributed form of soil degradation and has the greatest influence on soil carbon dynamics (Lal 2003). In Ethiopia, heavy erratic rains, deforestation, cultivation of steep slopes, overgrazing and land fragmentation are the main causes of soil erosion (Taddese 2001; Girmay et al. 2008). Along with reduced sources of fuel, deforestation changes the amount, distribution and intensity of rainfall (Aragao et al. 2008). A study conducted in the Ethiopian Highlands suggested that the determinant of rainfall erosion is large drop size (Nyssen et al. 2005). Free-grazing damages and changes vegetation from perennial to annual grasses, increases soil compaction and reduces porosity. Animals also destroy soil conservation constructions, complicating erosion control (Taddese et al. 2002).

Since the 1950's, agricultural soils have lost about 230–670 Mt of carbon in Ethiopia (Girmay et al. 2008). Soil loss rates from cropland range from 18 to 100 t ha^{-1} y^{-1}, equivalent to soil depths of 1.8–10 mm, depending on the soil characteristics, precipitation, topography and management (FAO 1986; Hurni 1988; Bewket and Sterk 2003). This loss of soil results in depletion of about 122 kg nitrogen (N), 13 kg phosphorus (P) and 82 kg potassium (K) ha^{-1} y^{-1} (Haileslassie et al. 2005). Together with more frequent erratic rains, soil nutrient depletion maintains low yields. Currently, cereal yields are about 1200 kg ha^{-1} on average (FAOSTAT 2014), making continuous international food aid a necessity (WFP 2014).

Permanent restoration of degraded soils could increase soil carbon storage, soil capacity to function and soil productivity (Schmidhuber and Tubiello 2007; Lal 2010a). Maximization of restoration benefits necessitates adaptation of agriculture to changing climate. Improving food availability requires higher yields and improved resilience of agroecosystems. The effect of increase in SOC stock in the root zone on crop yields is greater at lower than at higher level of SOC stock and at lower level of external inputs (Lal 2010b), such as in Ethiopia.

In Burkina Faso and Niger, adoption of indigenous soil and water conservation and agroforestry practices increased crop yields by 400 kg ha^{-1} and 100 kg ha^{-1}, respectively, enabled the initiation of cereal cultivation on poor-quality land, increased the proportion of marketed agricultural and forestry products, recharged village wells and improved access to fuel wood (Reij et al. 2009). Synthesis of several experiments (Lal 2010a) predicted yield increases per each incremental tonne of SOC in the root zone on wheat (*Triticum* L.) by 20–40 kg ha^{-1}, maize (*Zea mays* L.) by 200–300 kg ha^{-1}, great millet (*Sorghum bicolor* (L.) Moench) by 80–140 kg ha^{-1}, pearl millet (*Pennisetum glaucum* (L.) R. Br.) by 30–70 kg ha $^{-1}$, bean (*Phaseolus vulgaris* L.) by 30–60 kg ha^{-1} and soya-bean (*Glycine max* (L.) Merr.) by 20–50 kg ha^{-1} (Lal 2010a). The increase in soil carbon stock could also improve the buffering capacity of the soil, through improved soil water and nutrient holding, soil structure and biotic activity to resist extreme climate hazards (Lal 2004b).

Diverse income sources could help smallholders to recover from yield losses (Campbell 2009), to buy food and other necessities from the markets and prepare for new growing season. A study performed in West Africa by Gonzáles-Estrada et al. (2008), showed that incomes from carbon trading could increase farm profits by 2–32%.

1.3.3 MITIGATION POTENTIAL IN AGRICULTURE

The high contribution of agriculture to GHG emissions, low costs of agricultural mitigation actions and benefits of mitigation actions for productivity have motivated researchers to estimate the mitigation potentials of agriculture. Cole et al. (1997) estimated the total mitigation potential of the agricultural sector at 4.2–12.1 Gt carbon-dioxide equivalent (CO_2e) y^{-1} over a 50-year period. Smith et al. (2008) estimated that the technical potential for climate change mitigation in agriculture will be 5.5–6.0 Gt CO_2e y^{-1} by 2030 and the economic potential 1.5–4.3 Gt CO_2e y^{-1} at carbon prices of US$20–100 per tonne of CO_2e. About 90% of the total mitigation potential is comprised of carbon sequestration in agricultural soil (Smith et al. 2008). In Africa, despite the fairly low total GHG emissions in relation to the global level, the technical mitigation potential of the agricultural sector may be 0.97 Gt CO_2e y^{-1} by 2030, corresponding to as much as 17% of the global total mitigation potential, while the economic potential may be 0.27 Gt CO_2e y^{-1} by 2030 at a carbon price of US$20 per tonne of CO_2e (Smith et al. 2008). Exploiting the economic mitigation potential would compensate for 77% of the total annual emissions from Africa´s agricultural sector (CAIT 2014). Within Africa, the highest mitigation potential stands in the eastern parts of the continent: 0.109 Gt CO_2e y^{-1}, the highest potential provided by cropland management (26%) and grazing land management (25%) (Smith et al. 2008).

For the poorest people, adjusting food production to a variable climate is, without a doubt, more important and justifiable than concern about reducing emissions (Campbell 2009). However, turning agricultural soil from a carbon source to a carbon sink by adopting improved agricultural management practices would bring out synergies between climate change adaptation and mitigation, resulting in multiple benefits for poor smallholders and the environment (Pretty 2008). Exploiting the enormous mitigation potential of agriculture could, in addition to slowing down the progression of climate change (Smith et al. 2008), help to combat severe soil degradation, and increase soil productivity and yield stability (Lal 2004b). Trade of ecosystem services, particularly carbon payments, could enable considerable financial flows from the industrialized countries to the developing countries (Cazorla and Toman 2001; Messner et al. 2010, Kahiluoto et al. 2014).

1.3.4 CARBON SEQUESTRATION IN AGRICULTURAL SOIL

With 2.5 Tt of carbon, the soil carbon stock is 3.3 times the size of the atmospheric pool of carbon, containing 1.6 Tt of SOC and 0.95 Tt of soil inorganic carbon (SIC) (Lal 2004b). The SOC pool includes active humus and relatively inert charcoal carbon. The SIC pool of elemental carbon and two types of carbonate minerals, primary or lithogenic carbonates and secondary or pedogenic carbonates (Lal et al. 2007). Soil carbon sequestration means transferring and storing carbon from the atmosphere into long-term pools by adopting improved management practices (Lal 2004a). In agroecosystems, carbon is sequestered into soil in an indirect way as plants photosynthesize CO2 into plant biomass, part of which is allocated to the soil and transformed into SOC, and in a direct way by converting CO2 into secondary carbonates (Lal 2004a). Turning the soil carbon pool from a source into a carbon sink requires that carbon sequestration exceeds carbon release (Paustian et al. 1997). Implementation of improved agricultural practices influences mainly the SOC stock (Lal 2007).

In Ethiopia, the size of the SOC stock varies considerably under different land uses and climate conditions. In natural forests, the SOC stock ranges between 40 and 235 t ha^{-1} (Solomon et al. 2002; Lemenih and Itanna 2004; Lemma et al. 2006), in cultivated soils between 16 and 113 t ha^{-1} (Sillanpää 1982; Solomon et al. 2002; Lemma et al. 2006; Gelaw et al. 2014) and in open pastures or silvopastures between 39 and 53 t ha^{-1} (Gelaw et al. 2014) at soil depths ranging between 0–10 and 0–60 cm.

Degraded agricultural soils can re-accumulate about 50–66% of the historic loss of carbon through improved management practices, such as agroforestry, no-till, cover crops, water conservation and growing crops for energy on wastelands (Lal 2004b). Continuous use of improved management practices increases soil carbon storage to levels following a sigmoid curve, reaching a maximum rate 5–10 years after initiating improved practices and continuing the increase in carbon stock until reaching the new level of equilibrium, usually after 15–100 years (Smith et al. 1997; West and Post 2002).

Temperature, rates of evaporation and precipitation, vegetation, soil characteristics and management determine the rate and time of soil carbon sequestration (Post and Kwon 2000; Davidson and Janssens 2006). In agriculture, tillage type, vegetation cover, deposit of inputs to different soil depths and cultivation history show the most influence (Post and Kwon 2000). Under favourable conditions, such as under perennial vegetation, agricultural soils can conserve large amounts of SOC (Brejda 1997) in a passive pool of humus for hundreds, even thousands of years (Lal 2001; Batjes 2004). In some cases, the soil carbon sink potential in managed systems may be even higher than in natural ecosystems (de Moraes et al. 1996; Six et al. 2002) and have twice the potential of above-ground carbon stock (Tschakert 2004; Takimoto et al. 2008).

