Compost and Fertilizer - Alternatives or Complementary?

Management Feasibility and Long-Term Effects on Soil Fertility in an Ethiopian Village

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Abstract

Decline in soil fertility due to nutrient depletion is a concern for low-input crop production in the highlands of Ethiopia. Fertilizer addition is insufficient due to infrastructural and socioeconomic constraints. Effects of compost addition, alone or in combination with NP fertilizer, on crop productivity and soil fertility were studied in long-term on-farm experiments in Beseku, Ethiopia. The combined treatment resulted in an added benefit (synergy), i.e., a higher yield than when compost or fertilizer was added alone. The highest yield increase was found for maize where the combined treatment had 78% and 26% higher yields compared to the control and fertilizer treatment, respectively.

Plant available concentrations of B, P, S, and Zn increased in the compost and/or the combined treatment compared to the control. Soil organic carbon and total nitrogen stocks increased in the combined treatment compared with the fertilizer treatment. Substrate-induced respiration from the combined treatment was lower compared to the compost treatment, but catabolic versatility was higher in the combined treatment compared with the compost and the control. This suggests that a combination of compost and fertilizer induces a wider microbial catabolic capability which might lead to higher nutrient mobilization. The apparent yield synergy in the combined treatment likely attributed to; (1) alleviation of micro- and macronutrient limitations allowing for a more efficient use of fertilizer N and P and/or (2) improvement of the soil microbial catabolic capability. However, the indirect effects of compost on soil physical properties leading to improved nutrient use efficiency are also a possible explanation.

The plot level N balance was strongly negative for the fertilizer treatment and the control, whereas it was close to steady-state in the combined and compost treatments. All treatments except the control had positive P balances. Therefore, the addition of compost, alone or in combination with fertilizer, improves the nutrient status of the soil and serves as a complement to fertilizer use reducing the dependence on mineral fertilizer in low-input crop production systems.

The major factor limiting the adoption of compost by farmers was lack of knowledge. Practical and theoretical training had a positive effect on adoption.

Keywords: Compost; Fertilizer; Soil fertility; Nutrient balance; Smallholder; Substrate-induced respiration; MicroResp™; Compost adoption; Ethiopia.

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Dedication

This is for you, mama (Alem)!

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Bedada, W., E. Karltun, M. Lemenih, and M. Tolera (2014). Long-term addition of compost and NP fertilizer increases crop yield and improves soil quality in experiments on smallholder farms. *Agriculture, Ecosystems and Environment* 195, 193–201.

II Bedada, W., M. Lemenih, and E. Karltun (201X). Soil nutrient build-up, input interaction effects and plot level N and P balances under long-term addition of compost and NP fertilizer. Accepted for publication in *Agriculture, Ecosystems and Environment*.

III Bedada, W., S. Dahlin, C. Campbell, and E. Karltun (201X). Long-term addition of compost and NP fertilizer affects soil microbial activity and catabolic diversity (manuscript).

IV Bedada, W., L. Chiwona-Karltun, and E. Karltun (201X). Household characteristics affect compost adoption in an Ethiopian village (manuscript).

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The contribution of Workneh Bedada to the papers included in this thesis was as follows:

I Compiled and analyzed data previously collected from the experiments. Monitored and sampled the experiments for two seasons. Performed data analysis, interpretation of the results, writing of the manuscript, with assistance from the co-authors.

II Compiled and analyzed data previously collected from the experiments. Monitored and sampled the experiments for two seasons. Performed data analysis, interpretation of the results, writing of the manuscript, with assistance from the co-authors.

III Planned the soil sampling and laboratory experiments, together with second and fourth co-authors. Performed the field and laboratory experiments, data analysis, interpretation of the results, writing of the manuscript, with assistance from the co-authors.

IV Planned the field work, together with second and third co-authors. Performed the field work, data analysis, interpretation of the results, writing of the manuscript, with assistance from the co-authors.

Abbreviations

AB	added benefits in terms of extra yield or improved soil fertility due to combined addition of organic and inorganic inputs compared with the sum of the response with sole application of each input
AE-N	agronomic use efficiency of fertilizer N expressed as change in yield to applied N
BR	basal respiration
C	full dose of compost applied alone at 2.4 t ha^{-1} dry weight organic matter
CF	half dose of C and half of dose F combined
CLPPs	community level physiological profiles
CSA	Central Statistics Authority of Ethiopia
Ctrl	unfertilized control
CV	catabolic versatility
F	full dose of NP fertilizer as di-ammonium phosphate and urea fertilizers
FB	full nutrient balance
ISFM	Integrated Soil Fertility Management
SIR	substrate induced respiration
SSA	sub-Saharan Africa
SSI	Swedish Standard Institute

1 Introduction

1.1 Background

Ethiopia is an agrarian country that depends on agricultural production for the growth of the national economy. The agricultural sector accounts for nearly 46% of gross domestic product (GDP) and close to 80% of export earnings and 73% of total employment (ATA, 2013). The sector is mainly operated by smallholder farmers that directly rely on agriculture for their food supply and cash income. While the country's future development and self-sufficiency in food production is relying on enhanced agricultural production, the agricultural production system is still mainly rain-fed and has a low degree of mechanization. Increased productivity in the agricultural sector has been constrained by high population pressure, deforestation and resource base degradation, soil erosion and soil fertility depletion (Lemenih *et al.*, 2005a; Feoli *et al.*, 2002; Taddese, 2001; Shiferaw & Holden, 1999; Hurni, 1988). In order to accomplish the necessary agricultural intensification, the current land management practices need to be changed.

In the past, the decline in soil fertility was partly compensated by increasing arable land at the expense of forests, bush and grazing land or by putting cropland under fallow. However, in highly populated areas (e.g., the highlands), this alternative is no longer a possible alternative since land suitable for conversion to cropland is becoming scarce (Headey *et al.*, 2014; Josephson *et al.*, 2014; Lemenih *et al.*, 2008; Lemenih *et al.*, 2005b; Drechsel *et al.*, 2001a). Long fallow periods are no longer an alternative due to small and continuously decreasing farm sizes associated with population growth (Abegaz & van Keulen, 2009; Shiferaw & Holden, 1999). Smallholder farmers nowadays tend to continuously cultivate their cropland (Lemenih *et al.*, 2005a), and the soils no longer have time to recuperate fertility. This in turn leads to nutrient depletion (Abegaz & van Keulen, 2007; Haileslassie *et al.*, 2005). Fragmentation and scarcity of cultivable land continue to increase and remain a constraint in the highlands.

A more sustainable management of the soil resource can be achieved through improved agricultural management such as crop rotation with N-fixing legumes, addition and recycling of nutrients and erosion control. Direct addition of nutrients can be done through mineral fertilizer or organic inputs such as manure and compost, or through combination of both nutrient sources. In Ethiopia, mineral fertilizer is the main yield-augmenting off-farm input. However, due to economic, infrastructure and policy related constraints (IFPRI, 2010; Spielman *et al.*, 2010), the current level of fertilizer input, which is 16 kg ha^{-1} on average (Spielman *et al.*, 2010), is much lower than required to maintain soil fertility and ensure acceptable yield levels (Abegaz & van Keulen, 2007). Although organic inputs, such as farmyard manure and crop residues, are potential sources of plant nutrients and have beneficial effects on soil fertility, there is competition from alternative uses of these resources; both manure and crop residues are used for fuel and crop residues are also used as animal feed and for construction (Abegaz & van Keulen, 2009; Haileslassie *et al.*, 2005).

Compost is another alternative source of plant nutrients (Ngwira *et al.*, 2013; Odlare *et al.*, 2011; Vanlauwe *et al.*, 2011). Composting is a microbial (biological oxidation) process through which fresh organic matter is transformed into a stable product (de Bertoldi *et al.*, 1983). The transformation process results in mineralization and partial humification of the organic material. The metabolic activity and exothermic processes during the composting increases the temperature in the composting mass which creates a strong selective pressure in favor of thermophilic organisms. Various maturity indicators for composts have been suggested (Gómez-Brandón *et al.*, 2008; Said-Pullicino *et al.*, 2007; Goyal *et al.*, 2005). Though there is no single parameter that completely defines maturity, the C:N ratio and reduced rate of CO_2 evolution from mature compost can be used as reliable indicators. Composting results in a reduction of the volume of organic material, destruction of weed seeds and sanitation through reduction of harmful pathogens. However, the process can also result in loss of N through ammonia volatilization (Goyal *et al.*, 2005). Amendment of soil with compost improves the biophysical and chemical properties of soils. Increases in soil organic matter (SOM), enhanced soil fauna and increased microbial biomass have been documented as a result of compost addition (Erhart & Hartl, 2010).

However, for resource constrained small-holder farmers organic resources, such as manure or compost, may not be available in sufficient quantities to reach optimum application rates and hence, may not supply sufficient nutrient amounts (Vanlauwe *et al.*, 2011). When mineral and organic resources are limited, combined use of smaller amounts of mineral and organic nutrient resources is an alternative option for restoring soil fertility since it is a more affordable investment in a low-input farming system (Vanlauwe *et al.*, 2010). The mineral fertilizers available to most Ethiopian farmers, di-ammonium phosphate (DAP) and urea only supply nitrogen (N) and phosphorus (P), whereas organic inputs replenish SOM fractions that contain different soil micro- and macronutrients. SOM is also known to improve soil structure and water holding capacity. Combined use of these often scarce resources has the potential of replenishing soil fertility, maintaining SOM and thereby enhancing productivity (Vanlauwe *et al.*, 2011).

1.2 Plant nutrient depletion in the highlands of Ethiopia: an overview

The Ethiopian highlands are endowed with inherently good biophysical conditions for agriculture production, and the majority of humans and livestock are found there (Amsalu *et al.*, 2007; Shiferaw & Holden, 1999). However, there is an increased pressure on the land from growing human and livestock populations. Consequently, agricultural land expansion has been and is widespread leading to deforestation (Kindu *et al.*, 2013) and cultivation of marginal soils that are less suitable for agriculture (Drechsel *et al.*, 2001a; Drechsel *et al.*, 2001b). Land use systems are not sustainable and problems with erosion and plant nutrient depletion are common (Amsalu *et al.*, 2007). Furthermore, cropping intensities are high in the highlands resulting in a substantial nutrient removal due to high population growth driven continuous cultivation of the same land without fallow periods (Lemenih *et al.*, 2005a; Drechsel *et al.*, 2001a).

However, in order to attain food self-sufficiency and achieve the desired long-term economic growth, the decline in soil fertility need to be halted and land use intensification need to be accompanied by sufficient external nutrient inputs to compensate for the nutrient removal through harvested products and losses (Bekunda *et al.*, 2010; Mugwe *et al.*, 2009). It is believed that integrated soil fertility management can improve African food security (Breman & Debrah, 2003), and that Ethiopia is no exception. Across the region of the sub-Saharan Africa (SSA), combined use of organic resource with mineral fertilizer has been recognized as a means to counterbalance the soil fertility problems (Palm *et al.*, 1997). For the smallholder farmer, the investment in mineral fertilizers constitutes the major annual cash investment. Due to low cash flow and limited availability of credit the recommended fertilizer application rates are not within the reach of most resource poor farmers. Since the required rates of application for organic inputs to compensate for this would be very high, the combined application of these inputs can be a sound strategy for the smallholder farmers (Vanlauwe *et al.*, 2011; Gentile *et al.*, 2008).

1.3 Integrated plant nutrient management and soil nutrient budgets

Following the abolition of fertilizer subsidies in SSA (Stoorvogel *et al.*, 1993), increased use of organic resources (e.g., alley cropping, live-mulch systems) became an area of interest to sustain agricultural production. Nevertheless, constraints such as insufficient availability of organic resources and labor intensive technologies have limited the potential of such low input sustainable agriculture methods to increase the agricultural production in SSA (Vanlauwe *et al.*, 2001b). The integrated soil fertility management (ISFM) concept has evolved through these experiences, advocating the use of both organic and mineral input because: (i) the two resources fulfill different functions to maintain plant growth, (ii) under most small-scale farming conditions, neither of the two inputs is available or affordable in sufficient quantities to be applied alone, and (iii) synergies can be achieved when applying both inputs in combination (Gentile *et al.*, 2008; Palm *et al.*, 1997).

Integrated soil fertility management (Figure 1) was defined by Vanlauwe *et al.* (2010) as:

> A set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions, aiming at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity. All inputs need to be managed following sound agronomic principles.

That is, ISFM recognizes the combined use of available and locally relevant technologies aiming at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity. In a meta-analysis based on literature data aiming to quantify the impact of ISFM component on agronomic efficiency of nitrogen fertilizer, Vanlauwe *et al*. (2011) found that mixing fertilizer with manure or compost resulted in the highest agronomic efficiency of the nitrogen fertilizer, and this effect was higher at low N input rates.

