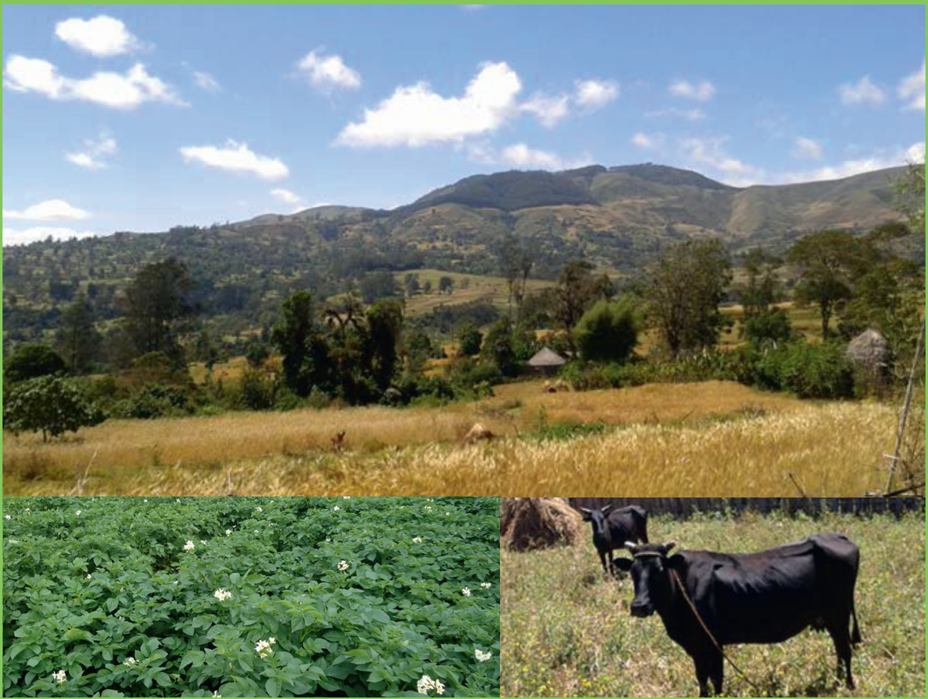
Agronomic and socioeconomic sustainability of farming systems

A case in Chencha, South Ethiopia



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Thesis

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To my families

Abstract

Dersseh, W.M., 2017. Agronomic and socioeconomic sustainability of farming systems: a case in Chencha, South Ethiopia. PhD thesis, Wageningen University, The Netherlands, 157 pp.

Potato has multiple benefits and thus can play a vital role in ensuring food security in Ethiopia. However, for diverse reasons, its productivity is low. The farming systems in Ethiopia in which potato is grown, are predominantly mixed farming systems.

Most of the research in Ethiopia is focused on crop-specific constraints and thus there is limited research in which the interrelations between crop and livestock management practices are investigated. There is also not enough research focused on combined analysis of soil nutrient and animal feed balances and agronomic and socioeconomic efficiencies at farm level.

This study assessed production constraints and agronomic and socioeconomic sustainability of the farming systems in South Ethiopia and explored the possible synergetic options to alleviate major constraints. More specifically, the study intended to quantify the variation in input and output among farms, to identify constraints hindering expansion of potato production, to evaluate the sustainability of the farming systems at farm level, to identify constraints of sustainable intensification, and to explore synergetic solutions for the major constraints. Different research approaches were used ranging from lab analysis, household surveys, group discussions, to farm surveys.

Results showed that constraints related to input and product use in potato production vary across households indicating a need for a pluriform advisory model recognizing (and building upon alleviation of) the diversity of constraints identified in this analysis. The sustainability of the farming system is constrained by low agricultural productivity, low soil fertility, poor labour efficiency and limited economic return associated with improper crop rotation, inappropriate soil fertility management practices, shortage of animal feed, labour- and economically inefficient farm practices and labour shortage. However, there is ample scope to overcome the major constraints and simultaneously to optimize farm management.

The core messages of the study can be summarized as follows:

1) the current potato production is characterized by low productivity and economic returns due to various socioeconomic, agronomic and biological factors;

2) the soil fertility is low and there is uneven distribution of nutrients over plots with relatively high fertility levels in the homestead areas;

3) the current labour shortage can be attributed to mainly inefficiency of agricultural management practices and labour migration to towns for economic reasons indicating that the farming system is not sustainable in terms of labour;

4) considering the direct return from animal production, most of the farms had very low gross margin with the current management system and this reduced the overall operating profit of farms. The low return from animal rearing was offset by the relatively high profit from crop production indicating the benefit of mixed farming system in sustaining agricultural production; and

5) each farm can have a wide range of optimized solutions mainly through introduction of improved technologies and subsequent redesigning of the farm managements.

In general, the findings of the current study indicate that it is worthwhile to assess the sustainability of agricultural production in different farming systems and agro-ecologies of Ethiopia. In addition, the combined effect of introducing improved agricultural technologies and subsequent reconfiguring the farm management is very crucial to increase and sustain agricultural production.

Key words: crop rotation, economic efficiency, farm design, feed self-sufficiency, Irish potato, labour efficiency, operating profit, optimization, soil nutrient balance, sustainability

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Chapter 1

General introduction

1. Geography and socioeconomic features of Ethiopia

1.1. Geographical location, land use and population

Ethiopia is located between 3 degrees and 14.8 degrees latitude and between 33 degrees and 48 degrees longitude, in the Horn of Africa, lying between the Equator and the Tropic of Cancer. It has a total area of 1,127,127 km². Altitude ranges from 125 m bsl at Danakil to 4,533 m asl at Ras Dejen with an average elevation of 1600 m asl. Based on 2011 estimates, agricultural land accounts for about 36% of the land area, out of which 15% is arable and 1 and 20% are covered by permanent crops and pasture, respectively (The World Factbook, 2016). The human population is well over 90,000,000 (UN, 2013). The majority of the population is rural and dependent on agriculture, mainly in subsistence and rain-fed farming and livestock production with small land holdings, often fragmented into several plots. Most of these farmers live in the highlands at elevations of 1,500 to 3,000 meters. According to 2015 estimates, the labour force is over 49 million; about 85% of that labour force is engaged in agriculture. In the year 2012, the unemployment rate was 17.5% and the proportion of the population below the poverty line was 39%.

1.2. Ethiopian economy and agriculture

The economy of Ethiopia is based on agriculture and coffee is a major export crop. Livestock products, particularly leather and leather products, also play an important role in export earnings. The agricultural sector is challenged by poor farming practices, low soil fertility levels and frequent drought resulting in low productivity and recurrent food insecurity. According to 2015 estimates, about 41% of the gross domestic product (GDP) is derived from agriculture and the majority (>84%) of exports come from this sector.

Ethiopia has achieved double-digit growth rates for the past decade through government-led expansion of the infrastructure and development of commercial agriculture. The Government has demonstrated a strong commitment to agriculture and rural development by allocating more than 10% of the country's total budget to these sectors. Although the GDP is growing, based on high saving and high investment by public and private sectors, per capita income is still among the lowest in the world.

1.3. Agro-ecology and crop diversity in Ethiopia

Ethiopia is endowed with numerous agro-ecological zones suitable for the production of various types of crops. These zones are traditionally divided into six categories based on elevation ranging from *Berha* or hot lowlands (< 500 m asl) to *Kur* or very cool highlands (> 3700 m asl) (IFPRI, 2006). There are 33 elaborated agro-ecological zones based on elevation, temperature and length of the growing period. The major zones that cover wider areas are the warm arid lowland plains (20%), warm moist lowlands (15%), hot arid lowland plains (11%), warm sub-moist lowlands (10%) and tepid moist mid highlands (8%). The lowland areas (below 1830 m asl) have an average annual temperature of about 27 degrees Celsius with annual rainfall of about 510 millimetres. The midland areas (areas between 1830 and 2440 m asl) have an average annual temperature of about 22 degrees Celsius with annual rainfall between 510 and 1530 millimetres. The highland areas (above 2440 m asl) have an average annual temperature of about 16 degrees Celsius and average annual rainfall of about 1275 millimetres.