The global estimate of the potential of agricultural soils for sequestering carbon was estimated to be as high as 20–30 Gt C over 50–100 years (Paustian et al. 1997). Global estimates may however contain high levels of uncertainty, because they are based on highly aggregated data. Smith et al. (2008) estimated the mitigation potentials of non-livestock practices on cropland and grasslands for a warm-dry climate zone as 0.030–1.072 t C ha^{-1} y^{-1} by 2030. Reforestation of abandoned tropical croplands and pastures may sequester 1.30 t C ha^{-1} y^{-1} during the first 20 years after establishment and 0.41 t C ha^{-1} y^{-1} during the following 80 years (Silver et al. 2000). Most of the regional estimates were performed in temperate regions.

1.3.5 PAYMENTS FOR CARBON SEQUESTRATION

Carbon trading between the industrialized and developing countries could enable mitigation actions to be carried out cost-effectively, simultaneously financing climate-smart development. Carbon trading may offer perhaps the only feasible way of keeping the rise in global mean temperature below the 2 °C critical limits (German Advisory Council on Global Change WBGU 2009). The flow of funds from North to South could enhance global climate-equity between countries historically the most responsible for contributing to climate change and those most vulnerable to the impacts of climate change (Cazorla and Toman 2001). Implementing mitigation could provide a new source of income, diversifying the livelihoods of smallholders (Campbell 2009; Lal 2010a).

Within the regulatory carbon markets and the Kyoto Protocol, the Clean Development Mechanism (CDM) enables a country with emission commitment to implement a mitigation project in the developing countries. The buyer can use the emission credits issued for mitigation to offset emissions by paying the host partner of the mitigation project (United Nations Framework Convention on Climate Change UNFCCC 2014). Although agriculture is not directly included in the treaty, land-use- and energy-related projects can to some extent be realized in the agricultural sector. In addition, voluntary carbon markets offer an opportunity for voluntary emission compensation in agriculture (Bryan et al. 2010).

In recent years, the global carbon markets have increased their volume and value (Kossoy and Guigon 2012). Despite Africa's considerable mitigation potential, the number of projects has remained marginal, less than 3% of all CDM projects (United Nations Environment Programme UNEP 2014). Exclusion of soil carbon sequestration from most climate agreements and the various requirements of the treaties which are difficult for SSA countries to qualify, were suggested as major constraints restricting access to markets (Jindal et al. 2008). In addition, low institutional capacity, economic and political in-stability, tenure insecurity and high transaction costs are often referred to as preventing the scaling up of mitigation projects in SSA (Jindal et al. 2008; Smith et al. 2008).

1.4 RESEARCH NEEDS

During recent decades, numerous studies have increased our knowledge of the direct effects of climate change on agricultural production (Lobell et al. 2008; Knox et al. 2012; Kurukulasuriya and Rosenthal 2013; Sultan et al. 2014). At the time when the demand for agricultural products has been estimated to increase, this justifies agricultural intensification and adaptation to changes remaining highlighted in the agenda. However, understanding the rich picture of the complex interaction between climate change and food security requires further inspection of the dimensions of access, stability and utilization of food. These aspects currently represent only 30% of published studies in the field of food security and climate change (Wheeler and von Braun 2013). So far, studies have provided the results narrowly, avoiding integration of the social, economic and biophysical perspectives and focusing on the easily accessible regions (Wheeler and von Braun 2013). However, in political discussion and decision-making aiming at enhancing sustainable development globally, the context of food security has been highlighted (Gregory et al. 2005). There is a need for a holistic approach that acknowledges the complex ensemble instead of the disconnected sectors. Such an approach will contribute to a more comprehensive assessment, which is crucial to solving obstacles and constraints hindering efforts to enhance food security in the changing climate. The potential synergies between climate change mitigation and adaptation in agriculture and particularly the considerable benefits for the livelihoods of poor smallholders in the developing countries call for research to increase our understanding of the relationship between food security and climate change mitigation.

Exploiting the potential of climate change mitigation in agriculture for enhancing food security requires understanding of the agroecological and socioeconomic factors that may promote or constrain achievement of the goals. Existing frameworks illustrate the influence of climate change on food security (FAO 2008) and feedbacks between food systems and environmental and socioeconomic drivers (Ericksen 2008). However, the inter-linkages of climate change mitigation and food security have not been demonstrated before. There is a need for conceptualizing the relationship of climate change mitigation and food security. Such thinking could comprehensively piece together the influence of alternative mitigation options on the various aspects of food security and facilitates identification of the bottlenecks and solutions.

The implementation of potential mitigation actions occurs at the smallholders´ farming system level. Population pressure, decreased holding sizes and deforestation have resulted in tough competition for the use of crop residues and manure, either for fuel or soil amendment (Corbeels et al. 2000; Berhanu 2005; Bationo et al. 2007). Reduced return of carbon residues to the soil further depletes the already low soil carbon stock. Directing a higher proportion of carbon into the soil could contribute to turning agricultural soil from a carbon source to a carbon sink and improve soil productivity (Lal et al. 2011). Currently, there are few estimates of the potential for improving resource-use efficiency in farming systems in Africa (Manlay et al. 2004; Giller et al. 2006; Rufino et al. 2006). Organic carbon flows and losses of carbon have not been studied before in farming systems in East Africa. Quantitative estimates of the flows of harvested and imported carbon and carbon losses would increase our understanding of the magnitude and causes of carbon losses and the potential for ecologically intensifying the use of carbon in farming systems.

The effects of improved agricultural management practices on soil carbon stock have sparked great interest, due to the high estimated potential for climate change mitigation and restoration of degraded soils (Smith and Olesen 2010; Schmidt et al. 2011). So far, studies conducted in Ethiopia have quantified soil carbon stocks in various land uses, changes in soil carbon stocks after transition from forest to agricultural land and the effects of exotic reforestation (Solomon et al. 2002; Lemenih and Itanna 2004; Lemma et al. 2006; Gelaw et al. 2014). There are only a few available estimates of the soil carbon sequestration potential of agricultural practices in SSA. Existing estimates concerning SSA are mainly based on process models developed and validated under temperate conditions (Farage et al. 2007; Kamoni et al. 2007; Smith et al. 2008; Batjes 2012). The lack of rigorous estimates of the soil carbon sequestration potential of the improved practices has been argued as one of the major bottlenecks for including agriculture in carbon markets, preventing the introduction of carbon payments to smallholders (Bryan et al. 2010; Kahiluoto et al. 2014). Therefore, empirical knowledge of the agricultural carbon sequestration potential in East-Africa is needed.

2 AIMS OF THE RESEARCH

Here I aim to explore the potential of climate change mitigation in agriculture for enhancing food security in SSA. Qualitative and quantitative approaches were used to answer the following specific research questions:

1. What are the determinants influencing possibilities of climate change mitigation in agriculture to enhance food security (**I**)?
2. What is the potential for enhancing the use of carbon for soil amendment (**II**)?
    - 2.1 What is the proportion of harvested and imported carbon allocated a) for food and b) for soil in smallholder mixed-farming systems?
    - 2.2 What are the major losses of carbon reducing the proportion recycled to the soil?
    - 2.3 What are the determining factors for the proportion of carbon used for soil and of the carbon losses?
3. What are the carbon sequestration potentials of agroforestry, restrained grazing and farmland terracing (**III**)?
    - 3.1 How large is the SOC stock of agricultural land under the three agroecological practices?
    - 3.2 Is the SOC stock higher under the agroecological practices than in traditional farming?

3 MATERIALS AND METHODS

3.1 RESEARCH SITES

The research was conducted during 2009–2013 in the Ethiopian Highlands in two regions representing major food-producing areas with contrasting agroecological and socioeconomic conditions. Data regarding creation of the analytical framework were also collected in Finland. Selection of the sites rested on the information-oriented selection of regions that represented extremes of the scale for food security. Kobo is located on the border of the cool semi-arid and warm semi-arid agroecological zones and Sire on the border of the cool semi-arid and cool sub-humid agroecological zones (Figure 1). Kobo represented the more food-insecure regions with its longer cultivation history, higher population and animal density, smaller holdings, more severe soil degradation rate and higher water stress, lower crop yields and longer distance to markets than Sire, which represented a region of higher food security (**I–III**) (Figure 2a,b).