As documented in several case studies, combined use of organic and mineral fertilizer has resulted in a higher crop yield and improved soil quality attributes (Chivenge *et al.*, 2011; Vanlauwe *et al.*, 2011; Chivenge *et al.*, 2009; Gentile *et al.*, 2009; Gentile *et al.*, 2008; Palm *et al.*, 1997). The terms *interac-*

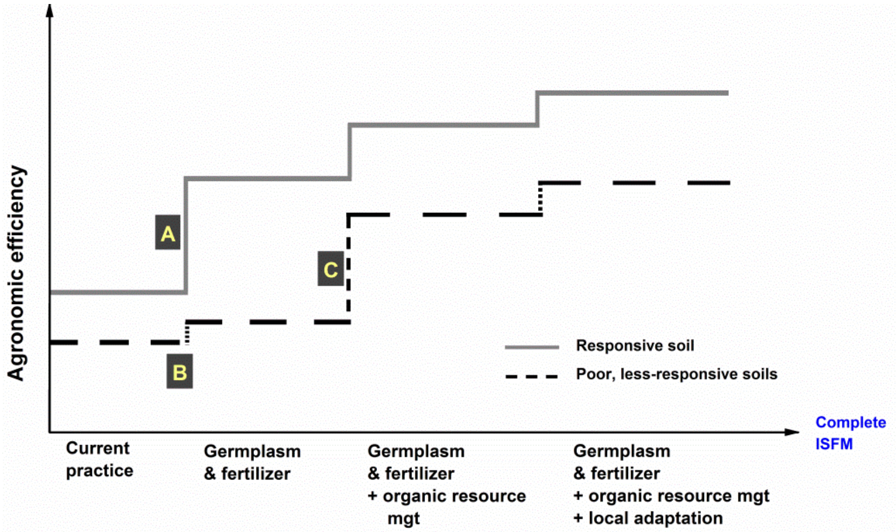

Figure 1. Conceptual relationships between agronomic efficiency of fertilizer N and implementation of various components of ISFM towards complete ISFM. Soils that are responsive to fertilizer and those that are poor and less-responsive are distinguished. The 'current practice' step assumes the use of the current average fertilizer application rate in SSA of 8 kg fertilizer nutrients ha^{-1}. Paths A and B refer to soils that show acceptable response to management (*'responsive soil'*) and soils that show minimal or no response (*'poor, less-responsive soil'*) due to other constraints beside the nutrient contained in the fertilizer, respectively. Path C refers to the effect of rehabilitation of less responsive soil by addition of an organic matter resource. Redrawn from Vanlauwe *et al.* (2010).

tion and *added benefit* (Chivenge *et al.*, 2009; Gentile *et al.*, 2009; Vanlauwe *et al.*, 2001a; Palm *et al.*, 1997) have been used to describe the synergistic effect of combined use of organic and inorganic inputs compared with inorganic input alone. *Interaction* appears to be a commonly used term for this in literature (e.g., see Gentile *et al.*, 2008; Chivenge *et al.*, 2009; Gentile *et al.*, 2009), although *added benefit* is suggested as a better phrase (Palm *et al.*, 1997). In this thesis, it has also sometimes been referred to as *synergy*.

Added benefit (AB) can be quantitatively defined as:

$$AB = (Y_{OF} - Y_{ctrl}) - (Y'_O + Y'_F) \qquad [1]$$

where Y_{OF} is the response of the combined organic and mineral fertilizer treatment and Y_{ctrl} is the response of a unfertilized control treatment. Y'_O is the response increase of the organic treatment and Y'_F is the response increase of the mineral fertilizer addition. Y'_O and Y'_F are calculated as:

$$Y'_O = f_O\,(Y_O - Y_{ctrl}) \qquad [2]$$

$$Y'_F = f_F\,(Y_F - Y_{ctrl}) \qquad [3]$$

where Y_O is the response obtained from the an organic treatment alone and Y_F is the response obtained from an inorganic fertilizer treatment alone. The response differences in eq. [2] and [3] are multiplied with the fraction of the organic (f_O) and fertilizer (f_F) that are used in the combined treatment compared to the single organic (Y_O) and fertilizer treatments (Y_F).

Added benefits in terms of extra yield or improved soil fertility resulting from combined use of organic and inorganic inputs have been compared with the sum of the responses from either of the input added alone and possible hypotheses have been suggested. Vanlauwe *et al*. (2001a) proposed two hypotheses: the direct and indirect mechanisms as outlined in Figure 2. In the direct mechanism, temporary immobilization of mineral fertilizer N suggested to improve uptake of organic input derived N through N limited decomposition of low- or medium quality organic residues. The immobilized N is subsequently mineralized at a later time improving the synchrony between N availability and crop need. The findings by Gentile *et al*. (2008) and Gentile *et al*. (2009) corroborate this view point.

Residue quality is important for the observed added benefits as available mineral N (Gentile *et al*., 2008) and crop harvest increase (Gentile *et al*., 2009). Combining mineral fertilizer with low quality maize (*Zea mays* L.) residue (C:N ratio of 31) reduced N loss and resulted in a positive interaction

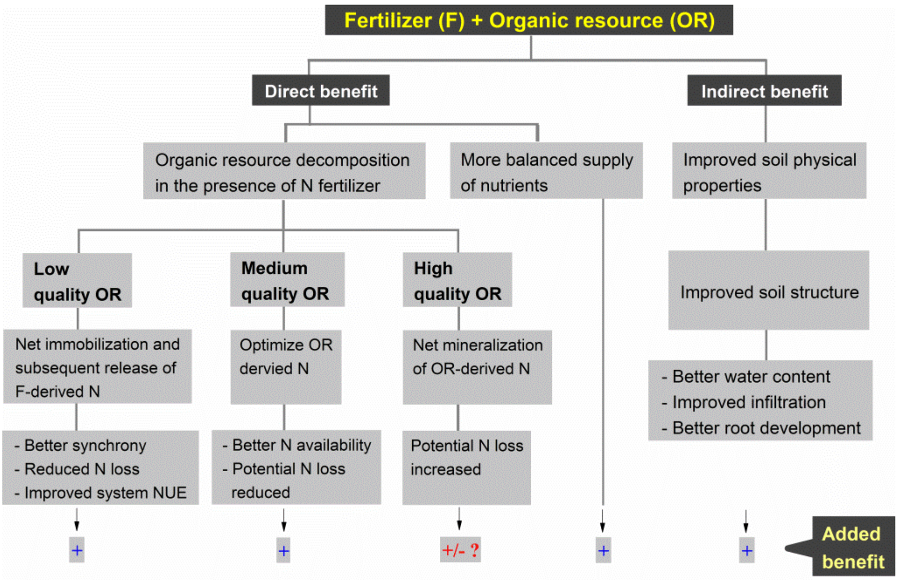

Figure 2. Schematic representation of added benefit due to combined use of organic and inorganic fertilizes.

effect. In contrast, addition of high quality tithonia [*Tithonia diversifolia* (Hemsl.)] residue (C:N ratio of 12) led to a net N mineralization that resulted in early season N loss and a negative added benefit. When low quality residue was combined with mineral fertilizer, a net immobilization and subsequent release of fertilizer-N thus resulted in a better synchrony between nutrient availability and crop demand by reducing early season available N. However, application of high quality tithonia together with mineral fertilizer eliminated the period of net immobilization by providing the N needed for decomposers. The incorporation of medium quality residue, e.g., calliandra [*Calliandra calothyrsus* (Meisn)]; with a C:N ratio of 14, together with fertilizer had the potential to optimize residue-derived N release without increasing potential N losses (Gentile *et al.*, 2008). Another direct mechanism that may explain the existence of the added benefit is that the organic resource contains a range of macro and micro plant nutrients that are not found in the NP fertilizer. Thus, the combined organic and mineral fertilizer input enhances crop harvest through alleviation of multiple nutrient limitations and may improve the nutrient recovery, as discussed in Palm *et al.* (1997) and references therein. Nutrients other than N and P that have been found to be limiting in many African soils include zinc (Zn), sulfur (S) and boron (B) (Wendt & Rijpma, 1997).

Soil microbes play a substantial role in the direct benefit since they respond to alteration of soils such as addition of organic inputs (Ritz *et al.*, 2009; Stockdale & Brookes, 2006; Wardle *et al.*, 1999). They mediate several soil ecological processes that are a part of nutrient cycling, organic matter degradation and plant root-microbes interactions. By using methods that looks at the response of the microbial community to soil management, it is possible to obtain indications on the importance of the microbes for different soil processes for an improved understanding of the interaction between fertilizer and organic matter addition. Methods that have been employed to assess changes in the soil microbial composition and functions under different soil environments, habitats or agricultural management practices are categorized into molecular profiling (Schwieger & Tebbe, 1998; Liu *et al.*, 1997), phenotypic/biochemical profiling (Bossio *et al.*, 1998; Frostegård *et al.*, 1993), and physiological profiling (Campbell *et al.*, 2003; Degens & Harris, 1997; Garland & Mills, 1991) approaches. Potentials and limitations of these methods are discussed in Paper III.

The indirect mechanism is explained by enhanced efficiency in the utilization of fertilizer N (agronomic efficiency of N, AE-N) through organic input addition-related improvement in soil physical properties such as improvement in soil structure, infiltration and water holding capacity, and a better crop root development, which may result in higher demand by the plant for the fertilizer nutrient.

1.4 Participatory approach

Farmers often have a good understanding of the decline in soil fertility and the drivers behind it. They respond to changes based on their accumulated indigenous knowledge and their experience but may not be in a position to adequately address the problem due to limited access to resources. It is also possible that their understanding of the problems have dimensions that are overlooked and difficult to observe by available scientific methods (Gray & Morant, 2003). In participatory research, scientists, farmers and other stakeholders get involved in a common process including problem identification, prioritization and implementation of interventions and subsequently, evaluation of outcomes. In participatory research, the farmer is not limited to being an object for research, but participates as a subject in the research process.

2 Aims of the study

Compost addition had been chosen through a participatory process by the farmers in the study area as an intervention of interest to mitigate declining soil fertility. It was hypothesized that the addition of on-farm made compost in realistic (i.e., raw material availability, workload) amounts can serve as a quantitatively important complement to fertilizer addition in crop production systems in the highlands of Ethiopia. Based on literature information, it was also hypothesized (i) that the simultaneous addition of mineral N and organic matter leads to improved N use efficiency and (ii) that compost addition alleviates nutrient limitations other than for N and P. Finally, it was hypothesized that farm household resource availability affects the decision to adopt compost as part of the farming system.

The overall aim of this research was to test the effects of compost addition on crop productivity, soil properties and function, agronomic N use efficiency and feasibility of adoption.

The specific aims were:

- to compare the effects of separate and combined addition of compost and NP fertilizer on the productivity of crops, build-up of soil organic carbon and plant available micro- and macronutrients in on-farm experiments (Paper I & II).
- to assess and quantify the added benefits (synergy) in terms of grain/tuber harvests and the agronomic N use efficiency under combined use of compost and NP fertilizer (Paper II).
- to examine differences in plot level N and P balances with respect to compost and NP fertilizer added alone or in combination (Paper II).
- to test if compost and NP fertilizer added alone or in combination affected the composition of the soil microbial communities and their capacity to utilize different C sources (Paper III).

- to evaluate if access to information and household resources affected the decision to adopt compost and to evaluate the practical feasibility of producing and using compost (Paper IV).

3 The study area

Research in the Munessa area, where this study has been done, started over a decade ago with the aim to assess the effects of deforestation and subsequent changes in the land-use on soil fertility and biodiversity (Figure 3). The research includes chronosequence and land-use comparison studies which described the decline in soil fertility over time as a result of deforestation and subsequent conversion to and utilization as cropland [e.g., Lemenih & Itanna (2004); Lemenih *et al*., (2005a); Tolera *et al.*, (2008)], participatory problem assessment and intervention identification together with the local farmers [e.g., Karltun *et al*., 2013a; Lemenih *et al.*, (2011); Karltun *et al.*, (2008)], and studies regarding the decline and gradual elimination of legumes from the cropping system due to theft (Chiwona-Karltun *et al.*, 2009) and the re-introduction of

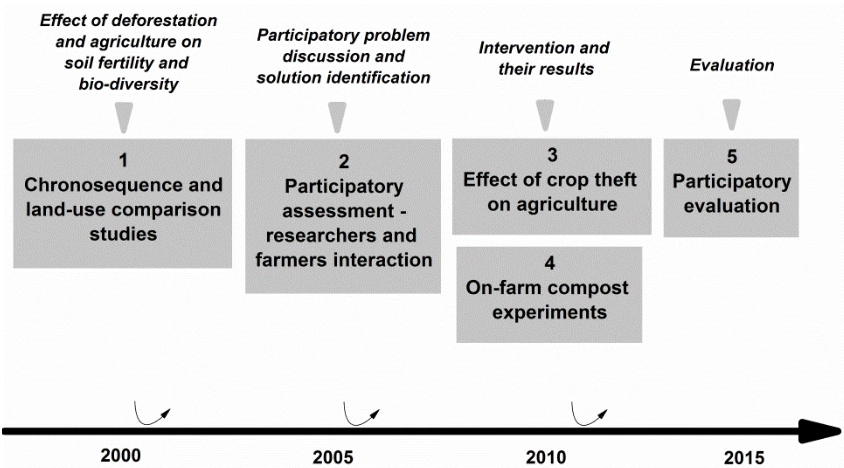

Figure 3. The Beseku studies since 2000; **1**: Lemenih *et al.*, 2008; Tolera *et al.*, 2008; Lemenih *et al.*, 2005a; Lemenih *et al.*, 2005b; Lemenih *et al.*, 2004; **2**: Karltun *et al.*, 2013a; Lemenih *et al.*, 2011; Karltun *et al.*, 2008; **3**: Karltun *et al.*, 2013b; Chiwona-Karltun *et al.*, 2009; **4**: (Bedada *et al.*, 2014; Bedada *et al.* Paper II & III; **5**: Karltun *et al.*, 2013b; Bedada *et al.* Paper IV.

faba bean cultivation through farmer-led participation (Karltun *et al.*, 2013b). The present studies of on-farm compost experiments and evaluation (Papers I, II, III and IV) are an integrated part of the studies on factors and processes that affect soil fertility in the Munessa area.