In most areas, the rainfall pattern is bimodal resulting in two main cropping seasons, the *belg* and *meher* seasons which receive rainfall from February to May and from June to October, respectively. The *meher* crop season is the main season and produces 90 to 95% of the nation's total cereals output. In some highland areas, the *belg* and *meher* seasons merge into one extended growing period whereby both long-cycle crops (such as sorghum and maize) and short-cycle crops (such as potato, wheat, barley, and teff) can be grown. However, climate variability and climate change are contributing significantly to the food security challenges in Ethiopia (USAID, 2015). The rainfall is increasingly erratic (with marked seasonal deficits when compared to long-term past averages), both droughts and heavy rainfall events appear to be increasingly frequent (with changes in rainfall patterns, including decreased reliability and reduced predictability), and temperatures are increasing (USAID, 2015).

A large diversity of crops is grown in Ethiopia, including cereals, pulses, oilseeds, stimulants, fibres, fruits, vegetables, root and tuber crops, and sugarcane. Cereals are the most important field crops, occupying 86% of the area planted and being the chief element in the diet of most Ethiopians. The principal grain crops are teff (*Eragrostis tef*), wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), which are primarily cool-weather cereals; and maize (*Zea mays*), sorghum (*Sorghum bicolor*), and millet (*Eleusine coracana*), which are warm-weather cereals. In terms of acreage, the second most important crop group after cereals is the group of pulses which are also the second most important element in the national diet, providing principal protein sources and an important dietary supplement to cereal consumption. The most common pulse crops are faba bean (*Vicia faba*), chickpea (*Cicer arietinum*), common bean (*Phaseolus vulgaris*), field pea (*Pisum sativum*) and lentil (*Lens culinaris*). Vegetables include onion (*Allium cepa*), tomato (*Solanum lycopersicum*), carrot (*Daucus carota*), pepper (*Capsicum annuum*), cabbage (*Brassica oleracea*) and kale (*Brassica oleracea*). The consumption of vegetables and fruits (such as banana, apple and orange) is relatively limited, largely because of their high cost. Root and tuber crops include potato (*Solanum tuberosum*), sweet potato (*Ipomoea batatas*), enset (*Enset ventricosum*), taro (*Colocasia esculenta*), cassava (*Manihot esculenta*) and yams (*Dioscorea spp.*).

1.4. The potato crop

The potato is the third most important food crop in the world after rice and wheat in terms of human consumption (CIP, 2016). There are more than 180 species and 4,000 varieties of native potatoes. Potato can grow from sea level up to 4,700 m asl. Potato can yield two to four times the food quantity of grain crops per hectare (CIP, 2016; Solutions Consulting, 2016). It produces more food per unit of water than any other major crop and is in fact up to seven times more efficient in using water than cereals (CIP, 2016; Solutions Consulting, 2016). Potatoes are produced in many countries worldwide and they are a fundamental element in the food security for millions of people. Thus, potato is a critical crop in terms of food security in the face of population growth and increased hunger rates (CIP, 2016).

Potato has been introduced in Ethiopia in 1858. In the early stages after introduction, the adoption of potato by farmers was slow and was confined to the cool highlands of the country. At the end of the nineteenth century, wider adoption of the potato occurred in response to a prolonged famine. The production of potato has increased considerably through the twentieth century. Currently, the crop is grown in all regions, but widely grown in the highland and mid-altitude areas of the country (MoARD, 2009). Over 29 potato varieties, which are high-yielding, disease-resistant and early-maturing, have been released in the country (Haverkort, *et al.*, 2012). In the main cropping season of 2015, the potato crop has been grown on 70,131 ha of land by 1,379,115 households and 943,334 t of yield has been obtained nationally (CSA, 2016). Potato production accounts for 33% of the total land allotted to root and tuber crops, followed by taro (23%) and sweet potato (19%). In the same main cropping season of 2015, the crop was grown on 10,724 ha of land by 319,495 households and 171,476 t of yield was obtained in the Southern Region (CSA, 2016). Potato is among the major food crops that are consumed across the country and in some areas potato is used as a staple food for a considerable portion of the population, particularly in the highland areas. Because of its high productivity and nutritious tubers, potato is a high potential food security crop in Ethiopia. The crop also matures earlier than many other crops and thus potato production serves to overcome food shortage periods which happen for a few months every year. However, the production of potato is constrained by several factors that include unavailability of healthy seed tubers and insufficient seed tuber quality (Hirpa *et al.*, 2010; Gebremedhin *et al.*, 2008; Berga and Gebremedhin, 1994), different diseases and suboptimal agronomic practices (Baye and Gebremedhin, 2013).

2. Farming system and sustainability

Different authors give different definitions to the term 'farming system'. A farming system is a unique and reasonably stable arrangement of farming enterprises managed by the household according to well-defined practices in response to physical, biological and socioeconomic environments and in accordance with the goal, preferences and resources of the household (Shaner *et al.*, 1982). According to Dixon *et al.* (2001), it is a population of individual farm systems that have broadly similar resource bases, enterprise patterns, household livelihoods and constraints, and for which similar development strategies and interventions would be appropriate. However, Giller (2013) suggested modifying this definition as follows: 'a population of individual farm systems that may have widely differing resource bases, enterprise patterns, household livelihoods and constraints'. According to Taunk and Shrivastava (2007), a farming system consists of an integration of different farm enterprises that ensure growth, stability and overall productivity.

On the other hand, it is also necessary to define the term farm household. A farm household is a social and economic unit undertaking any kind of agricultural and other income generating activities in which household members generally live together managing resources to obtain food, clothing, housing and other necessities (Langeveld *et al.*, 2007).

Analysis of farming systems includes:

1. a detailed analysis of the biophysical environment, socioeconomic and policy related factors that influence farming;
2. understanding of the relationships between different enterprises within the system; and
3. identification of opportunities and constraints that lead to the categorization of domains for intervention.

Therefore, analysis of farming systems helps to provide the information and data required to design, plan, implement, monitor and evaluate interventions to improve the productivity and sustainability of a particular farming system that can be used by extension workers, agronomists, policy makers and economists (Oben and Boukong, 2012).

Sustainability in agriculture is a complex and dynamic concept that includes a wide range of environmental, resource-based, economic, and social issues. Its goals include satisfaction of human food; enhanced environmental quality; sustained economic viability of farm operations; and enhanced quality of life for farmers and society (NAP, 2010). Therefore, a sustainable agro-system should maintain or improve the economic viability of agricultural production (Lescot *et al.*, 2007) without depleting the natural resource base (Gruhn *et al.*, 2000). A farming system is considered economically sustainable when it generates a net income per work unit higher or equal to the reproduction threshold (Canali and Segre, 2007). In addition, sustainable agriculture improves social relations between farmers and rural communities, enhances empowerment (e.g. by providing facilities to build a strong rural social infrastructure), alleviate rural communities poverty and ensure and possibly create employment (SAI Platform, 2010). Moreover, sustainability is a question of equity and justice which are matters of ensuring equal access to specific things to which all have equal rights. However, ensuring the economic, social and ecological sustainability of farms is a dynamic and complex adaptation process, in which strategies and contexts co-evolve (Darnhofer *et al.*, 2010). Therefore, sustainable farming system solutions need to include the spatially diverse farming enterprises (Lescot *et al.*, 2007).