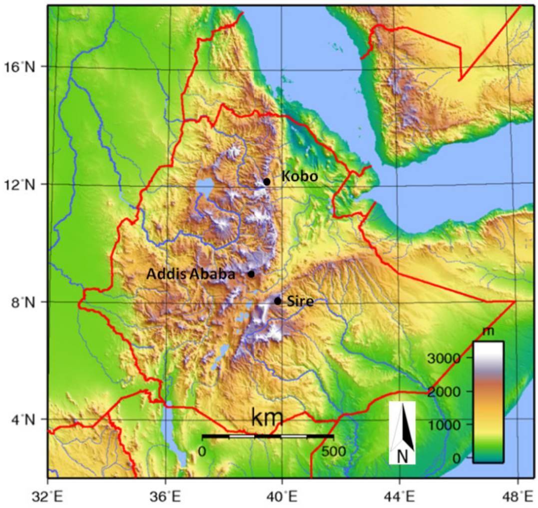


FIGURE 1. Location of the research sites.

FIGURE 2a,b. Landscape of the case regions: 2a: Kobo, 2b: Sire. Photos: Karoliina Rimhanen

In both case regions, agricultural production was characterized by highland temperate mixed farming, which occupies about 30% of the land area in Ethiopia and 5% of the area in East-Africa (Dixon et al. 2001; FAOSTAT 2014). Livestock are important for financial security, draft power, transportation, fuel and culture. Animals graze freely on communal land and on fields after harvesting. In Kobo subsistence farming is common. Great millet is broadly cultivated for its drought tolerance, while wheat, teff (*Eragrostis tef (Zucc.) Trotter*) and barley (*Hordeum vulgare L.*) are also grown. In Sire, crop rotations are more diverse, containing teff, wheat, barley, maize and various cash crops, such as vegetables and pulses. Home garden-type agroforestry is also practised on many farms.

The annual range of the mean annual temperature and precipitation was 21–25 °C and 105–958 mm (mean 631mm) in Kobo and 15–20 °C and 532–1123 mm (mean 868 mm) in Sire, on average (National Meteorological Agency of Ethiopia NMA 2010; NMA 2011). The figures indicate notable differences in precipitation deficits and difference in precipitation range between Kobo and Sire, which influence yield stability and reliability and determine farming strategies.

Ethiopia has two growing seasons. The main season ‘meher’ exploits rains between June and October and produces 90–95% of the total cereal outputs and the small growing season ‘belg’ between February and June (U.S. Department of Agriculture USDA 2008). Most of the annual precipitation falls in August (133 mm), July (125 mm), May (90 mm) and September (90 mm) (World Bank 2014b). Failures, particularly in belg rains, have been reported in the northern parts of the country, resulting in crop failures (USDA 2008). Farmer estimated that the precipitation in the 2008/2009 growing season was low and in 2009/2010 average.

In Kobo, the soil texture was loam, sandy loam, loamy sand and sandy clay loam. In Sire, the soils were substantially more fine-textured, including clay, silty clay loam, clay loam and silty loam soils. The soil carbon concentrations ranged between 0.9% and 3.2% in Sire and 0.3% and 3.6% in Kobo (**III**).

3.2 DESIGN OF THE STUDIES

3.2.1 CONSTRUCTING AN ANALYTICAL FRAMEWORK (I)

An explanatory case-study approach was used to create an analytical framework for identifying the causal relationships and mechanisms between climate change mitigation and food security in East Africa. The focus was on options for carbon trading in the agricultural and land-use sectors in general between Finland and Ethiopia. Two sets of interview data were collected, namely pilot interviews and in-depth interviews. A third set of data was generated from focus group discussions.

First, a hypothetical analytical framework of the factors affecting the potential of climate change mitigation for enhancing food security was created, based on existing literature (FAO 1996; Howden et al. 2007; Schmidhuber and Tubiello 2007; Jindal et al. 2008; Lal and Follett 2009; Organization for Economic Cooperation and Development OECD 2009).

Second, the hypothetical analytical framework was validated and defined through individual in-depth theme interviews (n = 14) and focus group discussions (n = 6). The in-depth theme interviews were conducted with actors at the global and national levels in Ethiopia and Finland and focus group discussions with farmer groups in the two Ethiopian case regions. Pilot interviews (n = 24) were performed in the Central Rift Valley of Ethiopia, to serve focusing on the in-depth interviews and focus group discussions. The pilot interviews comprised interviews with smallholders (n = 16), an agricultural scientist (n = 1), agricultural advisers (n = 2), an environmental expert (n = 1), forestry specialists (n = 2) and regional administrators (n = 2).

The in-depth interviewee at the global level typically demonstrated expertise in climate, energy, food policy and carbon trading (n = 1) matters. At the national level, the in-depth interviewees of the buyer country (Finland) represented experts in carbon trading (n = 2) and developmental policy (n = 2), nongovernmental organizations (NGOs) oriented towards environmental (n = 1) and developmental issues (n = 1) and research (n = 2). The in-depth interviewees of the host country (Ethiopia) represented experts in developmental and water issues (n = 2), administration (n = 1) and NGOs oriented towards carbon trading (n = 1) and development (n = 1). The interview guide of in-depth interviews included questions about smallholders' access to global carbon markets, preconditions of the buyer and host partners for carrying out mitigation projects and methods used in mitigation projects to enhance the various aspects of food security and distribution of benefits.

Focus group discussions were held in Kobo and Sire, separately for advanced better-off farmers with assets, resource-limited farmers with the least assets belonging to the government´s poverty safety-net programme and female farmers, with four participants in each discussion. The topics of the focus group discussions concerned the potential impacts of the mitigation options on food production and sources of income, constraints for scaling up mitigation practices and carbon trading, and distribution of benefits.

Pilot interviews were conducted in Amharic by an Ethiopian agricultural researcher trained by the author. Individual in-depth interviews were conducted by the author in English and Finnish. The focus group discussions were conducted in Amharic in Kobo and in Oromo in Sire by two Ethiopian socio-economic researchers trained by the author. The duration of the interviews ranged between 2 and 6 hours. The interviews were recorded, transcribed and translated into English.

The research material was coded and structured into themes. The themes that appeared from the in-depth interviews and focus group discussions were compared with the hypothetical analytical framework and developed to construct the final analytical framework. The determinants and bottlenecks for the synergies between climate change mitigation and food security and the potential for reducing losses of carbon (**II**), as well as the most prominent mitigation option (**III**) identified in the analytical framework, were explored in the two empirical studies that followed (Figure 3).

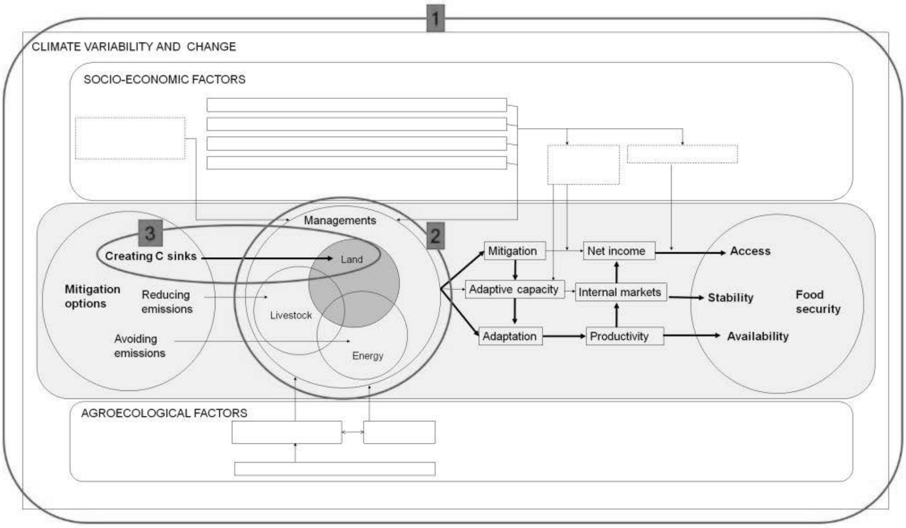


Figure 3. Focuses of the study

3.2.2 QUANTIFYING THE POTENTIAL TO ENHANCE THE USE OF CARBON TO SOIL (II)

A case-study approach was used as a research strategy to empirically quantify the flows of carbon harvested on the farm and imported to the farm that ended up in the food, soil and as losses in real-life farming systems (Figure 4). The farming system was outlined on a functional basis, composed of cropping, livestock raising, grazing, composting and food and energy consumption of the household. In both case regions, two case farms that represented the extreme range for the resource availability in the region were selected for the study (n = 4). The better-off farms with greater resources had larger holdings, more livestock and more advanced agricultural management practices than on average in the case region. The resource-limited farms had smaller holdings and fewer animals than on average in the case region and belonged to the government´s poverty safety-net programme.