The field study was conducted in Beseku in Arsi Negele district of the central highlands of Ethiopia. The village is situated at the border of Munessa natural forest, in the eastern escarpment of the Central Rift Valley, between 7°20′ and 7°25′ N and 38°45′ and 38°50′ E at an altitude of about 2100 meters above sea level (Figure 4). The area has a bimodal rainfall distribution, with a short rainy season between March and early June and the main rainy season between late July and the beginning of October (Lemenih *et al.*, 2005b). The mean annual rainfall in the area is 932 mm, with an annual mean minimum temperature of 9.4°C and maximum temperature of 22.7°C (Figure 1 of Paper I). The lowest minimum daily temperature is 5.5°C (December), with the highest maximum daily temperatures of 25.4°C in March. The soils in the experimental area are originating from volcanic lava and ashes through quaternary volcanic activities in the Rift Valley and its surroundings. They are classified as Humic Andosols with a loam texture, a CEC ranging between 25 and 32 $cmol_c\ kg^{-1}$, and a base saturation ranging between 48 and 68% (Lemenih *et al.*, 2005a).

The farming system in the area is a mixed crop-livestock production system (Lemenih *et al.*, 2005a). The two major cultivated crops are maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.), 43% and 33% of crop land area, respectively. Sorghum (*Sorghum bicolor* L. Moench) and barley (*Hordeum vulgare* L.) are also cultivated but with less areal coverage, 11% and 10% of crop land area, respectively. Between May and August, farmers may cultivate potato (*Solanum tuberosum* L.) as a food security crop to provide staple food between August and November until other crops (mainly maize and wheat) are harvested (Karltun *et al.*, 2013a). Late maturing varieties of maize are planted in late April/early May during the short rainy period: harvesting is during late November to early December. Wheat is planted in August and harvested four months later in November. Livestock, predominately cattle, have an important role in the farming system, as they support crop production by providing draught and threshing power and manure as an input to restore soil fertility (Lemenih *et al.*, 2005a). Manure is often applied to the fields close to the homestead, but is also used as dung cakes for fuel (Karltun *et al.*, 2013a). The more distant farm fields receive less or no manure. Crop residues are either fed to livestock or used as fuel source. The residues that are left on the croplands are sometimes also burnt to ease land preparation (Lemenih *et al.*, 2005b).

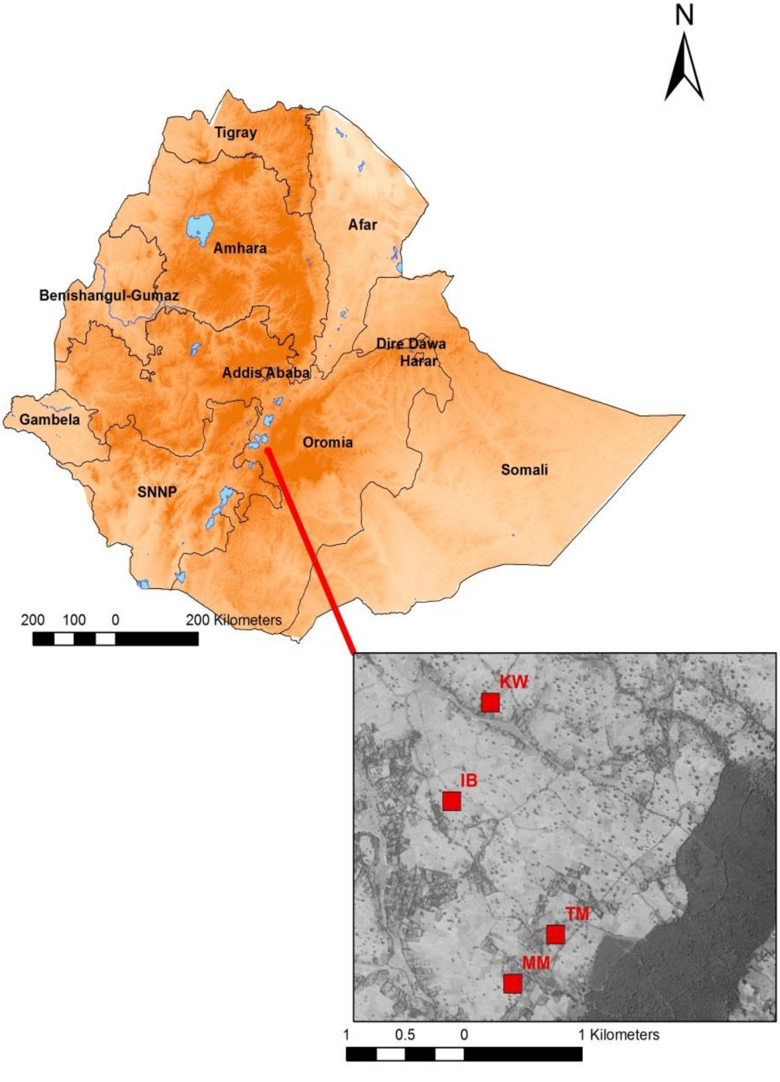

Figure 4. Location of the study area and the sites of on-farm experiments in Beseku, Ethiopia. The inset picture is extracted from Google™ earth, imagery date 22nd of December 2013.

4 Effects of compost added alone or in combination with NP fertilizer on crop productivity and soil nutrient buildup (*Paper I and part of Paper II*)

4.1 Background

The Munessa natural forest, which is found adjacent to the present study site, have for over 70 years been subjected to deforestation and large forest areas have been converted to cropland and grassland through this process (Lemenih *et al.*, 2005b). The soils are Mollic Andosols (WRB, 2014i; Lemenih *et al.*, 2005a) and have good potentials to be high yielding agricultural soils. As documented in the earlier research reports (Karltun *et al.*, 2013a; Lemenih *et al.*, 2005a; Lemenih *et al.*, 2005b), farmers have cultivated the deforested areas with little or no external nutrient inputs and this has consequently resulted in depletion of soil quality attributes and reduction in agricultural productivity. A previous study showed that almost all soil quality parameters considered are declining over time (Lemenih *et al.*, 2005a). Isotope studies using the natural abundance of ^{13}C and ^{15}N indicated that after deforestation there was an intensive mineralization of organic matter resulting in mineralization of large quantities of N. When the mineralization of SOM declined after 15-25 years, so did the release of N. As a result, N became limiting for crop growth and addition of fertilizer became necessary to sustain the crop production (Lemenih *et al.*, 2005b).

Recognizing this problem, a participatory research project aimed to develop strategies to cope with the declining soil fertility was initiated (Karltun *et al.*, 2013a). The target was to identify, implement and evaluate locally acceptable integrated soil nutrient management options to cope with the declining soil fertility. As outputs of these processes, the farmers brought up the idea of trying compost making and addition. Therefore, on-farm experiments with compost addition alone or in combination with mineral fertilizer were initiated (Figure 3) and implemented on four farms with the aim of using locally available composting materials. Since the prices for mineral fertilizers continue to increase, resource-poor farmers may not afford to purchase the desired amount for an optimal application or could afford to purchase considerably less compared with resource rich farmers (Haileslassie *et al.*, 2007; Elias & Scoones, 1999). From the local farmers' perspective, it was perceived that the compost could have a high significance as a potential replacement of fertilizer.

4.2 Aims

In order to address the key issue of continuous nutrient removal and depletion of soil quality attributes and consequently reduction in crop production in the low-input agricultural systems in Beseku, four on-farm experiments were conducted with the aims (i) to compare crop productivity and soil organic matter buildup in soils receiving mineral fertilizers (NP) and compost, either alone or in combination (Paper I); (ii) to test if long-term addition of compost and NP fertilizer, alone or in combination, results in differences in available soil nutrient status (parts of Paper II). The effects were assessed through measuring crop harvests and soil nutrient status based on measured data complemented with data from literature.

4.3 Materials and methods

A randomized complete block design with four treatments and three blocks was used for the experiments at all sites. The treatments (Table 1 of Paper I) were: (1) a full dose of compost (C) applied alone at 27 t ha^{-1} on fresh weight (FW) basis or a dose equivalent to 2.4 t ha^{-1} organic matter on dry weight basis; (2) a full dose of fertilizer (F), i.e., at a dose equivalent to 100 kg di-ammonium phosphate (DAP) ha^{-1} + 50 kg urea ha^{-1}; (3) half compost and half fertilizer (CF) at a dose equivalent to of 13.5 t ha^{-1} compost FW or 1.2 t ha^{-1} organic matter + 50 kg DAP ha^{-1} + 25 kg urea ha^{-1}; and, (4) a control with no input (Ctrl). Each treatment plot was 6 x 6 m with no spacing between plots and blocks. This was in accordance with the farmers' interest of not leaving any unused space on their farm fields.

The Beseku village is divided into four different sub-villages or '*gotes*'. In order for the experiments to be geographically distributed over the village and capture variations in soil status and farmer management, the experiment was replicated on one field for each of the four households. We selected one farmer from each *gote* based on willingness to participate and after assessment of the capacity to carry out the experiments. The assessment primarily considered the dedication of the farmer and did not consider wealth status, or specific farm and field properties. The selection of farmers was not entirely random and contained a systematic element, but the farm field assigned for the experiment was selected by the respective farmer with no external influence. The farmers participated in the on-farm research are referred to as IB, KW, MM, and TM in the thesis. On three farms, the treatment application and the recording of harvest and soil nutrient status was maintained throughout the experimental period (2007 to 2012). However, the fourth farmer (MM) dropped out after two years due to illness.

Di-ammonium phosphate was applied at sowing and urea was top dressed 40 to 45 days after sowing. The quantity of compost addition was determined in such a way that a full compost dose represented an N addition similar to mineral fertilizer addition; it was assumed 35% of the N in the compost would mineralize and become plant available during the crop-growing period. The participating farmers prepared their own compost in a pit dug under the shade of trees or bushes from organic materials that are accessible to the farm owners, but application on the plots was seasonal and was handled jointly by the researchers and farmers each year.

The rate of compost application was kept constant throughout the experimental period. The origin and composition of the composts (Table 1) were not standardized; instead, the compost reflected the organic resources available to each household. Each year, the farmers decided which crop they would grow on the experimental sites, and were provided with the appropriate varieties and amount of seeds needed for every season. The crops grown by the farmers are presented in Table 2 of Paper I. Maize was the most favored crop and was grown in five out of six years during the experimental period.

Table 1. *Average nutrient contents of the on-farm made compost sampled and analyzed in 2007 and 2012.*

Farm	**pH**[a]	**OC**	**Tot-N**	**C:N**	**Tot-P**	**P**	**S**	**B**	**Cu**	**Fe**	**Mn**	**Zn**
		%			g kg^{-1}	*Mehlich-3 extractable in mg kg^{-1}*						
IB	7.40	10.7	1.05	10.3	2.1	593	235	4.25	2.32	204	290	33.0
KW	8.39	10.9	1.03	10.8	3.0	843	442	5.96	2.29	146	372	35.6
TM	8.60	10.5	0.91	11.6	2.9	1000	523	6.77	1.62	152	321	30.6
Reference soil[b]												
10-yr	6.38	4.46	0.36	12.4		16.4	38.7	0.49	2.58	196	300	14.8

[a] pH (H_2O) determined on 1:2.5 soil to suspension ratio.
[b] Reference soil denotes soil from farm field cultivated for 10-years (10-yr).

Farmers preferred to grow late maturing maize varieties, therefore, sowing was done during the short rainy season (April) and the crop remained on the field through the main rainy season: harvesting was in late November to early December. However, potato and wheat were grown sequentially over one cropping season. The potato was planted during the short rainy period of the season (April-May) and wheat was sown after potato harvest at the start of the main rainy period of the season (August). Faba bean (*Vicia faba* L.) and wheat were grown on two fields during the course of the study and potato was grown on one field during the second and fifth years of the experiment (Table 2 of Paper I).

Four compost subsamples were randomly drawn from the mature compost pile of each site prior to field application. The samples were analyzed for organic carbon (OC), total N, nitric acid extractable P according to Swedish Standard (SSI, 1997) and Mehlich 3 extractable P, S and the micronutrients B, Zn, copper (Cu), iron (Fe), and manganese (Mn). Organic C and total N were analyzed by dry combustion on a LECO® CHN elemental analyzer. Micro- and macronutrients were extracted with the Mehlich-3 procedure (Mehlich, 1984), and analyzed with an ICP-OES (Perkin-Elmer Optima DV 5300). Compost pH was determined in a 1:2.5 compost to water suspension ratio. The mean nutrient contents of compost samples from each site are presented in Table 1.

Background soils had a pH-H_2O of 6.6, a soil OC content of 4.2%, a total N (Kjeldahl method) content of 3.9 g kg^{-1}, and a P-Olsen content of 15 mg kg^{-1} at the start of the field experiments in 2007. During the 2012 cropping season, another set of soil samples were collected from each experimental plot at all sites immediately after crop harvest for nutrient analysis. In this sample collection, two pits were dug near the center of each plot and soil samples were collected carefully and uniformly along each soil depth interval (0 to 10 cm and 10 to 20 cm) with a hand trowel. The samples were extracted with the Mehlich-3 procedure (Mehlich, 1984) and analyzed for P, S, K, magnesium (Mg), calcium (Ca), sodium (Na), B, Cu, Fe, Mn and Zn with ICP-OES. Organic C and total N were analyzed by dry combustion on an LECO CHN elemental analyzer. In the same season, another set of soil samples were collected at 0-10 and 10-20 cm soil depths with core sampler for bulk density determination. The soil carbon content for each depth was converted into stock (g m^{-2}) as: $C = z\rho c$, where C represents the carbon stock in g m^{-2}, z is the thickness of the sampled layer (m), ρ the bulk density in kg m^{-3}, and c the carbon concentration in g kg^{-1}. Total N (g N m^{-2}) stock was calculated with the same equation. However, the computed C and total N stocks were finally expressed in t ha^{-1} for ease of data presentation.