The rise in human population and land scarcity necessitates an increase in production through sustainable agricultural intensification to achieve both food security and sustainability (Struik *et al.*, 2014b). Particularly in Sub-Saharan Africa, where large yield gaps persist, intensification of smallholder agriculture is a must and the pathways to sustainable intensification should recognise the diversity of the farming environments (Struik and Kuyper, 2014). The challenge of achieving sustainable food security is particularly prominent in Ethiopia where subsistence farming prevails, farm sizes are increasingly smaller and fragmented, and where there is high climate variability and climate change. However, developing countries have relatively more options to intensify and increase food production with less environmental impacts than developed countries (Kuyper and Struik, 2014).

Constraints for sustainable intensification of agricultural systems in Africa are mainly of economic and institutional nature and constraints are caused by the absence, or poor functioning of institutions such as policies and markets, limited capabilities and financial resources, and ineffective interaction and collaboration between stakeholders (Schut *et al.*, 2016). Therefore, sustainable intensification in Africa requires a mix of technological and institutional changes and creation of:

(i) a more conducive environment to support agricultural development,
(ii) more diverse product chains,
(iii) market stability, or
(iv) collaboration in resource management (Struik *et al.*, 2014a).

Because of scarcity of resources, consideration of efficiency is very important for assessing sustainability of a farming system. A successful assessment methodology of economic and environmental performance of a farm household should combine (or integrate) knowledge from various disciplines and should describe the existing variability in farm livelihood strategies in relation to household endowment or prevailing existing conditions. Such methodology should not be too data intensive (its implementation should be possible using available data) or it should not require costly collection of additional data (Langeveld *et al.*, 2007).

3. Rational of the study

The farming systems in Ethiopia are predominantly mixed farming systems (CSA and World Bank 2013). Components of a farming system are interrelated and a solution to constraints in one component may have an impact on the other components in the system and this necessitates optimized solutions. Moreover, agricultural production is influenced by different biophysical, socioeconomic and climate factors and thus redesigning the current farming systems should be an integral part in searching for optimized solutions to ensure sustainable production (Martin *et al.*, 2013). Therefore, understanding at farm level the main obstacles and constraints for production is a base to find optimized solutions for sustainable production. In addition, in-depth understanding of the constraints of important crops (such as potato) which give high yield, and large quantities of energy and protein per unit area, is vital to ensure food security. However, most of the research in the country focuses on understanding of and finding solutions for an individual constraint and thus there is limited research to assess the interrelations between crop and livestock management practices in improving sustainability of production. There is also insufficient insight into the relationships between soil nutrient and animal feed balances and agronomic and socioeconomic efficiencies at farm level. Exploring solutions for different constraints, such as low soil fertility, inefficient labour and poor economic performances, using multi-objective optimization is also limited (Awulachew *et al.*, 2009). Moreover, most of the research concentrates on certain parts of the country while other areas such as Chencha receive limited attention.

4. Overall aim and objectives

The study aims to identify the constraints to the agronomic and socioeconomic sustainability of the farming systems of the study area and to explore synergistic options to alleviate these major constraints. The specific objectives are:

1. To create a baseline of the general production system, to quantify the variation in household and farming types, and to identify and rank constraints to improving potato yield as perceived by farmers;
2. To quantify the frequency of potato cropping in the rotation, to evaluate animal feed self-sufficiency, to understand the existing soil nutrient balance and status, the labour use and economic efficiencies at plot and farm level;
3. To explore synergistic solutions for operating profit, labour and organic matter balances and to explore how reconfiguration of the current and newly introduced practices and

technologies can contribute to higher production and better socio-economic and environmental performances of farms.

5. Methodology

5.1. Brief description of the study area

The Southern Nations, Nationalities, and Peoples' Region is one of the nine ethnic divisions of Ethiopia. It is located in the southern and south-western part of Ethiopia between 4°27' and 8°30' N latitude and between 34°21' and 83°11' E longitude. It accounts for more than 10 percent of the country's land area. The Region has a multi-ethnic society consisting of more than 80 ethnic groups which are distinguished by different languages, cultures, and socioeconomic organizations. The majority of the ethnic groups in the country are found in this Region. The Region is divided into 13 administrative zones and 8 special districts and has a total of 126 districts (including the 8 special districts) which are again subdivided into 3594 rural and 355 urban administrative units locally known as kebeles. Chencha is one of the 17 districts of the Gamo-Gofa zone and it consists of 45 kebeles. The district is located at 6°15' N 37°40' E and has two agro-ecological zones: midland and highland. The current study was conducted mainly in selected highland kebeles where potato is widely grown.

5.2. Methods and approaches

This study was conducted with households and farms in Chencha in close collaboration with two other PhD studies (which aimed to improve seed potato quality and understand efficiency of knowledge transfer) in the same project, called the Potato Centre of Excellence (Vita, 2015). The role of the current study was to understand the sustainability of farming systems at farm level. Fig. 1 describes the methodological approach used in the current study and the breakdown of the study into different chapters. In the beginning of the study, i.e. in 2012, a household survey and key informant interviews were conducted, jointly with fellow PhD candidate Yenenesh Gebresilase Tadesse. These research activities were carried out to understand the major crop production system and the bottlenecks of production in the potential potato production areas (midland and highland) of Chencha and to assess the potato farming system.

We focused on the variation in input and output use in household and farming types and related constraints, especially in the highlands. The questionnaire used in the household survey and secondary data collection covered socioeconomic situations and farm management practices. This was followed by an evaluation of the sustainability of the existing farming system using soil nutrient, economic performance and labour balance as main indicators. Detailed farm and household surveys were conducted across 12 farms throughout the year 2013. Key informant interviews were used for common issues across all farms. From plots of farms, soil and crop samples were collected for chemical analyses. These data (combined with weather and literature data) were used in the FarmDESIGN model to quantify nutrient flows and balances and calculate the economic performances and labour balances. The survey included assessment of the rotation or cropping sequence pattern of potato in the year 2013 and 2014. Subsequently, synergetic solutions were explored for the major identified constraints to maximize operating profit, minimize farm labour requirement and to maximize organic matter balance. We used data from the detailed farm survey and additional secondary data on improved technologies and practices as bases to explore synergetic solutions.

6. Outline of thesis chapters

This first chapter has presented an overview of Ethiopia's geographical location, land use and population. It has also provided descriptions of the country's agroecology and crop diversity, concepts of farming systems and sustainability and the rational of the study with its overall aim and specific objectives. In Chapter 2, descriptive statistics were computed on biophysical and socioeconomic data to understand the major crop production systems and bottlenecks in the two agro-ecological zones of the potential potato production areas of Chencha, i.e. the midlands and the highlands. The results were used as input for Chapter 3 which focuses on the highland agro-ecology areas where cropping systems are relatively similar and potato is widely grown. Chapter 3 shows the degree of association between input/output use and related constraints with household characteristics in potato production. The data were computed using a Principal Component Analysis. The major findings were used as criteria to select farms/farm households for the more detailed farm survey described in Chapter 4. Chapter 4 attempts to identify the main obstacles and constraints for sustainable intensification at farm level through a detailed farm survey conducted for one year in two growing seasons. Using the FarmDESIGN model, farm gate balances were computed for soil nutrients, animal feed, labour and economic gain, as well as nutrient flows for major soil nutrients. The soil nutrient statuses were determined for each farm through lab analyses. Moreover, the frequency of potato cultivation was described per plot and labour and economic efficiencies were quantified per farm and per plot. Chapter 5 explores optimized solutions for major constraints identified in Chapter 4, i.e. cash and labour shortages and low soil fertility. Again using the FarmDESIGN model, optimized solutions were explored in two scenarios, i.e. optimization based on the current farm configurations or based on partially intervened (with improved technologies and practices) farm configurations. This chapter discusses the possibility of simultaneous improvement of the constraints and possible challenges for implementation. The overall findings of the current studies were discussed in Chapter 6 focusing on the possible impacts and implications for further considerations.