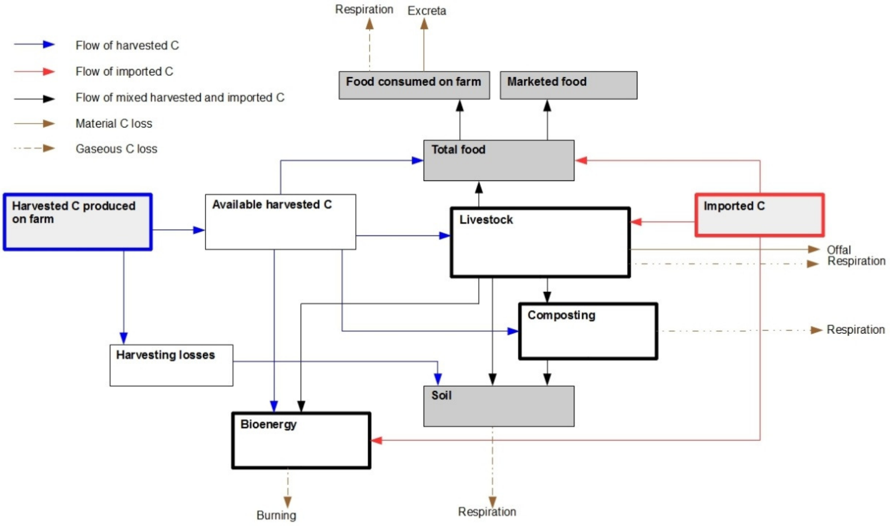


Figure 4. Conceptual model of the stocks and flows of carbon harvested on the farm and imported to the farm. Material carbon flows, represented as a solid line, were quantified directly. Gaseous carbon losses, represented as a brown dashed line, were calculated indirectly based on carbon balance counting, apart from respiration from food consumed on farm and respiration from soil.

Household interviews were conducted to collect basic information on the farming and household systems. Adult members, from one to three persons participating, of the farm households were included in the interviews. The interview guide included questions on farm characteristics and resources, land-use history, crop production, use of fertilizers, manure and crop residues, harvesting losses, composting practices, livestock management and grazing, household diet and acquisition of food, marketed crops and exports of animals, use of fuel wood and management of organic household waste within the farming system. The interviews were conducted by the author with the assistance of two Ethiopian socio-economic researchers, trained by the author, in Amharic in Kobo and in Oromo in Sire. The duration of the interviews ranged between 3 and 6 hours. The interviews were recorded, transcribed and translated into English.

The crop yields for the 2009/2010 growing season were manually sampled at harvest time in October–November 2010 on the same farms where the interviews had been conducted (Figure 5). Two 1m² plots in each field were sampled, and the fresh weights of the grain and straw were recorded. Three replicate samples were analysed. The dry matter percentage (DM%) (w/w) was measured by drying at 105 °C for 12 hours. The carbon concentration for the grain and straw of haricot bean, barley and great millet were determined, using a Leco CN-2000® analyser (Leco Corporation, St. Joseph, MI, USA). The carbon concentrations of wheat and teff were based on literature, since their export from Ethiopia was forbidden. In addition, the data were complemented and double-checked with literature from national and local archives, agricultural offices and publications.

Figure 5. Crop sampling. Photos Karoliina Rimhanen and Melesse Abera.

Material flow analysis (MFA) was used to determine the flows of harvested and imported carbon. The carbon contents in the flows were calculated by multiplying the mass of the flow by its carbon concentration. The carbon flows were examined over the 2008/2009 and 2009/2010 growing seasons and reported as the mean of the 2 years. The proportion of harvested carbon allocated to food was calculated as the quantity of harvested carbon ending up in food (kg) / the quantity of total harvested carbon produced on the farm (kg) * 100. The proportion of imported carbon allocated to food was calculated as the quantity of imported carbon ending up in food (kg) / the quantity of total imported carbon (kg) * 100. The proportion of harvested carbon allocated to soil was calculated as the quantity of harvested carbon ending up in soil (kg) / the quantity of total harvested carbon produced on the farm (kg) * 100. The proportion of imported carbon allocated to soil was calculated as the quantity of imported carbon ending up in soil (kg) / the quantity of total imported carbon (kg) * 100.

The gaseous carbon losses were calculated, based on the carbon balances for processes occurring before the carbon ended up in the food or soil (Figure 4), i.e. for biomass burning (bioenergy in Figure 4), livestock raising (livestock in Figure 4) and composting. The actual gaseous returns to the atmosphere from soil respiration or from respiration of the household consumers of the food were not needed and, hence, not included in the balance calculations in this approach. The losses were calculated as the difference between carbon imports and exports of each process included.

Uncertainty analysis for MFA (Hedbrant and Sörme 2001) was used to estimate the uncertainties of the data and results. The uncertainty factors were determined for each type of data by comparing the data collected in this study with that in Antikainen et al. (2005) and Danius (2002). The uncertainty range, i.e. the likely minimum and maximum values of each flow, was defined. Sensitivity analysis was conducted to test the influence of the uncertainty range on the order of the greatest carbon losses.

3.2.3 QUANTIFYING THE CARBON SEQUESTRATION POTENTIAL OF AGROECOLOGICAL PRACTICES (III)

The approach in assessing the potential of agroecological practices for carbon sequestration was based on comparing existing contrasting practices. Agroecological practices that the farmers had adopted and used for decades to improve productivity were chosen for comparisons with traditional farming. The agroecological practices varied in different case regions, due to variability in the agroecological conditions, such as available water resources and traditions.

A split-plot-type field study was conducted, with a main plot size of 0.25 ha. Three groups of plot pairs were included as an agroecological management practice comprising three system types: agroforestry, terracing and restrained grazing. The controls representing each traditional conventional management practice that contrasted with the agroecological practice included cultivated (arable) fields for agroforestry and terracing and uncultivated permanent pasture (freely grazed land) for restrained grazing. The three groups of plot pairs (agroecological practices) were the levels of the whole-plot factor and the two management practices (traditional and agroecological) were the levels of the sub-plot factor.

The home garden-type agroforestry sites were sampled in Sire and the terracing and restrained grazing sites in Kobo (Figure 6). The ages of the agroforestry systems ranged from 6 to 20 years. The vegetation in the agroforestry plots included acacia (*Acacia* Mill.) species, Arabian coffee (*Coffea arabica* L.), maize, ensete (*Ensete ventricosum* (Welw.) Cheeseman), cereals, fruits and vegetables. The ages of the farmland terracing ranged from 5 to 10 years. Cereals were cultivated on terraces and were ploughed annually. At the restrained grazing sites, free-grazing had been forbidden for 6–17 years, resulting in development of natural vegetation, but harvesting of dry branches and hay was permitted.

Sampling was conducted from eight agroforestry plots, eight terracing plots and seven restrained grazing plots, where these managements had been practised for the longest time. Each of these plots was paired with an adjacent control plot that was managed traditionally. The management history of the plots was determined by interviewing farmers. The agroecological practices had been under traditional management before implementation of the agroecological practices, and the use of fertilizers was similar within the plot pairs. The similarity within the matched pairs for topography and soil texture was confirmed. Positive evidence that the soil carbon stock had been the same in these pairs on adopting the agroecological practice was not acquired.

Figure 6. Agroecological practices (above) and their traditionally managed controls (below). Photos Karoliina Rimhanen.

To estimate the intraplot variation, each plot was split into three sections. Ten sub-samples from the 0–15-cm layer of soil were taken with an auger from each section and pooled for analyses (Figure 7). From each section, two bulk density (ρ_b) samples were taken at the same depth with core samplers of 104 cm^3 in Kobo and 98 cm^3 in Sire. The soil samples were air-dried and ground through a 2-mm sieve. The total carbon concentrations were analysed by dry combustion (1100 °C), using the Leco CN-2000® analyser. The carbonates were removed from the samples by dissolving them with 6 M HCl. The results of the soil organic matter (SOM) represent the carbon remaining in the organic matter after the HCl treatment. The ρb samples were dried (105 °C for 12 hours) and weighed. The ρb (g cm^{-3}) was calculated as the dry weight of the soil / the volume of the soil. The soil carbon stocks (expressed as t ha^{-1}) were calculated as the concentration (%) of soil carbon * the ρb * the volume (cm^3 ha^{-1}) of soil in a 15cm hectare layer and also expressed in kg t^{-1} of soil. The means of the measurements from the three sections were utilized as observations in the statistical analyses.

Figure 7. Soil sampling. Photos Kbrom Berhe.