4.4 Results and discussion

4.4.1 Effects on harvests of different crops

Treatment effects on crop harvests were significant ($P < 0.05$) for all crops grown across the sites and seasons. For maize, the highest yields were obtained from the combined treatment across seasons and sites compared to the full dose of compost or the fertilizer alone treatment (Figure 5). The overall mean for maize yield for the experimental period followed the order CF > C > F > Ctrl, with the highest yield of 4.53 t ha^{-1} from CF and the least from the control at 2.59 t ha^{-1}. The yield pattern, with the lowest yields in the control and the highest in the CF treatment, was consistent despite seasonal variations in crop performance (Figure 4b of Paper I). The overall mean yields from C and F were comparable, whereas the CF treatment resulted in a relative yield increment of 11% over sole application of compost and 25% over sole application of fertilizer. For wheat and potato, the yields obtained from CF, C and F were comparable (Figure 6). For faba bean, CF had a relative increase in harvest of 45% compared to the control. The overall combined yield was in the order of CF > C > F > Ctrl for faba bean, CF > F > C > Ctrl for potato, and F > CF > C > Ctrl for wheat. The higher crop yields from the CF treatment indicate a synergy when adding compost and NP fertilizer together. While harvests from compost alone and the combined treatments were comparable, the grain yields from the different crops are enhanced in soils receiving the combined treatment, compared with fertilizer alone. This finding is in agreement with other research reports from SSA, which documented improved crop harvests under combined use of organic and inorganic plant nutrient sources (Chivenge *et al.*, 2011; Vanlauwe *et al.*, 2011; Chivenge *et al.*, 2009; Vanlauwe *et al.*, 2001a).

4.4.2 Effects on soil properties

Long-term application of compost alone or in combination with NP fertilizer improved soil properties such as soil organic carbon (SOC), total N, P, K, Ca, and Mg in the upper 10 cm of the soil (Figure 7, Table 2). Compared with the F treatment, the SOC and total N stocks significantly increased ($P < 0.05$) in C and in CF treatments (Table 2). This result corroborates the findings of Bhattacharyya *et al.*, (2009), Goyal *et al.*, (1999), Srivastava *et al.*, (2012), who reported increases in SOC and total N from long-term experiments with organic materials alone or in combination with mineral fertilizer. Application of F alone slightly decreased both SOC and total N stocks compared with the unfertilized control in the surface soil layer. While the addition of fertilizer alone reduced soil pH, the compost alone had the opposite effect of increasing soil pH, compared with the other treatments. The reduction in soil pH with the F

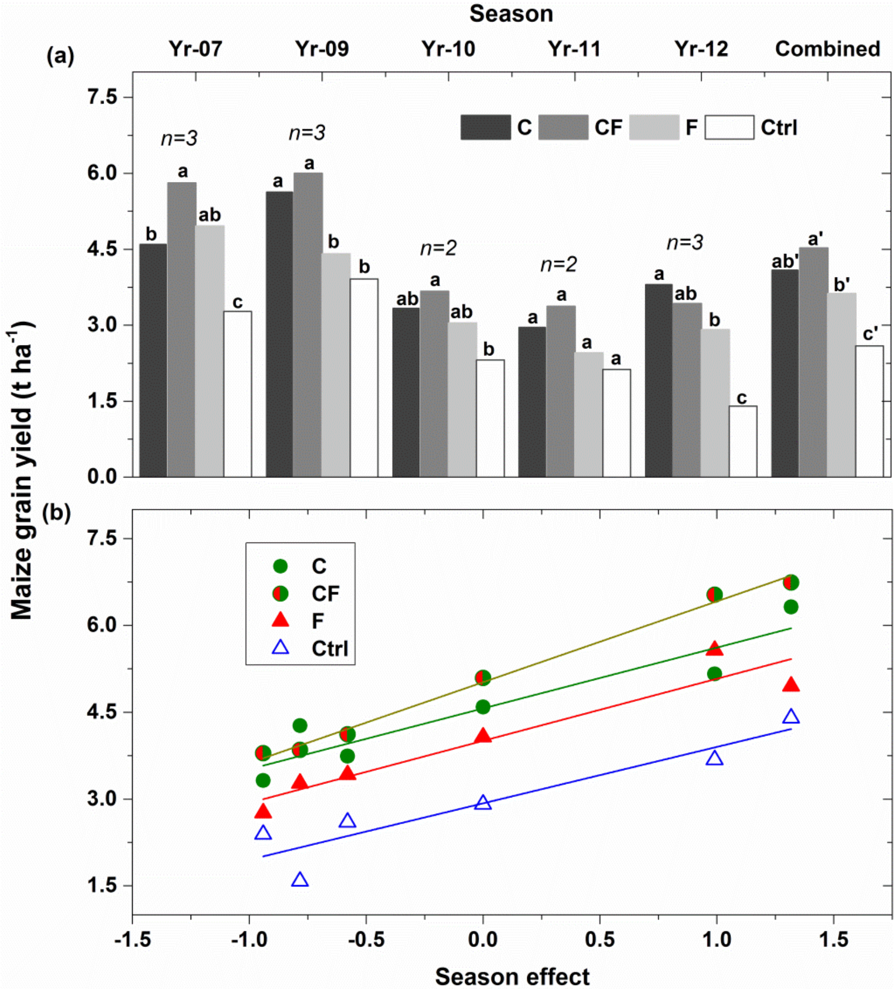

Figure 5. Effect of combined and sole addition of compost and NP fertilizer on maize grain harvests: (a) mean seasonal maize grain harvests averaged over sites, and combined over seasons and sites (the far right bars), and (b) treatments mean harvest against season effect. Yr-07, Yr-09, Yr-10, Yr-11, Yr-12, and Combined denote seasons 2007, 2009, 2010, 2011, 2012, and data combined over seasons and sites, respectively. Maize was not grown in 2008. C = compost alone; CF = half C and half F combined; F = NP fertilizer alone; Ctrl = unfertilized control. Means not sharing the same letters within a season [a–c (2007–2012), a–b (2009– 2010), and a–a (2011)], and combined over seasons and sites (a′–c′) indicate significant difference among treatments ($P < 0.05$).

treatment could be attributed to the acidifying effects of the di-ammonium phosphate fertilizer, as the long-term use of acid forming N fertilizers acidifies the soil through microbial oxidation of ammonium (Schroder *et al.*, 2011; Barak *et al.*, 1997).

Table 2. *Initial soil condition and treatment effects on some soil properties in the upper 10 cm layer from on-farm experiments at Beseku, Ethiopia after 6-years of treatment application. Means in a column not sharing the same letters indicate significantly differences at P < 0.05*.

Treat-ment	**BD**[a]	**pH**	**Soil OC** %	**Soil OC** t ha^{-1}	**Total N** g kg^{-1}	**Total N** t ha^{-1}	**C:N**	**B**	**Cu**	**Zn**
								Mehlich-3 extractable in mg kg^{-1}		
C	1.01	6.93a	3.95a	38.4a	3.91a	3.80a	10.1	0.83a	2.41ab	18.1a
CF	1.03	6.74b	3.83ab	38.5a	3.80ab	3.83a	10.1	0.67ab	2.48a	16.9ab
F	1.01	6.54c	3.57b	33.8b	3.58bc	3.38b	10.0	0.49b	2.32ab	15.6b
control	1.03	6.65bc	3.52b	34.5ab	3.52c	3.45b	10.0	0.53b	2.31b	15.4b
$Pr>F_{trt}$[b]	ns	17.2***	5.0**	5.6**	7.1***	7.1***	ns	9.3***	3.6*	6.5**
Initial soil condition (0-10 cm)[c]										
control		6.61	4.22		3.86		11.1			

C = compost alone; CF = half C and half F combined; F = fertilizer alone; control = unfertilized control.
[a] BD = bulk density (g cm^{-3}); Soil pH was determined on a 1:2.5 soil to water suspension.
[b] $Pr > F_{trt}$ = F-values for the treatment effect and level of significance [$P < 0.05$ (*), $P < 0.01$ (**), $P < 0.001$ (***), and ns= not significant at $P < 0.05$]. Data was taken at the end of 2012 cropping season.
[c] Soil C, N and P were determined by oxidation, Kjeldahl method and the Olsen method, respectively.

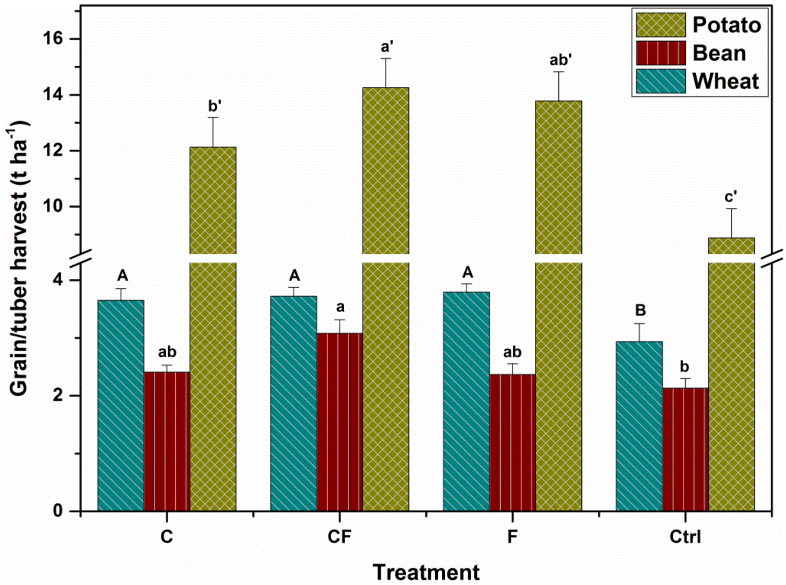

Figure 6. The effects of compost addition, with and without NP fertilizer, on the harvests of potato tuber (FW), wheat and bean grain. C = compost alone; CF = half compost and half fertilizer combined; F = NP fertilizer alone; Ctrl = unfertilized control. Mean values with different letters indicate significant difference ($P < 0.05$) among treatments for the wheat (A–B), bean (a–b) and potato (a′–c′). Error bars show standard error of the mean.

While application of NP fertilizer only contributed to increased soil P levels, compost application increased the concentrations for several nutrients, and there were expected dose-response patterns with compost addition (Figure 7). Available P increased more in the C and CF treatments than in the control, due to the addition of P through the compost (Table 1). In agreement with this result, Takeda *et al.* (2009) observed enhanced mineralization of organically bound P with the application of organic inputs in Andosols through increased phosphatase activity and microbial biomass P in the soil. Despite the obvious increase in available P in the CF and C treatment (Figure 7), the P level for all treatments was well below a calculated average (30.9 mg P kg^{-1}) for published soil P critical levels (Rutgers, n.d.; Savoy, 2009; Fixen, 2006; Sawyer *et al.*, 2003; Chilimba *et al.*, 1999; Wendt, 1995). The available P concentration in the F treated soils was lower compared to the C treatment, but the application appeared sufficient to maintain the soil P status at a higher level compared to the control.

Addition of compost with or without NP fertilizer increased Mehlich-3 extractable concentrations of S, though these values were lower than the critical

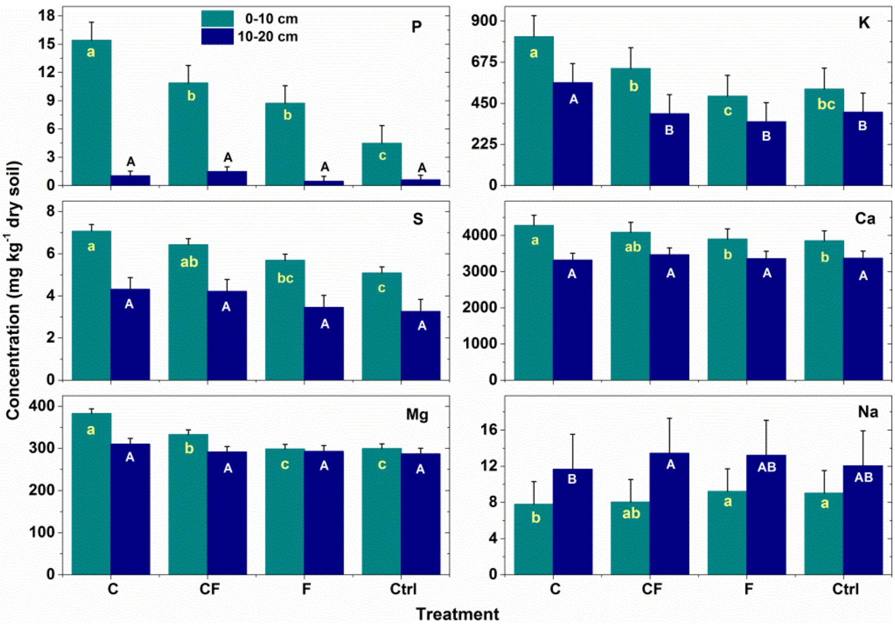

Figure 7. Treatment effects on some Mehlich-3 extractable concentration of macronutrients in the 0-10 cm and 10-20 cm soil depths in on-farm field experiments at Beseku, Ethiopia after 6-years (seasons) of treatment application. Data present means of three sites and three replications at each site. Bar graphs not sharing the same letters denote significant differences ($P < 0.05$) among treatments for 0-10 cm (a-c) and 10-20 cm (A-B). Error bars show standard error of the mean. C: alone; CF: half C and half F combined; F: NP fertilizer alone; Ctrl: unfertilized control.

levels reported in literature, 10 mg S kg^{-1} extracted by ammonium acetate and acetic acid (Grobler *et al.*, 1999). This implies that the Mehlich-3 extractable S levels in soil in the current study are low, especially since Mehlich-3 method extracts relatively more soluble S than the calcium chloride extraction method and other methods such as monocalcium phosphate and monocalcium phosphate + acetic acid, as described by Rao and Sharma (1997). The Mehlich-3 extractable K, Mg and Ca concentrations were higher in the C treatment than in the control, and there were elevated levels in the CF treatment although only significant ($P = 0.011$) for Mg indicating a dose-response relationship for the compost addition (Figure 7). The addition of ash to the compost during preparation (Paper I) probably contributed to the treatment effects for Ca and Mg. In this study, the Mehlich-3 extractable concentrations of all the three cations fell within the very high range reported by Rutgers (n.d.).