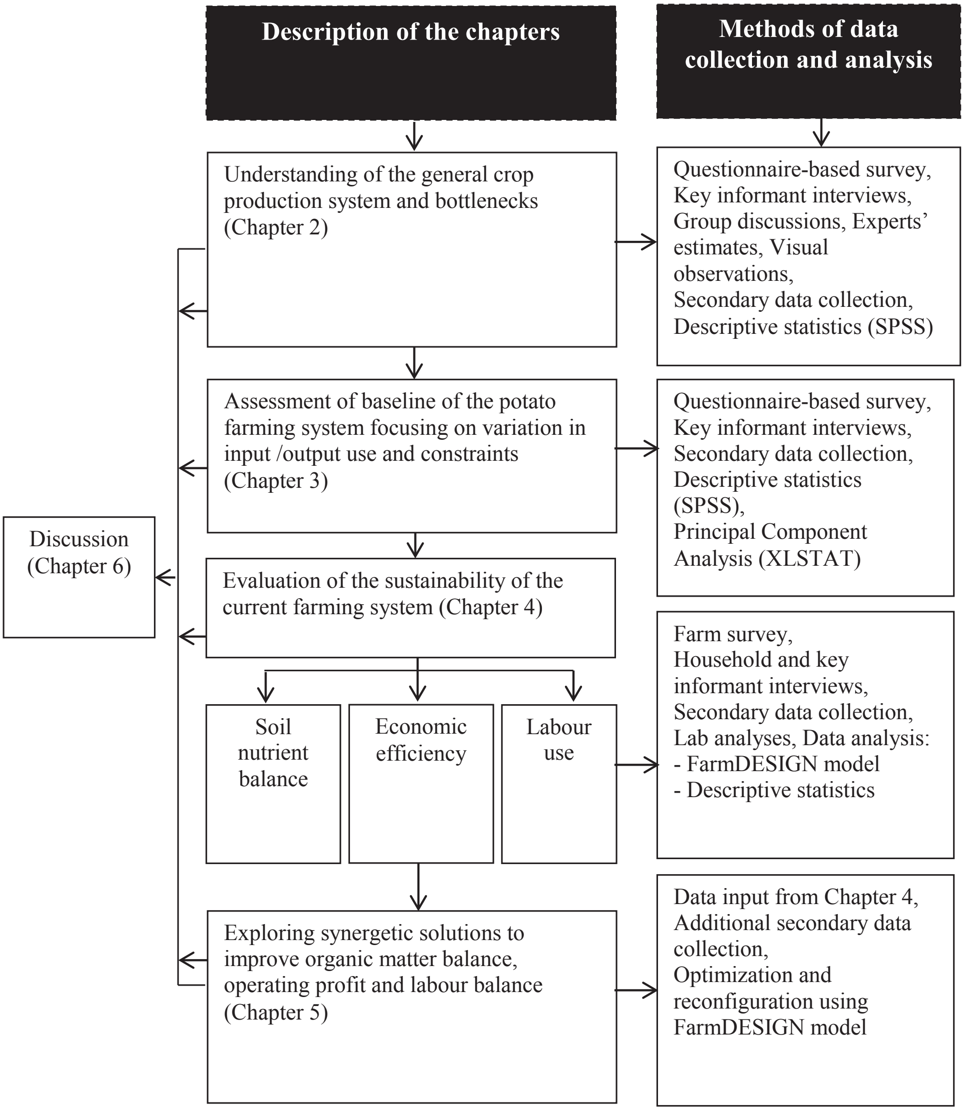

Fig. 1. Outline of methodology used in the current study

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Chapter 2

The farming systems of potential potato production areas of Chencha, Southern Ethiopia

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Abstract

A survey was conducted in 2012 to assess the diversity of farming systems in the potential potato production areas of Chencha in southern Ethiopia. It was part of a PhD research study on evaluation and optimization of sustainability of farming systems which is part of an initiative to make the area a potato centre of excellence. Household surveys (n = 57) and farmers' group discussions were used to collect data from 21 villages. A mixed farming system was the prevailing system in the area where crops and livestock are simultaneously grown. The major crops grown in the area were potato, enset, wheat, barley and kale. Most crops were grown as food and cash crops. Barley and enset were mainly grown for household consumption. Farmers used improved varieties mainly for potato (73% of respondents) and wheat (77%). There are two cropping seasons per calendar year and crop rotation is common in the area. The dominant rotation system practised by 95% of the respondents was planting potato followed by wheat or barley. The common intercropping practices were mixed intercropping of barley with lentil and wheat with linseed. Based on local classification there were 12 soil types. The most common ones were Modo (dark loam), Gobo (red clay) and Kalta (brown clay). Fertilizers used were farmyard manure (97% of households), compost (40%), urea (78%) and diammonium phosphate (DAP) (81%). Farmers used low rates of inorganic fertilizers due to shortage of cash. Most of the households (55%) obtained a cash income from agricultural activities, mainly from crop production. The most important off-farm activity was weaving. Household food demands were met from own farm and external sources. Constraints of the farming system that need research and policy interventions include soil fertility depletion, low productive crop varieties, shortages of land, and lack of improved seed and of cash.

Keywords: Chencha, Ethiopia, farming system, potato, *Solanum tuberosum*

1. Introduction

Potato has been cultivated in Ethiopia since 1858. Its production area has reached 59,504 ha in the country and 8978 ha in the Southern Nations Nationalities and Peoples' Region (SNNPR) in the main cropping season (CSA, 2012). Chencha is one of the areas in SNNPR where potato is one of the most important crops. Shortage of seeds of improved varieties is one of the bottlenecks of potato production in the area. Non-governmental organizations such as Vita and World Vision have recently been involved in disseminating improved potato varieties. Vita has capacitated and organized farmers to produce and sell seed potato tubers at the local level. Recently, a research-based development project has been launched to make Chencha a centre of excellence for seed potato with the technical and financial support of Vita, Teagasc and Wageningen University. One of the aims of the project is to ensure sustainability of the farming system while producing potato in Chencha. A farming system is a system where different farm enterprises that ensure growth, stability and overall productivity are integrated (Taunk and Shrivastava, 2007). Potato is one of the components of the farming systems in Chencha and its production is linked with other prevailing farm and off-farm enterprises. Therefore, there was a need to conduct an initial survey to understand the major crop production systems and the bottlenecks of production in the potential potato production areas of Chencha. This chapter presents the findings of this survey.

2. Materials and Methods

2.1. The study area

The study area was Chencha which is a district in the SNNPR of Ethiopia. The area of the district is 373.5 km^2 with a human population density of 388 persons/km^2 (CSA, 2011). The altitude ranges from 2000 to 3000 m above sea level (m asl). The agroecology is classified as highland (> 2500 m asl) and midland (2000–2500 m asl). The district is divided into 45 lower administrative units which are locally known as kebeles. Potato is produced in all kebeles. However, the potential potato production kebeles are 33 out of which five were selected for the study in consultation with experts of Chencha Office of Agriculture (COoA). Four of these kebeles represent the highland agroecology, whereas one kebele represents the midland agroecology. A total of 21 villages were selected from all kebeles. Each kebele was represented by two to six villages (Table 1).

Table 1. Selected kebeles and number of villages and their agroecology

Kebele	Number of villages	Altitude[a] (m asl)	Agroecology
Losha	4	2749	Highland
Yuera	5	2600	Highland
Laka	6	2578	Highland
Tegecha	4	2250	Midland
Gendo Gembela	2	2640	Highland

[a] The altitudes were taken using a GPS (global positioning system) where the interviews were conducted and might not show the range of altitudes in a kebele.

2.2. Farmer selection

A total of 57 households were selected randomly from all selected kebeles. Care was taken to make sure that different wealth classes and genders were included. Nine to 14 households were selected to represent each kebele. Local classification of wealth classes was adopted for selection. Indicators used to classify wealth status were: (i) type and number of houses; (ii) number of cattle and horses; (iii) size of land holding; (iv) age of owned enset plants; and (v) amount of bamboo and eucalyptus trees. The proportions of selected rich, medium and poor households were 30%, 40% and 30%, respectively.