Comparison of the agroecological practices with their traditional controls with respect to the soil carbon stock was based on statistical analyses in which the common mixed model for a split-plot design was employed with three fixed effects (main effects of the whole-plot and the sub-plot factors and their interaction) and two random effects (whole-plot error and sub-plot error). The soil carbon stocks were log-transformed to satisfy the assumptions of the constancy of variance for all observations and normality of the data. To compare the agroecological management practices and to eliminate the differences, both in durations of the agroecological practices and in the carbon stocks of the control plots from the comparison, analysis of covariance was utilized. The soil carbon stocks were divided by the duration of the agroecological practices and the ratio was used as a response variable in a model in which the corresponding carbon stock of the traditional control was included as a covariate to account for differences in the sizes of the carbon stocks of the traditional plots. The relationship between the response and the covariate was modelled by a regression line, enabling different intercepts and different slopes for the agroecological practices. The analyses were performed using the MIXED procedure of the SAS/STAT software (version 9.3; SAS Institute Inc., Cary, NC, USA).

4 RESULTS AND DISCUSSION

4.1 ENHANCING FOOD SECURITY THROUGH CLIMATE CHANGE MITIGATION

Increasing the productivity of severely eroded agricultural soils through soil carbon sequestration was considered as the principal strategy to enhance food security through climate change mitigation (**I**). Increasing the productivity would directly increase food and fodder availability in farming systems. The maximization of mitigation benefits is dependent however, on adaptation of the agroecosystem. At the regional and national levels, contributing to the operability of internal markets was considered crucial to enhancing access to food (Figure 8). Additional income from carbon sequestration was considered important to cover the costs of monitoring, reporting, verification and advisory services and as compensation for agricultural development activities, such as fencing land and reduction of cattle numbers while soil production recovers.

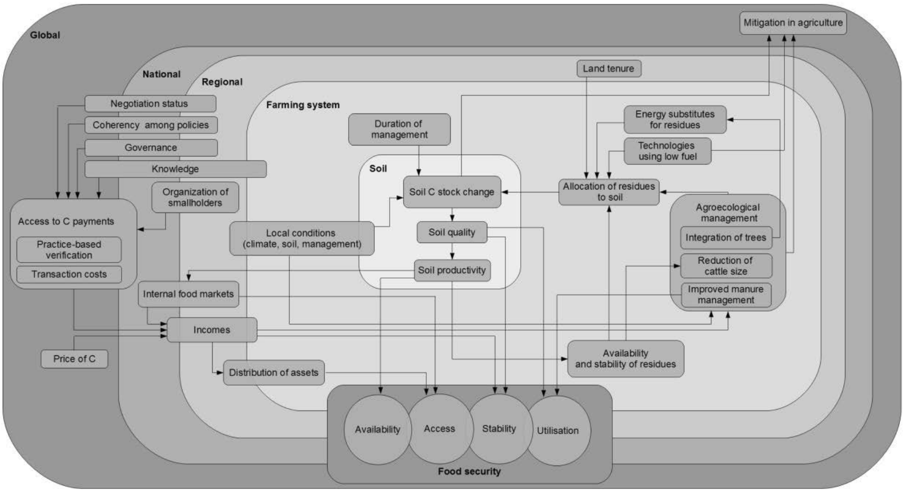


Figure 8. Opportunities and means of the agroecological practices for mitigating climate change and enhancing food security at the soil, farming system, regional, national and global levels.

The need to restore large areas of severely eroded agricultural soils, due to historical land use, was highlighted among the respondents (**I**). Such soils have high potentials for accumulating carbon (Smith et al. 2008) and nutrients, contributing to enhanced crop yields (Lal 2004b). Sequestering carbon in the stable fraction pool of SOM requires taking care of not only carbon, but also sufficient availability of the key nutrients N, P and sulphur (S), which contribute to and maintain vital soil functions (Kirkby et al. 2013). Improved nutrient- and water-holding capacity (Doran and Zeiss 2000) could reduce production risk in the long run under fluctuating weather conditions, thus enhancing the stability of the food supply. Increased soil quality could also improve the nutritional value of food grown in the soil, enhancing the health and utilisation of food (Lal 2004b) (Figure 8).

The selection of locally suitable mitigation options was dependent on the agroecological factors and the prerequisites for implementing mitigation practices on the socioeconomic factors (Table 1). Local farming systems, land management and access to water sources set the frame for the selection of mitigation options under local conditions (**I**). The tradition of free-grazing and low availability of water limited the establishment of agroforestry sites. Under such less favourable agro-ecological conditions, restoration of eroded slopes by farmland terraces and closing the area from grazing and collection of fuel wood were considered as feasible options.

Table 1. Factors influencing the potential of climate change mitigation for enhancing food security.

Socio-economic determinants	Agroecological determinants
Multi-level coherence of policy and actions	Local hydrology
Early access to financial incentives	Management history
Quality of governance	Current land management
Infrastructure of internal markets	
Population density	
Land tenure systems	
Knowledge about climate mitigation options, carbon markets and verification	

Supporting governance, policies favouring food security and access to financial incentives at the early stage were considered as important requirements for adopting mitigation practices. For the practical implementation of mitigation practices, population pressure in the region, sizes of the holdings, knowledge of and training for carbon markets and feasible mitigation options were highlighted (**I**). The ownership of the land by the State in Ethiopia, as in many other countries in Africa, can be a demotivating factor restraining smallholders' willingness to invest in land and also constraining the development of carbon payments in Africa (Jindal et al. 2008).

In comparison to other mitigation practices, such as reforestation or cultivation of bioenergy crops, carbon sequestration in agricultural land does not compromise food production, the priority of agriculture, because it does not result in competition in the food-producing land area (Sutter and

Parreno 2007; Smith and Olesen 2010). Multiple long-term benefits encourage smallholders to maintain and increase the soil carbon stock further, in contrast to saleable carbon stocks.

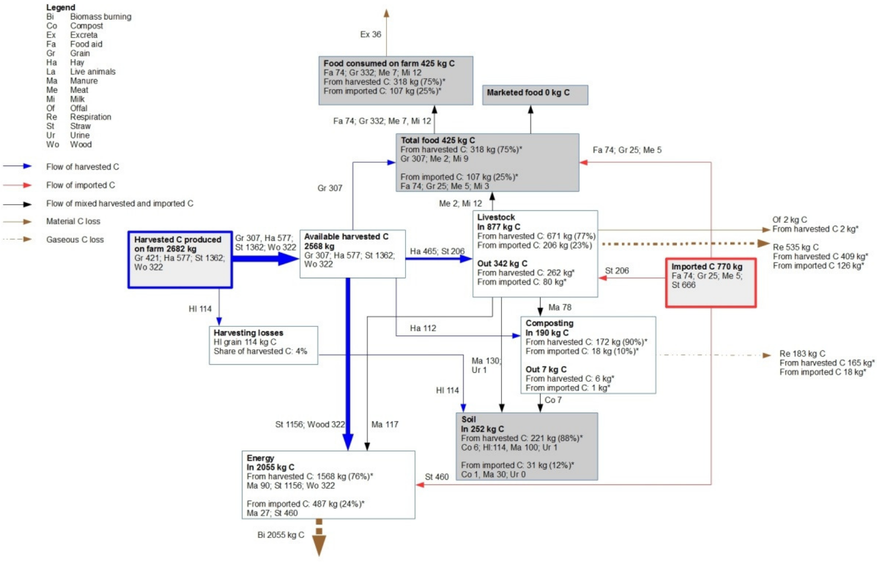
In consequence of the low price of carbon and the high costs of project implementation, complementary income sources, e.g. from marketed crops, were considered important. The increased proportion of crops for sales, resulting from improved soil productivity, could increase household income, further improving the affordability to purchase inputs and food from the market in case of crop failure, thus enhancing access to food through multiple positive feedbacks. Diverse sources of income would create an economic buffer for smallholders, thus enhancing the stability aspect of food security (Campbell 2009) (Figure 8).

Directing the carbon payments to the community instead of to individual households was seen as a contributing factor for the fair distribution of benefits. Democratic decision-making within communities could reduce the wielding power by the household head with relation to other members of the household, thus enhancing the distribution of benefits equally to the most poor and hungry. Organization of farms (e.g. farm cooperatives) could also expand the area for carbon agreement and thus facilitate access of smallholders to the carbon market.