The observed changes in the concentrations of macro- and micronutrients were mainly related to compost addition. The levels of Mehlich-3 extractable B and Zn were built-up in the surface soil layer due to the addition of compost, whereas, other micronutrients remained virtually unchanged, as the concentration range in the compost (Table 1 of Paper II) was similar to the intrinsic soil concentrations. The added micronutrients not taken up by plants appeared to remain in the upper 10 cm of the soil (soil plough layer), as no treatment effects on the soil below 10 cm were found (Table 1 of Paper II). It was noted that the micronutrients, such as B, Zn and Cu, increased with compost addition alone or in combination with NP fertilizer above the critical levels mentioned in the literature (Rutgers, n.d.; Horneck *et al.*, 2011; Wendt, 1995). Boron deficiency is reported in many crops all over the world, and Andosols are considered potentially deficient in B (Fageria *et al.*, 2002). Even crops with a small B requirement, such as cereals, can suffer from seed set problem if B soil levels are low (Shorrocks, 1997). Overall, addition of compost alone or in combination with NP fertilizer increased SOC, total N and several Mehlich-3 extractable nutrients in the upper 10 cm of the surface soil suggesting that compost can be a valuable complement to mineral fertilizer use.

5 Effects of compost added alone or in combination with NP fertilizer on plot level soil nutrient flows and balances *(part of Paper II)*

5.1 Background

Nutrient balances are useful tools used to assess sustainability of a given land use system and provide information of productivity or indicators of potential land degradation (Lesschen *et al.*, 2007). With the nutrient balance approach, the amounts of nutrients that are entering and leaving a system with predefined boundaries are estimated, and the balance is calculated as a difference between inputs and outputs (Lesschen *et al.*, 2007; Stoorvogel & Smaling, 1990). Nutrient flows and balances can be calculated at various spatial scale ranging from individual plant to plots of land or farms or higher levels (Schlecht & Hiernaux, 2004). Even though nutrient balance calculation at large-scale provides a good starting point to target soil fertility polices at broader scale, crop or farming system specific balances can be chosen as entry point where soil fertility decline is pronounced (Lesschen *et al.*, 2007).

Stoorvogel and Smaling (1990) introduced a nutrient balance approach where the soil nutrient balance is defined by five inputs and five outputs. The five major inputs are: mineral fertilizers, organic sources, wet and dry deposition from the atmosphere, biological nitrogen fixation, and sedimentation, whereas the five major outputs are: harvested products, crop residue removal, leaching, gaseous losses, and soil erosion. The balance between the inputs and the outputs indicates whether an agriculture system is a net gainer or net looser of soil fertility (Stoorvogel & Smaling, 1990).

5.2 Aim

Increased nutrient addition does not always improve a negative nutrient balance since nutrient removal can increase through increases in harvests and other losses. The aim of this study was to quantify the possible impact on N and P soil stocks as a result of the addition of compost alone or in combination with NP fertilizer. We examined plot level N and P flows and balances with respect to the different treatments we used in the on-farm studies.

5.3 Input-output fluxes and balance calculations

For the experimental plots, nutrient flows and balances were calculated with the revised methodology described in Lesschen *et al.* (2007): four input (IN_{1-4}) and five output (OUT_{1-5}) fluxes for N, and three input and three output fluxes for P. The input fluxes were inorganic (IN_1) and organic (IN_2) N and P fertilizers, symbiotic and non-symbiotic N fixation (IN_3), and atmospheric deposition (IN_4) of N and P. The output fluxes were crop harvest (OUT_1, N and P), residues (OUT_2, N and P), leaching (OUT_3, N), gaseous loss (OUT_4, N), and erosion (OUT_5, N and P). IN_1 and IN_2 were based on inputs used at farm plots (measured data). To estimate symbiotic N fixation, 55% (average values for legumes) of total N uptake was assumed to be fixed (Lesschen *et al.*, 2007; FAO, 2004). Non-symbiotic N fixation, as a function of rainfall, was estimated according to Lesschen *et al.* (2007) and FAO (2004). Wet deposition per year (IN_4, N and P) was estimated as a function of rainfall (Smaling & Fresco, 1993) and average nutrient contents in rainwater (FAO, 2004).

OUT_1 were estimated from the grain of maize, wheat and faba been and tuber of potato harvests (Paper I) and whereas OUT_2 was estimated based on biomass estimations, removal factors and nutrient concentrations of crop residues. Crop nutrient (N and P) concentrations were obtained from literature sources (Tesfaye *et al.*, 2012; Jensen *et al.*, 2010; Haileslassie *et al.*, 2007; Randall *et al.*, 2006; Roy *et al.*, 2006; FAO, 2004; Aldrich *et al.*, 1986). Our assumption was that the variation in grain yield and residue biomass is normally much larger than the variation in concentrations of N and P in grain and residue biomass.

Residue removal factors were used to account for part of the crop residues left on the field after harvest; however, data on residue removal are scarce. Elias *et al.* (1998) assumed about 80% of the crop residues are completely removed from the field in the highlands of Ethiopia. Based on field observations and farmer interviews at the present study site, a residue removal factor of 0.85 for maize, 0.90 for faba bean, 0.80 for wheat, and 0.30 for potato (as it is a low-residue crop) were assumed in the calculation of OUT_2. For the maize crop, biomass was determined after harvest; for other crops, harvest indexes published in literature sources were used (CSA, 2013; Alemu *et al.*, 2012; Jensen *et al.*, 2010; Roy *et al.*, 2006; Keftasa, 1987).

OUT_3 and OUT_4 were estimated from measured data for clay content (%), SOC content (%), CEC (cmol kg^{-1}), precipitation (mm yr^{-1}), mineral and organic fertilizer N ($IN_1 + IN_2$) and amount of N in SOM (kg N ha^{-1}) (Bedada *et al.*, 2014; Lemenih *et al.*, 2005a), and data from literature sources: crop maximum rooting depth (m), (FAO, 2004); and decomposition rate of organic resources (Haileslassie *et al.*, 2007). Then, N leaching (OUT_3) was calculated according to a regression model developed by De Willigen (2000), and considered valid for a wide range of soil and climatic conditions. Leaching loss was considered less important for P fluxes, and was not considered in the P balance calculation. Gaseous N (N_2O, NO_x and NH_3) losses (OUT_4) were estimated according to a regression model proposed by Lesschen *et al.* (2007). We have estimated soil erosion (OUT_5) at field level to be low (0.5 to 1.6 ton soil ha^{-1}) depending on crop types. Since the Mollic Andosol soil type is classified as a low erodible soil by FAO (2004), and all experiments are on flat or very gentle slopes, no evident signs of on-going erosion have been observed in the experiments. We assumed proportional losses of P at an N:P ratio of 4:1. Full nutrient balances (kg N or P ha^{-1} yr^{-1}) were calculated for both treatments and crop types as a difference between inputs and outputs.

5.4 Results and discussion

In Paper II, we presented details of the difference between N and P balance calculations and the differences in inputs and outputs. For the balance calculation, total N and P concentrations in the compost input were used. The compost dose in the experiment was calculated based on the assumption that 35% of the N in the compost was mineralized in the first cropping season and that the mineralized N represented an N addition similar to that of the full fertilizer treatment. This had effects on the total input of P in fertilizer and compost. The C treatment had a dose of 11 kg ha^{-1} yr^{-1}, whereas, in the CF treatment, P additions were higher, with 6 kg ha^{-1} yr^{-1} in compost and 12 kg ha^{-1} yr^{-1} in fertilizer (Table 1 of Paper I). The CF treatment received less P than the F treatment, which gave 24 kg ha^{-1} yr^{-1}. Therefore, the higher yield in the CF treatment could not be considered a P effect alone. The N-fixing effect of the beans should be interpreted with some care, as it was not measured but estimated from an empirical relationship. The estimates indicated an N input considerably higher than the one through fertilizer in the F treatment (Table 5 of Paper II).

The export through grain or tuber harvest and crop residues is the highest nutrient output (Table 5 of Paper II). High biomass yields (e.g., potato) and high N amounts removed in the harvested edible parts explained that the highest N export rates were found in potato, wheat and beans. This was in agreement with Haileslassie *et al.* (2007), who reported similar results for potato in the highlands of Ethiopia. However, although potato and bean have low export through harvest residues, this is an important export pathway for maize and wheat. Crop residues from maize and wheat are generally either directly grazed or removed from the croplands for different purposes. Thus, there will be a considerable loss of nutrients from the system through harvest residues.

The control had strongly negative balances of –74 kg N ha^{-1} yr^{-1} and –14 kg P ha^{-1} yr^{-1} (Table 5 of Paper II, Table 3), and this can be considered an approximation of the mineralization of N and P from the soil organic matter. When averaged over the estimated balances for the crops, all treatments had positive P balances except the control treatment, which had a strongly negative P balance. The N balance for the F treatment was of a similar magnitude as the N balance in the control. This was logical as the mineralized N is utilized by the crop despite the nutrient addition in the fertilizer. If this mineralized N is not replenished through the return of N containing crop residue or other organic resources, it can be considered as soil mining. Comparison of the soil N stock with the original (initial) soil N stock at the start of the experiment indicated that ΔN for the control and F treatment were strongly negative ($P < 0.05$), suggesting depletion of N whereas the CF and C treatments appeared to be close to steady-state (Table 5 of Paper II, Table 3). This agreed with the C

Table 3. *Treatment effects on N and P full balances of different crops grown in on-farm field experiments in Beseku Ethiopia. Data are weighted averages based on number of years each crop was grown at all sites.*

Treatment	**Full N and P balances: kg ha^{-1} yr^{-1}**										**Δ soil N[a]**
	Maize		**Wheat**		**Potato**		**Bean**		**Mean**		
	N	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	
C	+26	+17	-7	+6	+4	+20	+68	+21	+23	+17	4ns
CF	-27	+10	-52	+1	-44	+9	0	+4	-30	+8	8ns
F	-55	+7	-98	-5	-85	0	-17	+5	-61	+5	-66*
Ctrl	-71	-13	-107	-23	-81	-16	-52	-17	-75	-14	-55*

[a] The change in soil N refers to the average soil N concentration difference between initial measured at the start of the experiment and at the end of the experimental period. The asterisk (*) denotes that the change in soil N pool is different from zero, i.e., H0 is rejected; whereas, ns indicates that the difference is not different from zero at $P < 0.05$. C: compost alone, F: NP fertilizer alone, CF: half C and half F combined, and Ctrl: unfertilized control.

treatment accumulating 0.4% N per season, (Figure 8a) and the CF treatment depleting N fractions of 0.5% per season, both as a percentage of soil N stock, compared with the average N depletion of 1.2% per season in the F and control treatments (Figure 8a).

The estimated proportion of different P fluxes in relation to measured available P in the soil stock was strongly positive or negative for all treatments (Figure 8b). Since the differences in the available soil P pool are the accumulated effect of 5 years treatments it implies that crops could mobilize P from sources not included in the operationally defined "plant available" pool. Alternatively, the plant has the capacity to 'pick-up' P from a larger soil volume, i.e., a greater soil depth. The N and P depletion values as percentage of soil nutrient stocks were greater than the values reported for Burkina Faso, which were 0.3% for N and 1.1% for P (Lesschen *et al.*, 2007).