2.3. Data collection and analysis

Individual household interviews were conducted using a questionnaire to collect data on crops, soils, and sources of income, food and inputs. The interviews were conducted with the household head from October to November 2012. Group discussions, key informant interviews, secondary data and experts' estimates were also used to collect some data such as productivity and constraints. The feeling method and visual observation were used to identify soil texture and colour, respectively. The household data were analysed using SPSS software.

3. Results and Discussion

3.1. Rainfall pattern

The rainfall pattern is bimodal (Fig. 1) resulting in two cropping seasons. The first season which is locally known as *belg* extends from February to May whereas the second season called *meher* is between June and October. The rainfall data from the COoA compound (unpublished) revealed that the average monthly rainfall was at a peak (179 mm) in April in the *belg* season although the total rainfall received was higher in *meher* (506 mm) than in *belg* (327 mm). The average total annual rainfall varies over years ranging from 830 mm to 1679 mm in 2003 and 2006, respectively (Fig. 2). Farmers complained that the distribution of the rainfall has changed over time and affected the performance of crops. Rainfall amount and distribution are commonly unpredictable in Ethiopia limiting the choice of crops, varieties, planting times and production (Belay, 2003).

3.2. Crop husbandry

3.2.1. Types of crops grown and their importance

There were 28 crop types grown in different agroecologies of the district (Table 2). The diversity of crop types included cereals, pulses, root and tuber crops, vegetable and fruit crops, oil and stimulant crops. The number of crops grown per household ranged from five to 14. However, most of the households grew seven to eight crops. The major crops grown by most (60–100%) of the households were potato (*Solanum tuberosum*), enset (*Enset ventricosum*), wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), kale (*Brassica oleracea*), faba bean (*Vicia faba*) and apple (*Malus domestica*) (Fig. 3).

Farmers mainly used improved varieties for a few crops including potato (73%), wheat (77%), maize (72%) and barley (21%) (Table 3). Few farmers used improved varieties of faba bean and field pea. Rich farmers were more inclined to use improved varieties of relatively more crops than medium and poor farmers. For instance, among the potato growers 100%, 86% and 33% of rich, medium and poor farmers, respectively, used improved varieties of potato. The major sources of seeds were own farm and external sources for all wealth and gender

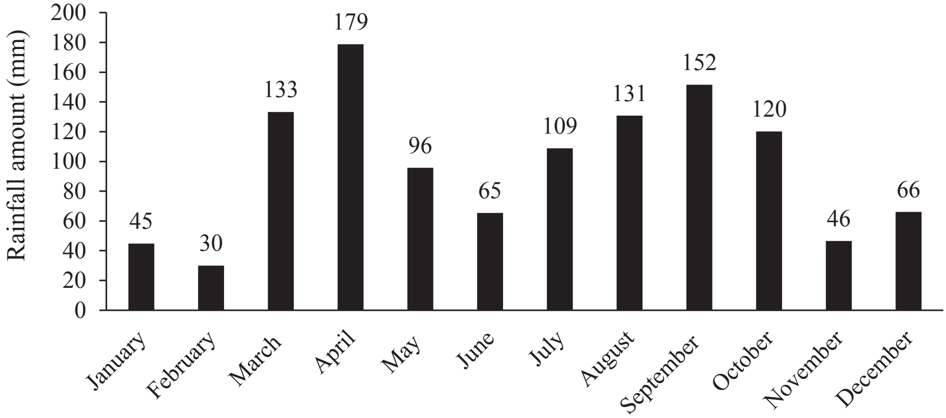

Fig. 1. Monthly average (8 years) rainfall at Chencha Office of Agriculture compound

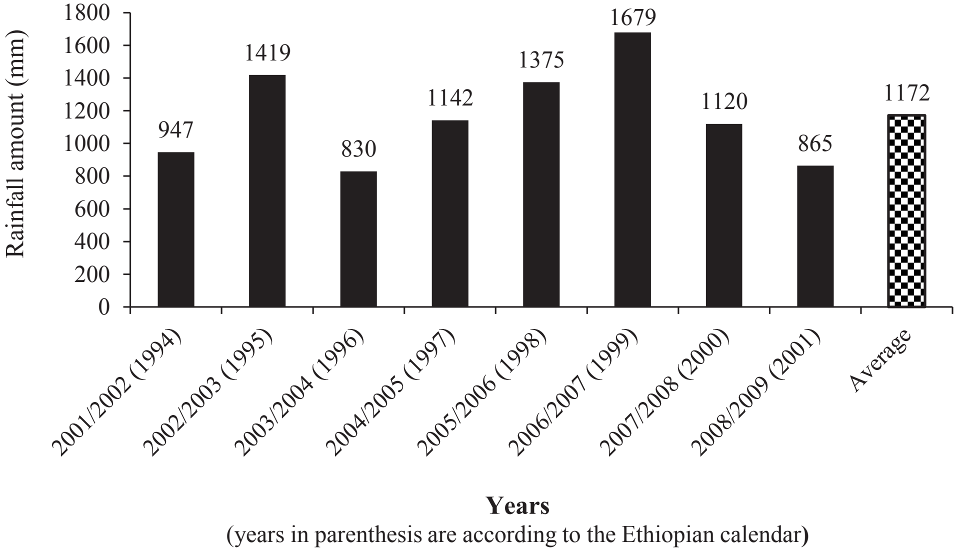

Fig. 2. Annual total rainfall in different years at Chencha Office of Agriculture compound

classes. Female-headed households depended more often on their own farm as the seed source than male-headed households. Assessment reports indicate that only 4.6% and 8.4% of sample farmers from SNNPR (n = 852) and Ethiopia (n = 4587), respectively, use improved varieties of crops (Amsalu, 2006), whereas the majority (80% and 75%, respectively) use local cultivars.

Table 2. Types of crops grown in different agro-ecologies of Chencha district

Crops grown in highlands only	Crops grown in highlands and midlands	Crops grown in midlands only
Faba bean (*Vicia faba*)	Wheat (*Triticum aestivum*)	Maize (*Zea mays*)
Fenugreek (*Trigonella foenum-graecum*)	Barley (*Hordeum vulgare*)	Sorghum (*Sorghum bicolor*)
Field pea (*Pisum sativum*)	Triticale (x-*Triticosecale*)	Teff (*Eragrostis tef*)
Lentil (*Lens culinaris*)	Potato (*Solanum tuberosum*)	Haricot bean (*Phaseolus vulgaris*)
Chick pea (*Cicer arietinum*)	Enset (*Enset ventricosum*)	Sweet potato (*Ipomoea batatas*)
Amochi (*Arisaema schimperianum*)	Welayta dinich (*Plectranthus edulis*)	Coffee (*Coffea arabica*)
Beet root (*Beta vulgaris*)	Kale (*Brassica oleracea*)	Sugar cane (*Saccharum officinarum*)
Carrot (*Daucus carota*)	Cabbage (*Brassica oleracea*)	
Linseed (*Linum usitatissimum*)	Garlic (*Allium sativum*)	
Plum (*Prunus domestica*)	Onion (*Allium cepa*)	
Apple (*Malus domestica*)		