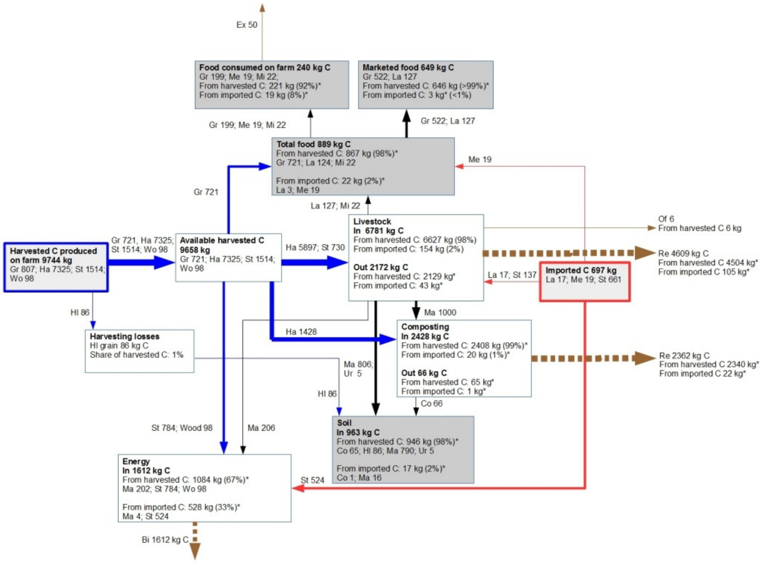
Concealment of the personal details of interviewees increased the reliability of the interview data. However, when asked about property issues, such as cattle or land area, contradictions between different questions were observed. The results allowed generalization of the case of interaction between the industrialized and East-African countries. The GHG reduction strategies of Finland are typical for industrial countries, and the agro-ecological and socioeconomic conditions of the case regions in Ethiopia represent the extremes of resource availability in the regions of crucial importance to food production.

4.2 POTENTIAL FOR INCREASING THE USE OF HARVESTED CARBON IN SOIL

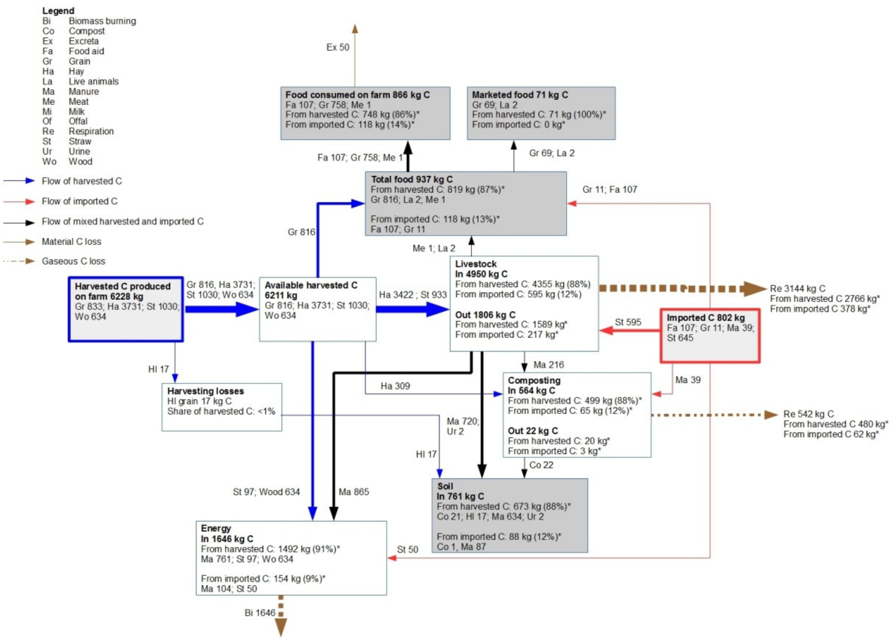
In farming systems, the proportion of harvested carbon used for food was 9–16% and in soil 8–12% and that of imported carbon used for food was 3–35% and in soil 3–11% (Table 2; Figure 9a–d) (**II**). All harvested and imported edibles were used as food. The lack of compensatory energy sources resulted in competitive use for straw and manure, leading to their use mainly for fuel, thus reducing their use in soil. The only untapped residues from the farming system were human excreta that were not recycled into agricultural soil, but dug into a pit outside agricultural land, and offal that was thrown to hyenas. The farmers justified this practice as reducing hyena attacks towards family members and livestock. Human excreta and offal combined amounted to between 38 and 66 kg C y^{-1}, which is 0.3–1.1% of the harvested and imported carbon and of negligible significance. Other uses of carbon were not mentioned during the study period and thus not considered. Occasional uses of carbon, such as manure in wall construction, served as temporary carbon stock for small amounts of carbon. Consequently, increasing the use of carbon in soil would be possible, mainly by reducing gaseous carbon losses from the farming system.



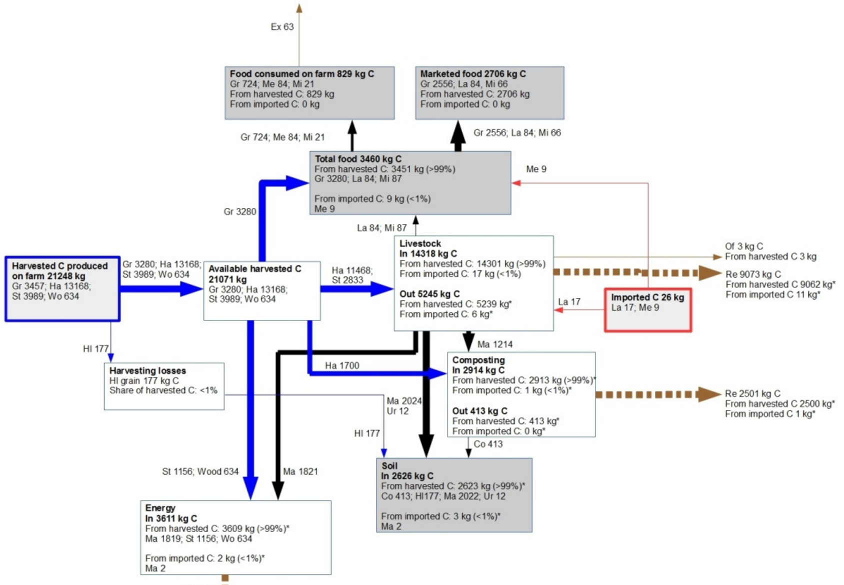
a. Kobo resource limited



b. Kobo better-off



c. Sire resource limited



d. Sire better-off

Figure 9a–d. Flows of harvested and imported carbon to food, soil and as losses (kg C y^{-1}). The figures marked by stars (*) are calculatory, founded on the proportions of harvested and imported carbon imported to the process concerned. The flows are means of the 2008/2009 and 2009/2010 growing seasons. The primary production represents the above ground yield. The field area of each case farm was in a) 0.75 ha, b) 1.5 ha, c) 2.5 ha and d) 6.25 ha.

The greatest carbon losses originated from biomass burning and livestock metabolism and minor losses from composting (Table 2). This is in line with the GHG emissions reported in Ethiopia, the main source being enteric fermentation, totalling 28 Mt CO_2e (Tadeke 2001). Considerable emissions were also generated by burning biomass: 66 Mt CO_2e (Tadeke 2001). In GHG reporting, these are considered as 'carbon-neutral', being equivalent to the amount of carbon bound in photosynthesis (Smith et al. 2008), despite various additional non-CO_2 compounds released during burning (Andreae and Merlet 2001).

Having livestock indicates social standing in the society and serves as insurance for food security in case of crop failure. The resulting high number of livestock, in relation to available fodder, led to low fodder use efficiency and thus emissions. Furthermore, the commonly practised free-grazing that extended even to field plots after harvesting likely aggravated the depletion of the soil carbon stock, particularly in the North with its high livestock density (**III**).

Table 2. Proportion (%) of harvested and imported carbon ending up in food, soil and as losses.

Case farms	Harvested carbon ending up				
	to food	to soil	to losses from		
			biomass burning	livestock metabolism	composting
Kobo resource limited	12	8	59	15	6
Kobo better off	9	10	11	46	24
Sire resource limited	13	11	24	44	8
Sire better off	16	12	17	43	12
Case farms	**Imported carbon ending up**				
	to food	to soil	to losses from		
			biomass burning	livestock metabolism	composting
Kobo resource limited	14	4	63	16	2
Kobo better off	3	3	76	15	3
Sire resource limited	15	11	19	47	8
Sire better off	35	10	8	41	5

During composting, the carbon stock in the biomass decreases as a result of decomposition by micro-organisms, reducing the size of the compost pile and decreasing the C/N ratio (de Bertoldi et al. 1983). The carbon losses in composts that include cattle manure can range between 30% and 70%, influenced mainly by the bedding material, bulking agent and environmental conditions (Bernal et al. 2009). Disturbance in conditions may further result in carbon losses through CH_4 production under anaerobic conditions, rapid degradation of organic matter at high temperature or leaching as dissolved organic carbon (Pel et al. 1997; Sánchez-Monedero et al. 2010). Carbon may also be sequestered from the compost pile into the soil below the pile by the soil fauna.