The N and P balance calculations presented in this study (Paper II) were based on data from field experiments and some literature sources. The nutrient composition data of each crop and the nutrients exported in the OUT_1 and OUT_2 were based on secondary data. The assumption was that crop nutrient concentrations might not vary considerably compared to the higher variability measured in grain/tuber and biomass yields and some of these data were from research based in Ethiopia. Some authors have been critical of the nutrient balance approach by Stoorvogel and Smaling (1990) for lack of validation with empirical measurement (Faerge & Magid, 2004) and the use of transfer func-

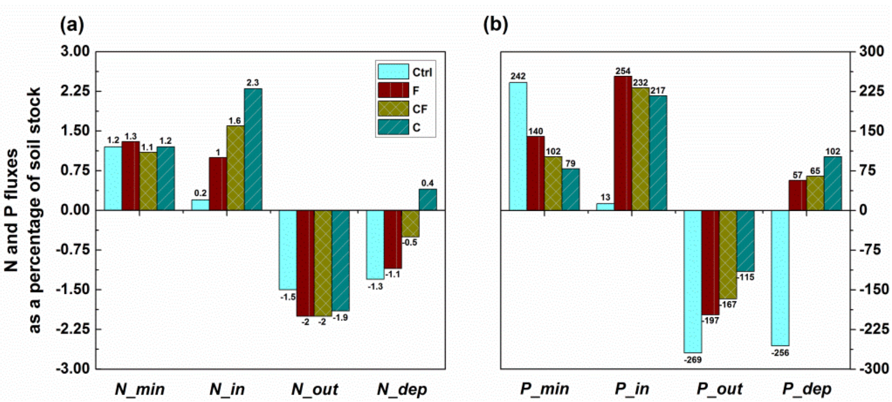

Figure 8. N and P fluxes in relation to (**a**) N, and (**b**) available P expressed as percent of soil stocks (0-20 cm) after six-years of treatment application in on-farm experiments in the highlands of Ethiopia. *N_min* and *P_min* are average N and P exported (% of soil stock) in the biomass of the unfertilized control treatment at respective farm fields, which indicate the soil supply capacity or amounts of soil N and P available through mineralization. The *N_in* and *P_in*, and *N_out* and *P_out* refers to the total N and P inputs (IN_{1-4}), and the total N and P exported (OUT_{1-5}) expressed as percent of soil N and P stocks, respectively. *N_dep* and *P_dep* denotes N and P depleted (%) in relation to soil N and P stocks.

tions in the absence of measured data (Hartemink, 2006; Schlecht & Hiernaux, 2004). Although the nutrient balance may contain some systematic errors, it gives a good sense of possible differences between treatments when applied to experimental setups since several potential systematic errors might be similar between the treatments. Given the combination of measured, observed and literature data, the calculated balances for N and P are approximate and associated with some uncertainty. However, when compared with independent data like the change in the soil pool and earlier studies in the area (Lemenih *et al.*, 2005a; Lemenih *et al.*, 2005b), the results confirm that the decline in the productivity of the farming system in the area can be explained with continued loss of soil organic matter and nutrient mining and that only NP fertilizer addition is insufficient to mitigate that trend.

6 Exploring crop production synergies under combined addition of compost and fertilizer (*Paper III and part of Paper II*)

6.1 Background

Above, I have described the effects of fertilizer and compost additions on SOC and micro- and macronutrients in the surface soil in the on-farm experiments (Paper I and II) and their effect on nutrient budgets for N and P. There was also an apparent synergy where crop harvests and N use efficiency for the added N were higher from the combined use of compost and NP fertilizer than other treatments when the crop was given either input alone (Paper I and II). In this section the major focus is on interpretation of and possible explanations for the added benefit of the combined application relating to the conceptual figure of the explanations presented in Figure 2.

6.2 Aims

To get an insight into the possible processes behind the apparent synergy observed in the compost experiments (Paper I and II), studies were conducted aiming: i) to assess and quantify the added benefits and agronomic N use efficiency due to combined use of compost and NP fertilizer (parts of Paper II); ii) to test if addition of NP fertilizer and compost added alone or in combination affected the adaptation of the soil microbial communities and their capacity to utilize different C sources (Paper III). Treatment effects were assessed through substrate induced respiration (SIR)/community level physiological profiles (CLPPs), functional diversity and catabolic evenness of the soil microbial community. We hypothesized that the capacity of the soil microbial community to utilize different carbon sources is affected by the type of input added and that the effect of this adaptation on nutrient mineralization can result in a nutrient mobilization that is more than additive which could explain the synergetic effects of the combined compost and NP fertilizer treatment.

6.3 Materials and methods

For these studies samples and data from the on-farm experiments described above were used. Details of the treatments and experimental setup are given in section 3.1. Crop performance due to treatment effects was determined as grain/tuber yield, as presented in Paper I. The extra grain/tuber yield generated in the combined treatment (CF), which is defined as added benefits (AB) according to Vanlauwe *et al.* (2001a), was calculated for each crop. Agronomic use efficiency of fertilizer N (AE-N, kg kg^{-1}), the change in grain yield per unit of fertilizer N applied, was determined according to Vanlauwe *et al.* (2011).

For the soil microbial study, soil samples were collected with an auger from the upper 10 cm of the surface soil of each experimental unit in 2011 when the maize crop was at a grain filling stage. At this sampling occasion, the experiment had received the same treatment for five consecutive seasons. Details of procedures including soil preparations for the MicroResp™ assay are given in Paper III. To assess the soil microorganisms' ability to metabolize different carbon sources, the total amount of respired CO_2 was quantified and the substrate induced respiration (SIR) from the 15 freshly prepared single carbon source calculated. Basal respiration (BR) was calculated from the no-substrate (water only) control. Basal respiration (BR) reflects the slow release of available carbon for microbial maintenance (Insam *et al.*, 1991), whereas SIR reflects the size of the active microbial biomass (Schomberg & Steiner, 1997). Catabolic versatility (*CV*), measures the degradative potential of the soil microbial community (Wenderoth & Reber, 1999b), was calculated according to Wenderoth and Reber (1999a). The higher *CV* value indicate ability of soil microbes to catabolize a wide range of carbon substrates.

6.4 Results and discussion

The F treatment had significantly lower ($P < 0.05$) mean basal respiration (BR) compared to the C and control treatments (Figure 9), which suggests lower carbon availability in the F treatment for maintenance at the time of sampling. In Paper I, we reported significantly ($P < 0.05$) lower SOC in the F than in the C treatment based on the combined data analysis. Crop harvests and biomass production in the F treatment were also comparable with that from C and control treatments (Table 1 of Paper III). However, the fact that the C and control treatments had significantly higher BR than the F treatment suggests that other factors, e.g., fertilizer-stimulated SOM degradation might have contributed in addition to low soil carbon in the F treatment. Enhanced initial turnover rate of organic carbon or plant residue under increased N availability has frequently been found and is often followed by a lower turnover rate at later stages (Ilstedt & Singh, 2005; Corbeels *et al.*, 2000; Henriksen & Breland, 1999). Such an effect may also have contributed to the similar BR in the CF and control treatments in spite of the compost addition in the former.

The average SIR induced by the addition of substrates varied significantly ($P < 0.05$) among treatments, with the highest mean SIR in the C treatment and the lowest in the CF treatment (Figure 9). The increased respiration rates from the C treatment compared to the CF treatment could be explained by increased activity of the soil-based microbial community due to higher input of compost (Fuchs, 2010; Knapp *et al.*, 2010; Saison *et al.*, 2006; Ros *et al.*, 2003) and increased soil microbial biomass (Ros *et al.*, 2003). Compost amendment has also been reported to affect size and composition of the soil microbial community (Saison *et al.*, 2006). Compost-borne microbial community composition and biomass could also contribute to changes in the capacity to respire different substrates. However, there is still little information available to substantiate if compost microbiota leaves an imprint on soil microbial communities in the long-term (Knapp *et al.*, 2010). However, the fact that both the control and the F treatments have SIR levels that are intermediate to the C and CF treatments

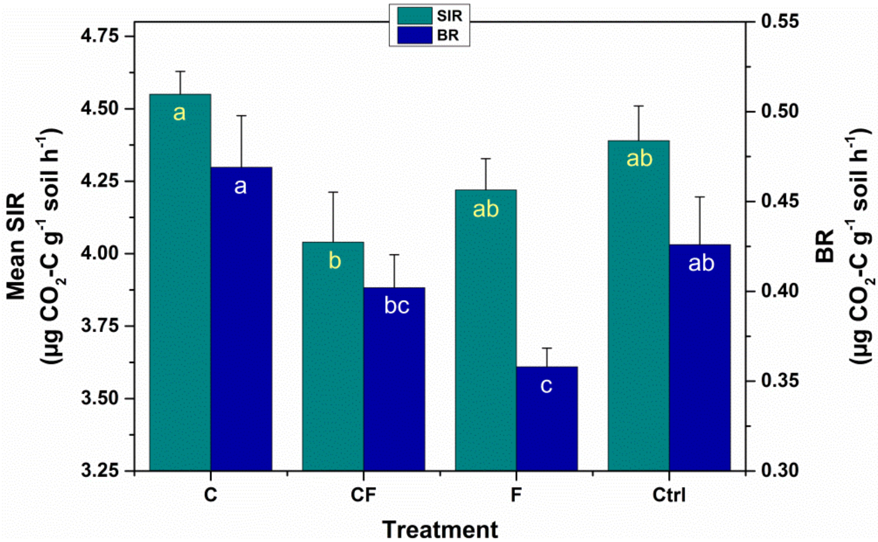

Figure 9. Mean substrate induced respiration (SIR) and basal respiration (BR) of soils from an on-farm field experiment in Beseku Ethiopia. Bars of same color not sharing the same letters (a-c) indicate significant treatment difference at $P < 0.05$. C: compost alone, F: NP fertilizer alone, CF: half C and half F combined, and Ctrl: unfertilized control.

does not necessarily mean that this is the only explanation. A direct effect of fertilizer could be one possible explanation for lower SIR in the CF compared with the C treatment. This may be a result of a shift in the relative importance of soil microorganisms (Geisseler & Scow, 2014), but this explanation needs further investigation.

Catabolic versatility was significantly higher in the CF than in the C and control treatments, with the least versatility obtained from the control plot (Table 4 of Paper III). There could be a possibility that the CF treatment better supported both fungal and bacterial communities which may have led to a better mobilization of plant nutrients and consequently resulted in increased crop harvests (Table 1 of Paper III, Paper I). Zhang *et al.* (2015) reported significantly higher phospholipid fatty acid levels for both bacteria and fungi under the combined use of compost and mineral fertilizer (NP) compared with the compost or fertilizer alone treatments which lends support to this explanation.

When grouped into different carbon guilds, carboxylic acids induced the highest respiration rates and amino acids the lowest (Figure 2 of Paper III). The higher utilization of the carboxylic group in the C treatment compared to treatments with mineral fertilizer, suggests fertilizer might have affected the activity and adaptation of the microbial community to utilize easily metabolized organic acids. Overall respiration in the CF treatment was larger than in the control (Figure 2 of Paper III). However, differences were non-significant for γ-amino butyric acid and cysteine when tested singly and respiration induced by *N*-acetyl-glucosamine was higher in the F than in the C treatment (Figure 10). A negative association between fungi:bacterial ratio and substrate-induced heat release from *N*-acetyl-glucosamine addition are reported by Herrmann *et al.* (2014). As fungal cell walls are typically composed of complex structures such as chitin, which is a polymer of *N*-acetyl-glucosamine (Zamani *et al.*, 2008; Adams, 2004), the higher respiratory response of fertilizer treated soils to *N*-acetyl-glucosamine could be related to its preferential utilization by fungi.

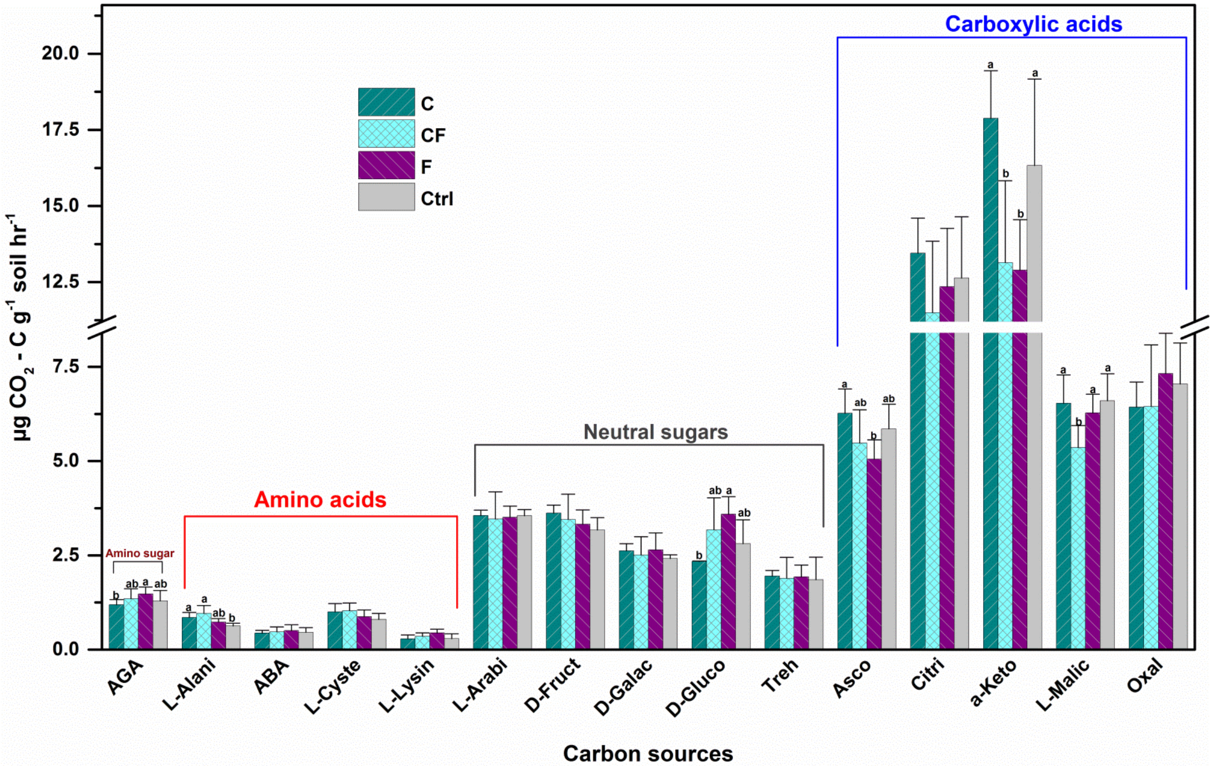

Figure 10. Colorimetric evolution of carbon dioxide (+ std., n = 9) for soils from an on-farm field experiment in Beseku of Ethiopia: substrate induced respiration (SIR) measured 6 h after addition of 15 different single-carbon sources based on MicroResp™ techniques. Bars not sharing the same letters (a-b) indicate significant ($P < 0.05$) difference between treatments for each carbon sources. C: compost alone, CF: half C and half F combined, F: NP fertilizer alone, and Ctrl: unfertilized control.