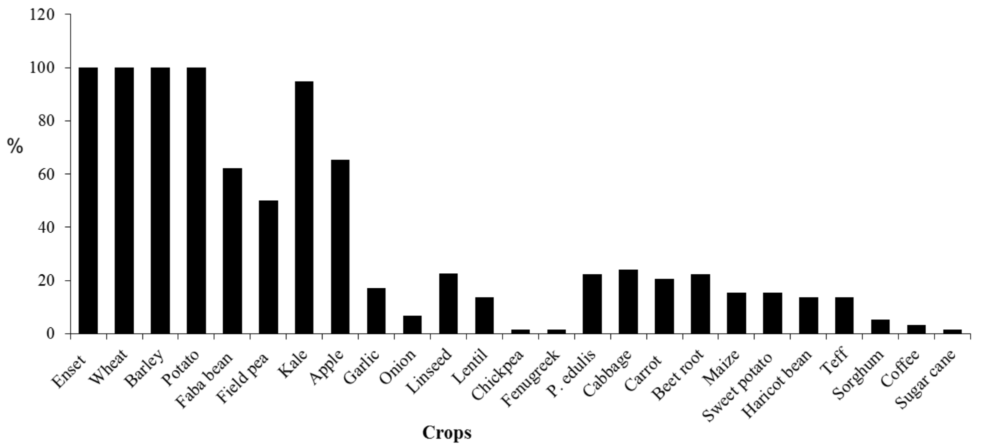

Fig. 3. Percentage of households cultivating different crops in Chencha area

Table 3. Percentage of households using improved varieties of crops and using different seed sources per wealth status and gender

Crops and seed sources	% of respondents and number of samples (n) by wealth status and gender										
	Wealth status						Gender				Total (%)
	Rich		Medium		Poor		Male		Female		
	%	n	%	n	%	n	%	n	%	n	
Crops											
Potato	100	17	86	22	33	18	-	-	-	-	73
Wheat	94	17	82	22	56	18	-	-	-	-	77
Barley	29	16	27	22	6	18	-	-	-	-	21
Faba bean	12	16	6	18	0	13	-	-	-	-	6
Field pea	6	16	0	18	0	13	-	-	-	-	2
Maize	100	1	50	4	67	3	-	-	-	-	72
Seed sources											
Own farm	26	5	17	3	28	6	14	12	33	2	24
Own farm & external	74	13	83	19	72	12	86	34	67	10	76

3.2.2. Purposes of growing crops

The main purpose of growing crops was either as sources of food (household consumption) or income, or both, depending on the crop type and wealth class. The majority of rich and medium households grew enset, wheat, potato and sweet potato as sources of food and cash, whereas the majority of poor households grew these crops as sources of food. Barley and haricot bean were mainly grown for food whereas apple was produced mainly as a cash source by all wealth classes. Vegetables were grown mostly by rich and medium farmers for home consumption and the market. Generally, poor farmers grew most of their crops primarily to meet their household's food demands implying that poor farmers do not have surplus produce to sell. About 56–85% of households in SNNPR use most of their crop products for home consumption (CSA, 2010). Relative to other crops, wheat, onion and coffee were largely used for sale by 30%, 42% and 55% of households, respectively. Potato was used for food, seed and sale by about 61%, 27% and 11% of households, respectively.

3.2.3. Overall importance of crops

Results of ranking the overall importance of crops within the wealth classes revealed that enset was the most important crop for all wealth classes for the main reason that enset is resilient to weather fluctuation and its product is available throughout the year in all households. Seifu (1996) also stated that enset is the best adapted crop in areas where land holding is small because of its high productivity. Potato was the second most important crop for rich and medium farmers while it was the third most important crop (like wheat) for poor farmers whose second most important crop was barley. The third and fourth most important crops for rich and medium farmers were barley and wheat, respectively, while the third most important crop for poor farmers was potato or wheat. Overall, the most important crops in the area were enset (84%), barley (40%), potato (36%) and wheat (28%) irrespective of wealth classes (data not shown).

3.2.4. Cropping systems

Sole cropping was most common in all study areas with some practices of intercropping. The most common intercropping practices in highland areas were mixed cropping of barley with lentil and wheat with linseed. Other intercropping practices were wheat mixed with a small proportion of barley, enset with kale and apple with either kale or garlic. Amochi (*Arisaema schimperianum*) was usually not grown as a sole crop because it takes a long time to mature. Therefore, it was intercropped with different crops except field pea (the yield of which is strongly affected by intercropping) and triticale which highly affected Amochi. There was a little practice of mixed cropping of faba bean with a small proportion of field pea. The main reasons for intercropping were shortage of land and to utilize the wide open spaces of permanent crops. Welayta dinich (*Plectranthus edulis*) was not intercropped with any other crop as it is easily affected through competition with other crops. Maize–haricot bean intercropping was also common in the midland areas.

Double cropping and crop rotation in two seasons per year were very common practices in all areas. There were different practices of crop rotation arrangements. The most dominant double cropping or rotation system practised by about 95% of the respondents was planting potato followed by either wheat or barley. Other important practices included barley followed by either potato or wheat, faba bean, or field pea. Usually the same crop was not successively double cropped although sometimes barley, potato and sweet potato were double cropped on the same plot. Most vegetables were planted in home gardens and they usually succeeded each other. Pulse crops were commonly sown as the succeeding crop in double cropping.

3.2.5. Sowing dates

Some crops such as potato, barley and kale are sown in both *belg* and *meher* seasons (Table 4). Potato is grown more in the *belg* season. Welayta dinich can be planted in the beginning of the two seasons. Kale has a wide range of sowing dates extending from February to September but the best time is the beginning of the *meher* season. Most crops in the highland areas are sown in the *meher* season, predominantly in August, whereas most crops in the midlands are sown in the *belg* season. Enset can be planted before the onset of rainfall as it is less affected by a delay of rainfall. Vegetables could be produced either using irrigation during the off-season or as a rain fed crop. The first 1 or 2 months before planting (transplanting) are seedling-raising times particularly for cabbage. Amochi is usually planted immediately after harvest and there is no specific planting date as the crop is usually grown as a volunteer. Generally, farmers determine specific sowing dates of most crops depending on the onset of the rainfall.

3.2.6. Seeding rates, harvesting dates and productivity of crops

Variations were observed in the seeding rates used by farmers across villages for the same crops (Table 5). The seeding rates used for local cultivars of potato were 600 kg/ha and 1600 kg/ha in Gendo Gembela and Laka areas, respectively. However, farmers who had access to improved varieties of potato and had received training used seeding rates similar to the national recommendation which is 1800–2000 kg/ha (MoA, 2006). The seeding rate used for wheat in the Gendo Gembela area was 88 kg/ha whereas in Laka it was 125 kg/ha and 160 kg/ha for improved and local varieties, respectively. The national recommendation is 125–175 kg/ha.

The seeding rates used for faba bean and field peas were low but that of barley was near to the recommended rate.

Potato is ready to be harvested within 3–4 months (Table 5). Most cereal crops were harvested within 4 months with exceptions of triticale and sorghum which were harvested in 9 months. Depending on the cultivar type and management, enset matured between 36 and 120 months. However, most cultivars matured between 60 and 84 months and most cultivars grown for their corm product matured in 36 months. The first fruit setting of apple ranged from 36 to

Table 4. Sowing dates of different crops throughout a year in Chencha

Crop type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Enset		La	La									
Wheat							La	GG, Lo, La				
Barley												
Potato												
Faba bean							La	GG, Lo				
Field pea												
Kale												
Linseed												
Lentil												
P. edulis		GG			Lo							
A.schimperianum												
Cabbage, carrot, beet root, onion & garlic		Trans plant - rain fed GG, Lo, La		La					Raise seedlings		Trans plant - irrigation	Raise seedlings
Apple							GG, Lo	La				
Maize			Te									
Sweet potato	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te
Haricotbean			Te									
Tef			Te					Te				
Sorghum			Te									
Coffee				Te								

Source: Group discussion with farmers from Gindogembela (G), Losha (Lo), Laka (La) and Tegecha (Te)

Table 5. Seed rate, harvesting dates and productivity of major crops across locations in Chencha