The proportion of carbon used as fuel appears as the main determinant, with negative correlation for the proportion of carbon allocated to the soil (**II**). Unlike losses of carbon from livestock metabolism and composting, carbon losses from biomass burning could even be totally avoided by exploiting energy substitutes for manure and straw and new technologies using less fuel. This would most likely increase the allocation of residues to the soil (Figure 8), since their value for soil restoration has been well acknowledged (**I**). The total amount of straw and manure harvested on farms and used as energy ranged between 216 and 2792 kg DM, and 334 and 5203 kg DM, respectively (**II**). Assuming that this amount would be used as a soil amendment, the nutrient inputs within farming system would range between 990 and 2977 kg for C, 23 and 121 kg for N, 4 and 26 kg for P and 33 and 142 kg for K, contributing to carbon sequestration, as well as soil quality and productivity.

Sufficient supplies of fodder could improve the productivity of livestock and, together with more stable and diverse income sources, even lead to reduction in the total number of cattle, thus reducing emissions and damage from free-grazing. Restricting free-grazing and integrating multipurpose trees into agroecosystems could restore some of the carbon storage (III) by increasing the return of carbon residues to the soil and reducing soil disturbance. Changing manure management to anaerobic digestion with recovery of CH4 could reduce carbon losses compared with current composting practices, produce biogas for fuel, thus replacing biomass burning, and produce nutrient-rich digestate, which could be used as fertilizer (Holm-Nielsen et al. 2009). Such development could enhance the stability of the food and fodder supply and improve food safety and utilization by destroying harmful pathogens (Edwards and Daniel 1992).

As for the imported carbon, the data do not reveal the carbon use efficiency, because the management of the systems that harvested the imported carbon were not studied. Bias can occur if the system examined is different in terms of the carbon use from that of the farm where the imported carbon was harvested. For example, the system examined uses the imported carbon to food and soil efficiently, but the origin of the carbon is in a system with notable carbon losses. The uncertainty is higher in systems that import high volumes of carbon. In this study, the proportion of the imported carbon out of the total varied between 11% and 22% on the resource-limited farms and between 0.1% and 7% on the better-off farms. The similarity of the carbon allocation results between the resource-limited and better-off farms increases the probability that the origin of the imported carbon is similar to that in the system examined.

The contrasting case regions in the Highlands of Ethiopia, expressing a broad range of resource availability, and the smallholder mixed-farming systems that are most common in the country, make the results representative for Ethiopia. The similarity of the results in the various regions supports this generality. Empirical data gathered over 2-year period, covering a representative range of weather variation, provide a strong basis for estimates of the flows and losses of harvested and imported carbon in Ethiopian farming systems. Interviews and partial reliance on published literature all contain a degree of uncertainty. To decrease the errors, the results were double-checked, using several data sources.

Carbon flows consisting of estimates coming from the literature and multiple data, such as the flow of carbon in hay from rangeland to livestock subsystems and the flow of carbon in manure and compost, result in the greatest uncertainty. In contrast, the uncertainties of the flows estimated, based on our own empirical measurements, such as yields, were smaller. Due to the high level of uncertainty of the size of the carbon flows, there is thus uncertainty about the order of the greatest carbon loss (**II**).

4.3 POTENTIAL OF AGROECOLOGICAL PRACTICES FOR SEQUESTERING CARBON IN SOIL

In Kobo, the carbon stocks varied from 6.6 to 41.7 t ha^{-1} (a single discrepant value for terracing excluded) and in Sire from 17.8 to 63.6 t ha^{-1} (Figure 10). In most of the pairs of plots, the soil carbon stock was higher under the agroecological practice than under the traditional practice, particularly in the agroforestry and restrained grazing plots. In the agroforestry plots, the carbon accumulation was on average 1.2 Mg ha^{-1} y^{-1} (95% confidence interval (CI): 0.3–2.0) and in the restrained grazing plots 0.7 Mg ha^{-1} y^{-1} (95% CI: 0.3–1.3) higher than in their controls. In relative terms, the soil carbon stock was in the agroforestry plots 30% (95% CI: 3–65 %) (11.4 t ha-1) higher after 6–20 years of the practice, in the restrained grazing plots 52% (95% CI: 19–95 %) (9.6 t ha-1) higher after 6–17 years and in the farmland terracing plots 15% (95% CI: -10–47%) (1.7 t ha-1) higher after 5–10 years than in their adjacent, traditionally managed control plots (III). The common relative gain averaged across the agroecological practices was 32% (95% CI: 15–51%) higher than in the control plots (medians 26.0 and 19.7 Mg ha-1, $p < 0.001$).

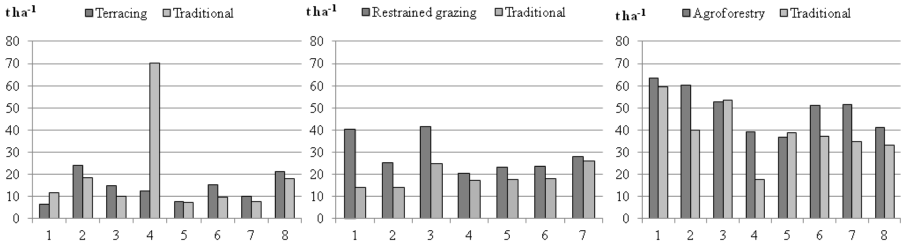


Figure 10. Carbon stocks in plot pairs in which existing traditional management was contrasted with existing agroecological management.

The differences in magnitude of the carbon stock gains by the agroecological practices do not necessarily reflect the difference in impact by the agroecological practices, but could have resulted from the various conditions under which the agroecological practices were implemented. The carbon stocks were also dependent slightly on the duration of the agroecological practice, tending to be lower as the duration became longer.

Tests of the equality of the slopes and the equality of the intercepts of the regression lines revealed that a common regression line fitted the data for each agroecological practice when a single discrepant observation for terracing was excluded. This indicates that the differences in rate of carbon stock accumulation among the plots of the agroecological management accounted for the corresponding differences in the traditional controls. In the case of agroforestry, the agroecological and socioeconomic conditions in Sire yielded higher soil carbon stocks than did the case region in Kobo, where restrained grazing and farmland terracing were implemented. Covariance analysis showed that the increase in carbon accumulation rate of the agroecological management was 1.09 Mg ha^{-1}, on average, for every 1.00 Mg ha^{-1} increase in the accumulation rate of the traditionally managed plots, since adopting the agroecological management practice. At the soil carbon stock level of 20 t ha^{-1}, such a 9 % carbon accumulation rate would gain an annual accumulation of 1.8 t C ha^{-1}.

In the agroforestry and restrained grazing plots, the increase in soil carbon stock of the agroecological management practices probably resulted from a higher above ground biomass of which part was deposited to soil, multilevel root system and reduced soil disturbance that decreased the decomposition of organic matter (Schlesinger and Lichter 2001; Smith and Olesen 2010). Terracing results in accumulation of organic carbon stock by reducing erosion on sloping land. The gradual shifts at the sites of the soil-made terraces, due to frequent collapses, may have reduced the difference with the adjacent field and thus hidden the true impact of terracing on the soil carbon stocks. This may have contributed to the mixing of carbon-scarce subsoil and thus dilution of the carbon-rich topsoil when the terraces were established. The difference with the restrained grazing declined when the shorter duration time of terracing among the practices investigated was taken into account. The short duration may, however, have been a property of the terracing practice under conditions in East Africa with high erosion rates.

The soil carbon stocks of the traditional agricultural lands were even lower than previously published values in Ethiopia (Sillanpää 1982; Solomon et al. 2002; Lemma et al. 2006; Gelaw et al. 2014). This may have been due to yet worsening ongoing soil degradation or higher precipitation in regions where previous studies used for comparison were conducted, resulting in larger biomass production. The agroecological management practices explored empirically in this study showed even greater carbon sequestration potential than those few proposed earlier (Tschakert 2004; Farage et al. 2007; Smith et al. 2008). However, previous estimates were mainly based on process-modelling studies developed and validated under temperate conditions for different types of farming systems than those represented in East Africa (Andrén et al. 2012). The higher carbon accumulation may also have been the result of greater actual soil degradation rates than have usually been used in process models. Consequently, the new equilibrium for the soil carbon stock of the improved management practice would have been in reality further away from the current soil carbon stock. Due to this high restoration potential, the initial accumulation rate at implementing the agroecological management practices would have been very high.