All substrates induced respiration rates above the control (water only) as indicated by positive SIR values of individual substrates (Figure 10). However, only six of the fifteen substrates exhibited significant treatment effects on carbon utilization. The α-Ketoglutaric and citric acids induced 5.1 and 4.2 times higher respiration than that of glucose, respectively (Figure 10). The least soil microbial response was obtained from lysine, which was 12% less than that of glucose. For sludge treated soils collected from Lanarkshire, Scotland, Campbell *et al.,* (2003) reported the highest respiration from fructose and the lowest from lysine. Elsewhere, Sradnick *et al.* (2013) and Herrmann *et al.* (2014) respectively reported high respiration responses (6 µg CO_2-C g^{-1} h^{-1}) for oxalic and citric acids and for α-ketoglutaric acid (6-10 µg CO_2-C g^{-1} h^{-1}). Compared with the results reported by Herrmann *et al.* (2014) and Sradnick *et al.* (2013), the patterns of respiration from the multiple carbon sources are similar, but with generally higher respiratory responses from the present study soils suggesting higher microbial activity and functional capacity. Overall, the variability in respiration response to the added substrates indicates that certain carbon sources may be too insensitive to discriminate different systems (input types in this case) due to their ease of utilization by microorganisms or to differences in their availability owing to changes in other soil properties.

The canonical discriminant analysis successfully separated the MicroResp™ profiles (CLPPs) data or treatments (*Wilks' Lambda*: 0.023, F = 3.09, P < 0.001) (Table 5 of Paper III, Figure 11); implying that the CLPPs were actually dependent on the input types added. The discrimination was seen in the first (Can1, P < 0.001) and second (Can2, P < 0.05) canonical variables, which together explained 94% of the variation. The correlation coefficient between the individual substrate respiration rates and the canonical variables indicated that ascorbic and α-ketoglutaric acids were responsible for the discrimination of CLPPs in the compost from the three treatments on Can1 (Table 6 of Paper III; Figure 11). On Can2, alanine and cysteine-HCl (P < 0.01) contributed most to the discrimination of the CF from the unfertilized control (Table 6 of Paper III; Figure 11), whereas, glucose, *N*-acetyl-glucosamine and lysine were responsible (P < 0.05) in separating the F, CF and control treatments from C treatment on Can1. Ascorbic and α-ketoglutaric acids were easily utilized under the C treatment, and amino acids alanine and cysteine-HCL were efficiently degraded under CF treatment, whereas *N*-acetyl-glucosamine was readily utilized under F treatment (Table 6 of Paper III). According to Sradnick *et al.* (2013), the strong correlation coefficients of these substrates with the canonical variables would indicate that soil microorganisms with similar function are associated to specific carbon sources.

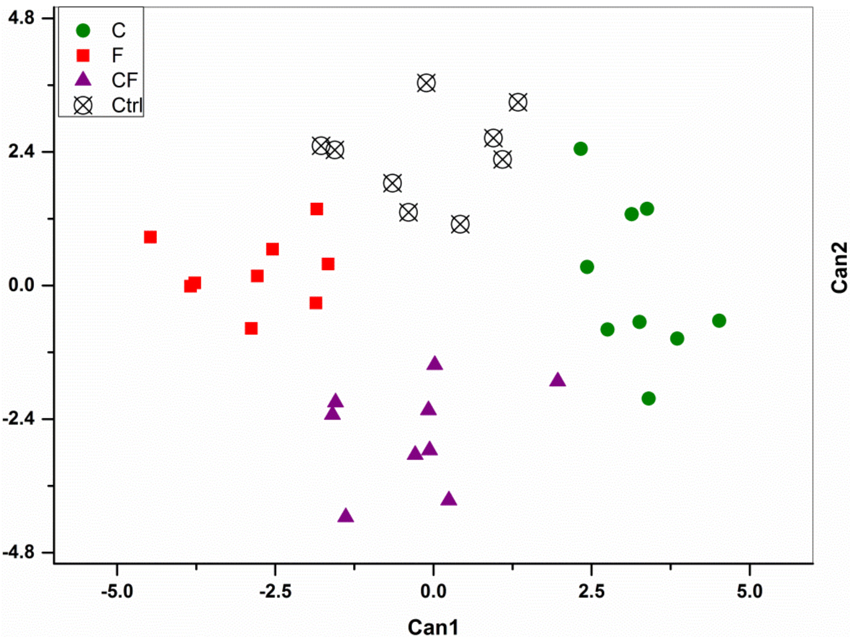

Figure 11. Canonical discriminate analysis of the MicroResp™ profiles under different input types (amendments) for soils from an on-farm experiment in Beseku, Ethiopia. The R^2 between Can1 and the group variable is 0.84, which is larger than the corresponding R^2 for Can2 (0.78). C: compost alone, F: NP fertilizer alone, CF: half C and half F combined, and Ctrl: unfertilized control.

Table 4. *Added benefits (AB, t ha^{-1}) in terms of extra maize and bean grain harvest obtained by combining compost with NP fertilizer in on-farm field experiments in Beseku, Ethiopia.*

Variable	**Maize**				**Faba bean**		
	IB	**KW**	**TM**	**Pooled**	**MM**	**KW**	**Pooled**
Y'_O [a]	0.62	0.67	1.26	0.85	0.24	0.05	0.14
Y'_{NP} [a]	0.39	0.43	0.93	0.59	0.14	0.09	0.12
AB	**0.57**	**0.76**	**0.83**	**0.72**	**0.23**	**1.16**	**0.69**
Significance level (H_0: AB = 0) [b]	ns	*	**	*	ns	*	*

[a] Y'_O and Y'_{NP} are the yield responses to organic and mineral fertilizer, respectively (see eq. 1, 2 and 3 of Paper II). The calculations were done according to Vanluawe *et al.* (2001), and yield data are taken from Paper I.
[b] Significance level, $P < 0.05$ (*) or $P < 0.01$ (**), denotes that the extra maize grain yield generated is greater than zero (i.e., H_0 is rejected); ns: not significant at $P < 0.05$.

In *Paper II*, we computed input interaction effects as added benefits. Added benefits in terms of extra grain yield harvest from the combined addition of compost and NP fertilizer treatment were over 700 kg ha^{-1} in maize and over 1100 kg ha^{-1} in faba bean (Table 4). As described above, the positive interaction effects can be explained either by the direct or indirect mechanisms formulated by Vanlauwe *et al*. (2001a). The findings by Gentile *et al*. (2009) support the view of Vanlauwe *et al*. (2001a) that when mineral fertilizer is combined with maize residue, a net immobilization and subsequent release of fertilizer-N results in better synchrony between nutrient availability and crop demand by reduced early season available N. In addition, the incorporation of medium quality residue with fertilizer has the potential to optimize residue-derived N release without increasing potential N losses (Gentile *et al.*, 2008). The direct mechanism may have contributed to the added benefits generated in the current study. However, they reported a negative added benefit when fertilizer is combined with high quality residue of tithonia, which the authors ascribed to net mineralization and potential losses of N (Gentile *et al.*, 2009). In contrast to these findings, we found positive added benefits due to combined application of a high quality organic resource (C:N ratio c. 11) and mineral fertilizer. This may question the improved synchrony as an explanation of our results and other explanations need to be examined. There is also an argument that combined application of organic input and mineral fertilizer enhances crop harvest through alleviation of multiple nutrient limitations (Palm *et al.*, 1997). The application of compost resulted in increased micro- and macronutrient concentrations in the soil (Table 1 of Paper II; Figure 7). It is interesting to note that critical nutrients like S, B and Zn which has been found to be low in many Ethiopian soils in the country-wide inventory of agricultural soils carried out within the Ethiopian Soil Information System (Gustafson, 2014) all had significant positive treatment effects as a result of the compost addition. The same elements have also been reported to be deficient in other parts of Africa (Wendt & Rijpma, 1997). Thus, the direct mechanism may have contributed to the added benefits generated in the current study.

The indirect mechanism (Vanlauwe *et al.*, 2001a) is explained by enhanced efficiency in the utilization of fertilizer N (AE-N) through organic input addition related to improvement in soil physical properties such as improved in soil structure, infiltration and water holding capacity, and better crop root development, with improved nutrient uptake as a result (Figure 12). The soil in Beseku is a fine textured soil with high concentration of soil organic matter, the top soil contained as high as 52 g SOC kg^{-1} in a bulk soil cultivated for a decade after deforestation (Lemenih *et al.*, 2005b). Despite this, significant treatment effects have been observed in the on-farm experiments on the soil physical properties such as improved infiltration rate (Yimer & Karltun, 2012) for both the CF and C treatments. Thus, the indirect mechanism cannot be ruled out as a possible explanation.

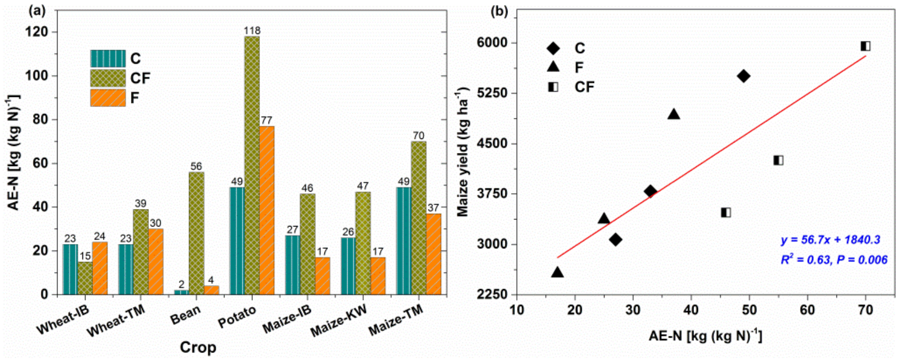

Figure 12. Agronomic efficiency of N (AE-N) of three treatments for different crops (a), and linear relationship between AE-N and average maize grain yield combined over sites by seasons (b). Simple linear regression equation (y), line of best fit, and statistical significance are presented. Yield data is taken from Paper I. C: compost alone, F: NP fertilizer alone, CF: half C and half F combined.

On the basis of the results here, it is not possible to point out one single mechanism that resulted in the added benefits of the combined use of compost and mineral fertilizer. Most probably, more than one of the suggested mechanisms have contributed and both alleviation of multiple nutrient limitations and indirect effects on soil properties may well have played important roles.

7 Household resource availability and adoption of compost (*Paper IV*)

7.1 Background

Declining soil fertility due to unsustainable land-use has long been identified as a bottleneck to improved productivity in the highlands of Ethiopia (Karltun *et al.*, 2013a; Yirga & Hassan, 2010; Lemenih *et al.*, 2005a; Lemenih *et al.*, 2005b). Contributing factors include increased population growth, land shortage and unsustainable land management (Headey *et al.*, 2014; Josephson *et al.*, 2014; Berry, 2003), absence of N-fixing crops from crop rotation in the agricultural systems (Karltun *et al.*, 2013b; Chiwona-Karltun *et al.*, 2009), insufficient use of mineral fertilizer due to infrastructure or economic related constraints (IFPRI, 2010; Spielman *et al.*, 2010).

In the context of on-going research in the Munessa area in Ethiopia, a project was initiated aiming at testing the use of compost as an alternative strategy to cope with the declining soil fertility. This was done after a series of focus-group discussions and in-depth interviews with the community members to identify locally acceptable integrated soil nutrient management options. Four participatory on-farm experiments with compost making and addition were initiated and the experiments were used as field demonstration sites for six seasons (Paper I). In connection with the experiments field training on compost making and integration in the crop production were organized. A stakeholder workshop where farmers, agricultural extension staff, local politicians and researchers discussed how to enable farmers to improve their management of soil fertility was also held in connection with the experiments. The field experiments have been scientifically evaluated) and results from these long-term field experiments indicated that application of reduced rate of compost alone or in combination with NP fertilizer improved crop harvests, soil micro- and macronutrient status and soil organic carbon (Paper I-II). However, the uptake of this technology among other farmers has not been systematically studied.

Studies indicate that although considerable efforts have been made to enhance the diffusion and uptake of various agronomic management options that help improve productivity and income of smallholder farmers in Ethiopia, the success rate in terms of adoption has yet been very low (Wossen *et al.*, 2015; Abate *et al.*, 2011). Socio-economic variability and differences in soil fertility management (Cobo *et al.*, 2009; Haileslassie *et al.*, 2007; Elias & Scoones, 1999; Gray, 1999) are important factors that affect soil fertility. Farm households also differ in their access to farm household resources like cash, labor, livestock and access to land (Haileslassie *et al.*, 2007), which might impact their capacity to adopt new technologies in order to maintain a sustainable nutrient balance of the cropping system. For instance, farmers who have few cattle (often poor farmers), only have limited access to manure, and the amount of fertilizer they are able to buy is limited.