Crop type	Seed rate (kg ha^{-1})		Harvesting dates (months)			Yield (kg ha^{-1})			
						Estimated by farmers		Annual report[a]	
	Gendo Gembela	Laka	Gendo Gembela	Losha	Laka	Gendo Gembela	Laka	*Belg*	*Meher*
Potato	600-2000	1600-2000	42828	4	3	7000, 2000 (local)	24000, 12000 (local)		18500
Wheat	88	125-160	4	4	5	1200-2200	1200		2600
Triticale	-	-	9	-	-	1600	2000		
Barley	120	140	4	4	5	1600	1600	3690	(152)
Maize	-	-	-	-	5-6	-	-		
Sorghum	-	-	-	-	9	-	-		
Teff	-	-	-	-	3.5	-	-		(450)
Faba bean	40	-	4	4	5	500	-		940
Field pea	80	-	4	4	5	300	-		840
Lentil	-	-	4	4	5	-	-		
Linseed	-	-	4	4	5	-	-		
Haricot bean	-	-	-	-	3	-	-		
Enset[b]	1 x 1m	2 x 2m	36-72	60	36-84	-	-	7000 (11464)	
Kale	-	-	3	3	3	-	-		(7275)
Cabbage, carrot, beet root, onion & garlic	-	-	3	3	4-5[c]	-	-	19000	19000
Plectranthus edulis	-	-	7	7	9	-	-		
Arisaema schimperianum	-	-	36	$\geq$36	$\geq$24	-	-		
Sweet potato	-	-	-	-	42890	-	-	18000	
Apple			36-60	36-60	36-60			(6857)	
Coffee	-	-	-	-	36	-	-		

[a]Annual report (2012) of COoA (unpublished). Numbers in parentheses were taken from report (2012) of Gendo Gembela Development Office.

[b]Enset yield estimates did not consider growing years (average = 6).

[c]Onion and garlic are harvested in 5 months while other vegetables are harvested in 4 months.

60 months depending on the crop management.

The productivity of potato was variable across locations (Table 5). In Gendo Gembela, it ranged from 2000 to 7000 kg/ha for local cultivars and improved varieties, respectively. This productivity of potato was lower than its productivity in the 2012 cropping season both at the national (7989 kg/ha) and the regional (9015 kg/ha) level (CSA, 2012). But, the productivity of potato in Laka was relatively high (i.e. 12,000 kg/ha and 24,000 kg/ha for local and improved varieties, respectively). The productivity of potato in Chencha was very high (18,500 kg/ha) as reported by COoA. The productivity of wheat ranged from 1200 to 2200 kg/ha for local and improved varieties, respectively, while the national and regional productivity was about 2000 kg/ha in 2012 (CSA, 2012). The productivity of enset ranged from 1167 to 1911 kg/ha/year. However, enset yield can reach 7000 kg/ha/year (Hiebsch, 1996).

3.2.7. Tillage and weeding frequency

Frequency of ploughing for the same crops was more or less similar in different areas (Table 6). The differences observed were related mainly to the methods of ploughing and whether the land was previously virginal or cultivated. More frequent ploughing is required for oxen ploughing and virginal land. Hand ploughing turns the soil relatively deeper and is used for crops such as enset. The most common ploughing frequency for most crops including potato was four times. The frequency of ploughing for field pea, faba bean and linseed was usually once.

The frequency of weeding varies per crop type and depends on weed growth and method of planting (Table 6). A potato field is weeded three times in most areas, however, it varies from one to three times for row planting and local practice, respectively, in Laka. The frequency of weeding for young perennial crops such as enset and apple is higher than for old plant stands. It is not common to weed the fields of Amochi when it is grown as a sole crop. Wheat and barley plots are weeded once in all locations. Generally, the target of weeding in all areas is mainly to use weeds as feed for livestock and not to avoid the adverse effect of weeds (Farm Africa, 1994).

Table 6. Ploughing and weeding practices for different crops across locations in Chencha

Crop type	Frequency of ploughing per location[a]			Frequency of weeding per location		
	Gendo Gembela	Losha	Laka	Gendo Gembela	Losha	Laka
Potato	4	4	4	3	3	1-3
Enset	3	1	1-2	[b]	[b]	1-2
Wheat	4	4	3-4	1	1	1
Barley	4	4	3-4	1	1	1
Faba bean	1	1	2	1	1	1
Field pea	1	1	2	1	0	0
Kale	4	1	3	3	-	4-5
Linseed	4	4	1	1	-	1
Lentil	4	4	1	1	-	1
Plectranthus edulis	4	1	3	3	2	3
Arisaema schimperianum	1	1	1	0	0	0
Cabbage, carrot, beet root, onion & garlic	4	4	3	1	-	3
Apple	4	4	3	[b]	-	1
Maize	-	-	3	-	-	2
Sweet potato	-	-	3	-	-	2
Haricot bean	-	-	3	-	-	1
Teff	-	-	4	-	-	2
Sorghum	-	-	3	-	-	1
Coffee	-	-	-	-	-	1

[a] Includes seed bed preparation and seed covering.
[b] Depends on weed growth

3.2.8. Soil types and fertility management

Based on local classification, there were different types of soils in the study areas. However, the most commonly occurring soil types across locations were Modo (69%), Gobo (67%) and Kalta (50%). The colour of most soil types were red and brown. The soil texture was predominantly clay (data not shown). Fertilizer types used in the study areas were diammonium phosphate (DAP) (81% of households), urea (78%), farmyard manure (97%) and compost (40%). DAP was used by 100%, 86% and 56% of rich, medium and poor farmers, respectively (data not shown). Practices of using urea by wealth class were more or less similar to the practices of DAP. More households used farmyard manure than either DAP or urea in all wealth classes. Practices of use of inorganic fertilizers were negatively correlated with practices of organic fertilizers particularly compost (r = –0.81 and –0.88 for DAP and urea, respectively). Farmers also use leaves of *Croton macrostachyus*, *Erythrina abyssinica* and *Hagenia abyssinica* to reduce soil acidity in Chencha (Wassie and Shiferaw, 2009).

Most farmers used low amounts of chemical fertilizers due mainly to a shortage of cash. Most rich households used 100 kg DAP (39%) and 50 kg urea (44%) per year for all crops grown with inorganic fertilizers (data not shown). Most medium households used 50 kg and 25 kg DAP and urea, respectively. The majority of poor households did not apply DAP and urea fertilizers. Generally, the average amounts of fertilizer used per household were 63.5 kg and 29.1 kg DAP and urea, respectively.

Farmers used different types of fertilizers for different crops. Most rich and medium households used more inorganic fertilizer than organic for some crops such as potato and wheat. Most poor farmers applied either inorganic or organic fertilizer alone for potato but organic fertilizer alone for wheat. Most maize growers used inorganic fertilizer for the crop. At the national level, teff, wheat and maize account for the majority of inorganic fertilizer use (Spielman *et al.*, 2011). Organic fertilizer alone was more often used for some crops such as barley, enset, vegetables (cabbage, beetroot and carrot) and apple. Crops such as faba bean, field pea, sweet potato and teff were usually grown without any fertilizer by most of the households.

3.2.9. Constraints of crop production

The most important challenge in all locations was enset disease (Table 7) probably caused by bacterial wilt which is widely spread in the highlands (Quimio and Mesfin, 1996). Enset bacterial wilt has been a problem in Ezzo Tula Kebele (Farm Africa, 1994). The second important constraint in Losha was potato late blight (*Phytophthora infestans*) which was the third and fourth important constraint in other areas. Millipedes were the other important problem for potato production in all locations. Prevalence of potato diseases and insect pests were also important problems in the country as a whole (MoA, 2011). Similarly, an assessment study conducted in 2008 by South Agricultural Research Institute (SARI) showed that crop disease, including enset and potato disease, were the second priority problems in Doko Shaye

Kebele of Chencha. Yellow rust was a challenge for newly introduced wheat varieties in all locations. When it is severe, yellow rust (caused by *Puccinia striiformis*) can result in a yield loss of 100% on wheat (MoA, 2012). Disease occurrence was one of the problems of using improved varieties in many areas of the country (Amsalu, 2006). Weeds were not considered as a problem in most locations. The reason might be because of the importance attached to weeds as a livestock feed. *Guizotia scarab*, however, was considered a problem in cereals only in one location. Porcupines and apes were problematic in Laka and Tegecha.