The distribution of carbon in the soil is influenced by vegetation and climate. According to global estimates by Jobbágy and Jackson (2000), the top 20 cm in shrublands and grasslands comprise on average 33% and 42% of the soil carbon stock, respectively, relative to the first metre. Deeper soil horizons can also sequester notable amounts of carbon as the turnover time and chemical recalcitrance of the SOM increase with depth (Lorenz and Lal 2005). In the 100–200-cm layer, the proportion of soil carbon is 30–40% for shrublands and grasslands and in the 200–300–cm layer 39% for shrublands and 13% for grasslands (Jobbágy and Jackson 2000).

The availability of baseline data on soil carbon stocks and long-term experiments for soil carbon sequestration would increase the reliability of the assessments of the carbon sequestration potential of the agroecological management practices. The plots of the agroecological practices may already have contained more carbon at the time of adopting the improved management practices, and the soil carbon stock in the control plots may already have increased or decreased during the time the agroecological management practice was in use. However, comparison of the matched adjacent plot pairs of the traditional and agroecological practices, the similarity of which was confirmed, and adequate replicates increased the reliability of the results. The high correlation of the soil carbon stocks between the control and agroecological plots (Figure 10) suggests that the pairing worked and the results are reliable.

To assess the sensitivity of the results to the method of quantifying the soil carbon stocks, the results based on the fixed-depth approach were compared with those of the equivalent soil mass approach, which takes into account the possible change in soil ρb as a result of the management practices (Ellert and Bettany 1995). The ρb differences within the matched pairs were small, resulting in small differences between the approaches. In the agroforestry plots, the carbon concentration was 28% higher, in the restrained grazing plots 67% higher and in the terracing plots 24% higher than in the traditionally managed plots, on average. Comparison of the fixed-depth- and soil mass-based calculations confirmed that the results were not overestimated in this study.

4.4 SCALING UP THE BENEFITS OF THE AGROECOLOGICAL PRACTICES FOR FOOD SECURITY AND CLIMATE CHANGE MITIGATION

4.4.1 PREREQUISITES FOR CREATING BENEFITS THROUGH CARBON PAYMENTS

Currently, the lack of rewarding mechanisms for agricultural carbon sequestration prevents smallholders´ gaining financially from realizing the mitigation practices. The lack of methods suitable for verifying soil carbon, high transaction costs and vague land ownership were considered as barriers hindering the scaling up of the carbon sequestration projects. In addition, low and fluctuating prices of carbon, the time lag between investments and reward, and lack of investment support are, in coincidence with our findings, often mentioned as complicating project implementation (Jindall et al. 2008; Bryan et al. 2010). For development of the carbon payment mechanism, practice-based verification was considered more useful than case-by-case verification for achieving effectiveness for climate change mitigation and for making the transaction costs more reasonable.

Equal negotiation basis between the developing and industrialized countries, strong and transparent governance in the host country and creating co-operatives among farmers to achieve volume and strengthen the capacity of the communities were considered as contributing to the enhancement of benefits for rural smallholders. Early payments would also have reduced the need for credits during the project. Urging for a bottom-up approach and increasing the knowledge of climate change mitigation, adaptation and carbon trading among smallholders would contribute to adopting mitigation practices that are feasible under local agroecological conditions, as well as working out practical problems from the premise of local conditions.

4.4.2 INFLUENCE OF THE AGROECOLOGICAL PRACTICES ON MITIGATION, CROP YIELDS AND INCOMES

Adoption of the agroecological practices would theoretically bring about multiple benefits for availability, access, stability and utilization of food and simultaneously offset GHG emissions (Figure 8). Assuming the current carbon stock of agricultural land as 19.7 Mg ha^{-1}, the estimated median of the carbon stock of the traditionally managed cultivated fields (**III**), the 9% carbon sequestration achieved would gain 1.8 Mg C ha^{-1} y^{-1}. When the mitigation potential for the total agricultural area in Ethiopia (36.3 million ha) is scaled up, the carbon sequestration gain becomes 64 Mt C y^{-1}. Such a carbon sequestration would compensate for 1.5 times the total GHG emissions of Ethiopia expressed as the CO_2e.

When applied to previous estimates of the yield increase for cereals (Lal 2010a), a 1.8-Mg C ha^{-1} y^{-1} sequestration could increase crop yields by as much as 500 kg ha^{-1} y^{-1} (Table 3), thus improving the availability of and access to food. Equal carbon sequestration would create incomes from carbon trading totalling 35 € per hectare at a carbon price of 20 € per C tonne and 177 € per hectare at a carbon price of 100 € per C tonne. Such an income would, without a doubt, make a difference for smallholders with mean annual incomes of 260–350 € (Bluffstone et al. 2008). The current all-time lowest carbon price of about 1.4 € per C tonne, the result of too low emission targets, is too low to encourage climate-smart solutions (Carbon Market Watch 2014).

Table 3. Estimated increases for grain yields (kg ha^{-1} y^{-1}) with 1.8-Mg C ha^{-1}y^{-1} soil carbon sequestration (recalculated from Lal 2010a).

	kg ha^{-1} y^{-1}
Wheat	35–71
Maize	354–531
Sorghum	142–248
Millet	53–124
Bean	53–106
Soybean	35–89

4.5 FUTURE RESEARCH INTEREST

While there has been considerable progress in producing arguments and options for synergies of climate change mitigation and food security (e.g. Lal 2004b; Lal et al. 2007; Schmidhuber and Tubiello 2007; Woolf et al. 2010; Shindell et al. 2012), there is a need for research focusing on the prerequisites and incentives that encourage the scaling up of the carbon sequestration practices in the agricultural sector. One of the most acute targets is the development of payment mechanisms for climate change mitigation in agriculture. Further research should also focus on assessing the means to prevent carbon losses at the farm level. Feasible options for energy substitutes for manure and straw, improved manure management and stabilization of the food and fodder supply for closing the carbon cycle in the farming system are important research subjects. Moreover, further research is needed towards novel agricultural practices that would serve carbon sequestration under different agroecological conditions, while at the same time contributing to increased productivity of food.

5 CONCLUSIONS AND RELEVANCE

5.1 SCIENTIFIC CONCLUSIONS

- The most important means perceived to enhance food security through climate change mitigation is improving food availability for food-insecure communities through soil carbon sequestration by agricultural practices.
- Development of the infrastructure of internal food markets is required to enhance access to food at the household, regional and national levels.
- Income from carbon sequestration acts as a financial incentive for smallholders to adopt practices that enhance the synergy of food security and climate change mitigation.
- Income from the increased amount of marketed crops, a result of increased agricultural productivity, is also needed to enhance access to food at the household level.
- Socio-economic determinants, such as policy coherence for promoting mitigation and food security, supporting governance, clear land tenure, early access to financial incentives and knowledge of the carbon market, play the most important roles in the potential of mitigation for enhancing food security.
- The major losses of carbon from farming systems are gaseous, originating mainly from biomass burning for heat energy needs and from livestock metabolism.
- The proportion of carbon used for energy determines the proportion ending up in soil. Energy sources alternative to manure and straw and technologies using low amounts of fuel are needed to increase the use of carbon in soil and to reduce emissions.
- MFA is a useful tool for tracking the flows and losses of harvested and imported carbon when measurement of gaseous carbon losses is not feasible. Such assessments guide us towards the sustainable use of carbon.
- There is a greater potential than previously estimated for soil carbon sequestration in Ethiopian agriculture.
- The adjacent plot in traditional farming represents a useful control for assessing the sequestering potential of novel agricultural practices.
- The size of the soil carbon stock in the traditionally managed control plot defines the difference in soil carbon stocks between the agroecological practices and their controls.
- The higher potential for soil carbon sequestration of the agricultural practices estimated in this study by empirical methods, compared with previously published results, is most likely explained by the

development and validation of the process models used under temperate conditions for monocropping systems that are not representative in East-Africa, and for conditions under which the soil carbon stock is closer to the new equilibrium than in Ethiopia. Climate conditions, intercropping treatment and assessment of the distance of the soil carbon stock to the new equilibrium should be incorporated into process models to improve their adequacy for farming systems in East Africa.

- Assuming there are agroecological practices that, while maintaining or increasing food production, turn agricultural soils into carbon sinks, these would provide the technological potential to compensate for the current total anthropogenic GHG emissions in Ethiopia.

5.2 POLICY RELEVANCE

- The high potential of climate change mitigation with food security synergies in SSA agriculture offers new opportunities for global climate policy.
- Addressing key issues for mitigation impacts, alternative energy sources for manure and straw, technologies using low amounts of fuel and productivity of cattle in nationally appropriate mitigation actions (NAMAs) would be needed for increased carbon accumulation.
- Selective carbon accounting that recognizes the agroecological conditions, practice-based verification and soil degradation rate enable the accuracy needed for verifying the quantity of soil carbon.
- Smallholder carbon trading for global climate equity requires equal negotiation positions between the developing and industrialized countries.

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