7.2 Aims

The aims of this study were to assess if access to information and household resources affect the decision to adopt compost. We hypothesized that differences between farmers in the access to information and household resources availability would affect the decision to adopt compost.

7.3 Materials and methods

Household interviews were carried out on households (HH) of different socio-economic levels in the village of Beseku Ilala peasant association (PA). Details of the HHs selection procedures and characteristics studied are presented in Paper IV. Of the 45-50 HHs from each of the four sub-villages or *gotes*, 10 HHs were randomly selected from each *gote* and interviewed with a semi-structured formal questionnaire that consist of closed and open-ended questions.

A logistic regression model was used to study the relationship between HH characteristics and compost adoption defined as a binary dependent variable with a value of 1 when compost is used and 0 otherwise. Adoption of agricultural technologies such as this has been assumed to be motivated by utility maximization. Farmer adopts a new technology if the perceived utility of the new practice is larger than the older practices. In this case, adoption is expected if the perceived advantages of compost exceed the present (older) nutrient management options.

7.4 Results and discussion

Variables included in the logistic regression model explained 74% of the probability of the household decision to adopt or not to adopt compost, as indicated by significant ($P < 0.001$) log-likelihood ratio test (Table 5). Access to agricultural extension services or training (*TRNG*) on improved agricultural technologies such as different nutrient management options were used as a proxy for access to information (Table 5; Figure 13). Training was thus found a key variable that positively and significantly ($P < 0.01$) affects the compost adoption decision. The high percentage of farmers that said that they got information about compost making from other farmers in Beseku (Figure 2 of Paper IV) indicates the importance of farmer-to-farmer information exchange for technology adoption. Interestingly, of those who had compost-related practical and theoretical training, a significantly higher proportion (63%) had adopted compost compared to 21% for those who had only theoretical background (Figure 13), suggesting the importance of technology-specific training for better uptake (Weir & Knight, 2004).

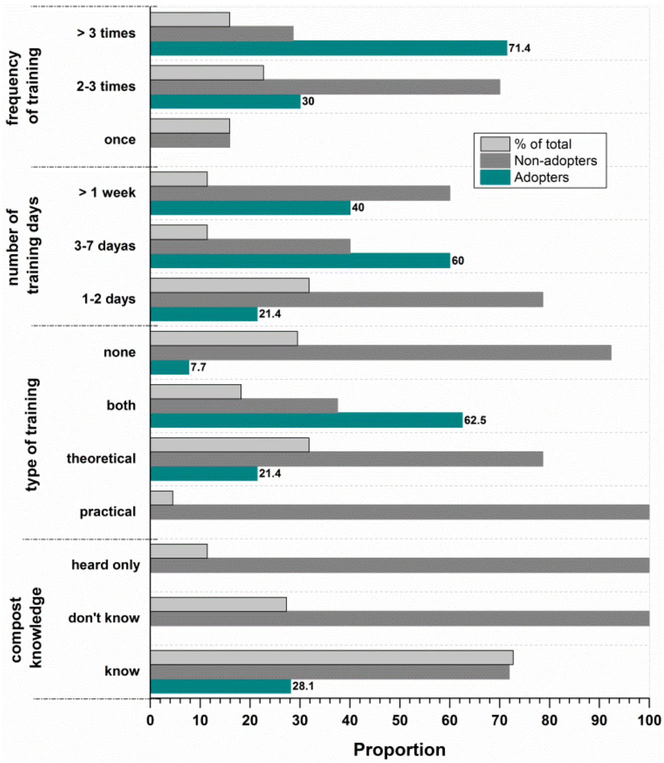

Figure 13. Prior knowledge and impacts of training and training frequencies on the adoption of compost in Beseku, Ethiopia. Percent of total is the proportion of the HHs who know compost or got training to total HH interviewed (*n = 44*).

Table 5. *Logit model estimated coefficients for factors affecting compost adoption in Beseku, Ethiopia.*

Variables	Estimated coefficient	S.E	*Wald* χ^2	*Pr >* χ^2	*Likelihood CI (95%)*	
					LCI	*UCI*
Intercept	-15.05	6.97	4.67	0.031	-37.05	-4.60
Access to information - *TRNG*	5.59	2.18	6.58	0.010	2.20	12.06
Total land owned in ha - *TL*	-1.93	0.99	3.83	0.050	-4.59	-0.20
Education level - *EDU*	0.78	0.37	4.58	0.032	0.28	2.06
Total family size - *TFS*	-0.66	0.32	4.42	0.036	-1.64	-0.20
Age of the farmer - *AGE*	0.25	0.13	3.96	0.047	0.07	0.65
Number of cattle owned - *NCATT*	0.38	0.21	3.39	0.066	0.05	0.99
Land holding certificate - *LHC*	2.00	1.81	1.23	0.268	-1.47	6.40
Labor force index - *LFI*	-0.01	0.04	0.01	0.909	-0.09	0.09

-2 Log-likelihood = 16.6; Likelihood ratio test (27.97) is significant ($P < 0.001$), with 8 D.F.; Max-rescaled pseudo $R^2 = 0.74$.

Access to information about a new practice has long been identified as a key determinant of adoption (Asfaw *et al.*, 2012; Wubeneh & Sanders, 2006; Adesina & Zinnah, 1993). Farmers who have access to extension services tend to be more progressive and receptive to new innovation (Asfaw *et al.*, 2012). However, some farmers may strategically delay adoption of a new technology until they build confidence through watching and learning from fellow farmers (Dercon & Zeitlin, 2009).

The probability of compost adoption was also positively and significantly ($P < 0.05$) associated to the education level (*EDU*) of the farmer. A positive impact of education on technology acquisition is generally expected as it enhances farmer's ability to acquire and analyze new ideas, and provides specific or general skills that contribute to farm productivity (Weir & Knight, 2004). Asfaw *et al.* (2012) reported positive or no impact of education on technology adoption. Age is another HH variable that affects technology adoption positively or negatively. Elderly farmers are supposed to have rich farming experiences and may rely more on traditional or indigenous knowledge and it might take times to compromise their practices. Elderly farmers may also tend to be more risk-averse than younger farmers or might wait until the new technology is taken up among fellow farmers. Somda *et al.* (2002) for instance, reported a negative association of age of farmers with compost adoption in Burkina Faso, which they attributed to differences in knowledge and willingness to take risks. The positive and significant ($P <0.05$) association of age with compost adoption at Beseku could be explained by more adult male aged between 18- and 60-year (Table 1 of Paper IV), which was 21% higher for the adopters compared to the non-adopters.

The number of cattle (*NCATT*) owned by the HH was positively associated with the probability of compost adoption at $P < 0.07$ as it provides manure for compost preparation. The adopter farmers all indicated that they use farmyard manure as a plant nutrient source and they applied significantly less DAP ha^{-1} compared non-adopter farmers ($t = -3.20$, $P < 0.01$; Table 1 of Paper IV). Total family size (*TFS*, $P < 0.05$) was negatively related to compost adoption. For labor intensive technology such as compost, large family size would provide the needed labor during peak time of the season and thus may directly affect adoption. For instance, in an inorganic fertilizer (Wubeneh & Sanders, 2006) and chickpea (Asfaw *et al.*, 2012) adoption studies in Ethiopia, family size was reported an important determinant of adoption. The effect of total family size on compost adoption was however negative in the present study (Table 5). Although the reason for this is not clear, it might imply that the availability of family labor was less important for the adoption decision. However, for the non-adopter group, labor shortage and knowledge gap were ranked high as variables constraining adoption (Figure 14). We also assessed if labor requirements for the major farm activities and their frequencies (the number of times these activities done) vary between adopter and the non-adopter farmers (Table 2 of Paper IV) but did not find significant difference between the two groups, implying that labor demands for the major farm activities are similar. Thus, there might be more important variables determining adoption than access to labor.

Land is an important asset in agrarian societies of any rural HH and possession of land could be an important determinant of agricultural technology adoption. In the present study, it was found that farmers with small landholdings had a higher probability of compost adoption than those with large farms. The

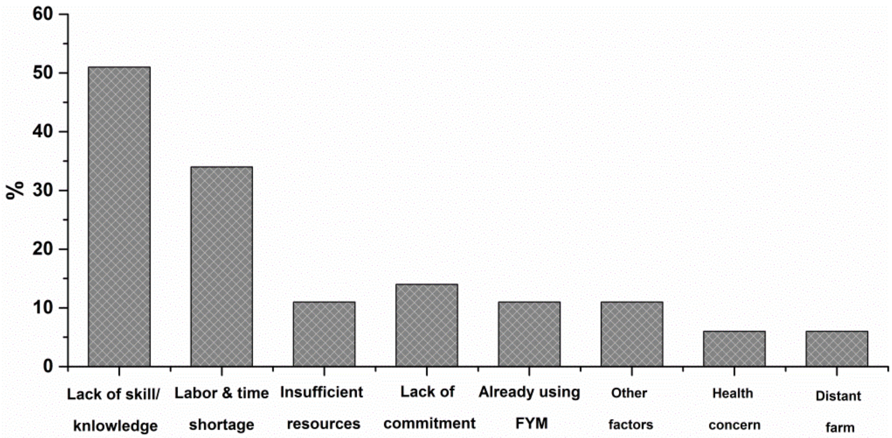

Figure 14. Constraints to compost adoption mentioned by non-adopters.

inverse relationship between compost adoption and landholdings could be associated with the pressing need to increase productivity on the already limited per capita farm size. The average landholding of the farm households surveyed was 1.2 ha, and 14% of the HH own less or equal to a quarter of ha and 52% ≤1.0 ha. One possible way of raising agricultural productivity is through putting more land under cultivation. However, land constrained farmers may opt for intensification. Feder *et al.* (1985) argued that farmers tended to intensify farming when their farm size is small. Furthermore, Headey *et al.* (2014) indicated that increased use of agricultural inputs are positively correlated with land-constrained households. We also observed that the adopter group increased their croplands by renting-in more cropland and was more involved in sharecropping than the non-adopters group (Table 2 of Paper IV), which could be a combination of land shortage and commitment to increase production.

However, research findings on the effect of farm size on agricultural technology adoption are not consistent. Asfaw *et al.* (2012) reported a positive correlation between farm size and chickpea (*Cicer arietinum*) adoption in Ethiopia, which they attribute to ease of access to improved seed and credit. Wubeneh and Sanders (2006) argued that a positive relationship could be explained by higher risk-bearing potential of HHs with large farms compared to small farms. However, this may not the case in Beseku as landholding is already fragmented. According to Feder *et al.* (1985), the association of farm size to technology adoption depends on fixed adoption costs, risk preferences, human capital, credit constraints, labor requirements and tenure arrangement. Since the adoption of compost does not require any large investment and cannot be considered to be a high risk option, these factors have not been obstacles for small farms to go for the adoption in Beseku.

In general, the present study indicated that technology specific training, farmer-to-farmer technology exchange and education level were important determinants for compost adoption. However, farmers with small farm size readily adopted compost suggesting the need for them to increase productivity by tenable means based on their livelihood options. The results also suggest a need to improve extension on compost preparation in order to improve awareness and knowledge in the farming community. Perceived health risk concerns in connection to compost preparation raised by farmers should be recognized and information on these aspects should be included in agricultural extension information and services. We show that compost can be prepared from locally available resources as seen from the present study. However, more research is needed to quantitatively assess the available resources for compost production in different farming systems, particularly in rural settings where population pressure is rising.

8 Conclusions

- This study provides compelling evidence on the positive effects of compost addition, alone or in combination with NP fertilizer, on crop harvests, SOC build-up, improvement in several plant available micro- and macronutrients and agronomic N use efficiency.
- The added benefits we obtained from the combined use of compost and NP fertilizer at a reduced application rate suggest that fertilizer and compost should be seen as complementing rather than substituting each other.
- Alleviation of multiple nutrient limitations, the indirect effects on soil properties and the improvement in catabolic versatility of soil microbes are likely explanations to the added benefits of the combined use of compost and mineral fertilizer.
- Access to information was a key determinant for compost adoption followed by farm size (higher adoption on small farms) and education level. The main perceived constraints for non-adoption were lack of knowledge, labor and time constraints, and/or lack of commitment.
- In general, local compost production has a potential to reduce farmers' need for investment in fertilizer.

9 Future perspectives

The results obtained in the on-farm experiments in Beseku are of significant importance for low-input farming systems where access to external inputs, such as mineral fertilizer, is a major production constraint. The present results may not necessary be similar in areas with different soils, climate or farming systems. More studies on the effects of the combined use of fertilizer and organic resources should therefore be carried out in different agro-ecological zones. Extension efforts also need to be strengthened for improved adoption of compost in the farming communities.

The lack of knowledge and the health risk concern raised by farmers in relation to compost preparation needs to be addressed through improved extension on compost preparation. Compost can be prepared from locally available resources as seen from the observed adoption. However, more research is needed to assess quantities of available resources for composting in different farming systems.

In order to better understand the mechanisms behind the synergy between compost and fertilizer on-farm research should be complemented with experiments where processes can be studied in detail under more controlled conditions. The possible macro- and micronutrient limitations can be verified in nutrient exclusion experiments. Studies using ^{15}N could be used to study the synchrony between N addition and N uptake. Finally, the rapid development in the area of microbial ecology based on high throughput genome sequencing might have potential to get a better insight in the microbial processes.

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