Shortage of improved crop variety seed and unpredictable rainfall were the second most important constraints in Gendo Gembela and Laka areas. Shortage of improved and quality seed was one of the problems of the potato value chain in SNNPR (Bezabih and Mengistu, 2011). Such seed shortages can be partly alleviated by involving farmers and producing seeds on farmers' fields (Agdew *et al.*, 2012). The high cost of chemical fertilizers was also a challenge while decline in soil fertility is aggravating over time. High cost of fertilizer was also a key problem at the national level (Amsalu, 2006). Labour shortage was a problem in Laka where about 62% of the households were female-headed households whose spouses migrated mainly

Table 7. List of constraints of crop production and their ranks over locations in Chencha

Constraints	Ranks[a]		
	Gendo Gembela	Losha	Laka
Enset bacterial wilt	1	1	1
Potato diseases	4	2	3
Millipedes on potato	5	4	4
Yellow rust on wheat	-	6	7
Aphid on field pea and kale	6	-	x
Weed	-	-	x
Decline in soil fertility	-	5	6
Unpredictable rainfall	3	-	2
Shortage of improved seeds	2	3	x
Low productivity of local cultivars	-	-	x
High cost of fertilizer	-	-	8
Land shortage	-	-	x
High cost of grain	x	-	x
Oxen shortage	-	x	x
Shortage of labour	x	x	9
Vertebrate pests (monkeys/apes and porcupines)	x	x	5

[a] A constraint ranked as 1 is the most important constraint to crop production; -, the problem exists in the area but is not ranked; x, not reported as problem

to Addis Ababa for weaving, resulting in a shortage of labour for the women. Land shortage was also a problem of most households.

3.2.10. Sources of food and income

Most households (76%) fulfilled their food demand from their own farm products and external sources (Table 8). Poor households were more dependent on external food sources than rich and medium households. Crop products were the main on-farm income sources practised by most households, particularly by rich and medium and male-headed households. Potato was one of the main income sources particularly for rich households. Weaving was a good off-farm income source mainly practised by poor and male-headed households. Trading was more practised by rich and female-headed households. Generally, crop products were ranked as the most important source followed by weaving (Table 8). Comparison of the overall on-farm and off-farm income sources also revealed that on-farm activities were very important to rich and medium households whereas off-farm income sources were more important to poor households (data not shown). A diagnostic survey conducted in Ezzo Tula Kebele also showed the most

Table 8. Sources of food and income for households (%) within gender and wealth class

	Gender		Wealth status			
	Male	Female	Rich	Medium	Poor	Total
Food sources						
Own farm	24	25	33	27	11	24
Own farm & external sources	76	75	67	73	89	76
Income sources						
Crop products	93	75	100	100	67	90
Livestock & their products	76	58	78	77	61	72
Weaving	50	17	17	45	67	43
Trading	17	25	44	9	6	19
Selling labour	11	0	0	0	28	9
Remittance	0	25	6	0	11	5
Hiring out oxen	2	0	0	0	6	2
Ranking income sources						
Crop products	54	58	78	64	22	55
Livestock & their products	2	0	0	5	0	2
Weaving	30	8	6	23	50	26
Trading	9	8	11	9	6	9
Selling labour	4	0	0	0	11	3
Remittance	0	25	6	0	11	5

important income sources of farmers were crops, remittances (remittance is money obtained from relatives in other places) and animals in that order (Farm Africa, 1994).

4. Conclusions and Recommendations

The farming system of Chencha is a mixed farming system where crops and livestock are simultaneously grown. The major crops grown in the area were potato, enset, wheat, barley and kale. The most common soil types were Modo, Gobo and Kalta which are more of a clay type of soil. Crop products were the main sources of income for most farmers. However, crop production was constrained by different challenges that need research and policy interventions. The following are the main constraints and suggestions to overcome these:

- Enset bacterial wilt was the key problem in the area. However, there is no reliable solution to the problem at the moment. Therefore, use of cultural practices and sanitary measures could be important measures to control enset bacterial wilt (Fikire *et al.*, 2012). A relatively tolerant variety called Mazea can be used in areas where the disease is severe.

- Specific potato pest types should be identified to plan proper control measures. Depending on the disease type, tolerant varieties with proper agronomic practices (e.g. crop rotation) and chemical treatments could be used. Practices which are successful to control insect pests elsewhere in the country could be adapted and used in Chencha. Vertebrate pests such as porcupines can be effectively controlled by using different local trapping methods through community participation (Leulseged *et al.*, 2012).

- Crop varieties should be evaluated at local level before being widely disseminated, to make sure that they are adapted to the climate, tolerant of the major diseases and accepted by the society. Tolerant varieties and chemicals could be used to control the yellow rust problem on wheat.

- Weeds could be managed through proper ploughing, cultivation and rotation. However, most farmers considered weeds as one of the main sources of livestock feed. Enhancing other sources of livestock feed may help to control weeds in time.

- Proper practices should be in place to restore soil fertility. Optimum and economical fertilizer rates should be determined and used with efficient management methods. The current integrated soil and water conservation work of the government should be strengthened to cover all sites. The physical and chemical characteristics of locally classified soil types should be known.

- Practices that improve water use efficiency at farm level could be options to overcome the challenge of intermittent dry spell(s).

- Shortage of seeds of improved crop varieties is a problem that occurs throughout the country. One way of solving the challenge might be to strengthen on-farm production of seeds by farmers of at least the self-pollinating crops.

- Introduction of better on-farm and off-farm income-generating activities would solve problems related to the high cost of fertilizers and shortages of oxen, labour and land. The practice of using available horses and the method of single ox ploughing would also help to partly alleviate the oxen shortage.

- Farmers grow many types of crops using different management practices on relatively small areas of land. However, there is no information on the efficiency of these agricultural components in terms of production, economics and labour use. Therefore, for sustainability of production there is a need to know the efficiency of local management practices that are environmentally friendly.

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Chapter 3

The Analysis of Potato Farming Systems in Chencha, Ethiopia: Input, Output and Constraints

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Abstract

A household survey was conducted for mixed farming systems in Chencha, Ethiopia. Goals of the survey were to establish a baseline for the current production system, to quantify the variation in input and output, and to identify constraints hindering expansion of potato production. Descriptive statistics and principal component analysis were computed using SPSS and XLSTAT. Input and product use constraints varied over household characteristics. Using improved varieties, inorganic fertilizers, and selling products strongly and positively correlated with the households' wealth, adoption, and education levels. Problems of cash and inadequate produce negatively correlated with wealth, adoption factors, and education levels. Access to improved varieties, training, and fertilizer were positively correlated with age, family size and gender. Land and labour shortages and pests were identified as cross-cutting constraints. Results of the analysis identify a need for a pluriform advisory model recognizing and building upon alleviation of the diversity of constraints identified in this analysis.

Key words: improved varieties, inorganic fertilizer, labour shortage, training

1. Introduction

Potato (*Solanum tuberosum* L.) is the fourth most important food crop and the primary non-grain food commodity in the world. It has been cultivated in Ethiopia for over 150 years; currently it is grown in many parts of the country. In Ethiopia, its production area has reached 59,504 ha cultivated by over one million households in the main cropping season of 2011 (CSA, 2012). There is a high potential to expand the cultivation area of the potato crop, as most arable land is in principle suitable for cropping with potato. Potato has multiple benefits for low income households and where land shortage is a constraint. The potato grows quickly, has a high yield, and contains more energy and protein per unit area when compared to a cereal crop. Therefore, it plays a vital role in ensuring food security, which is a major concern for the country. However, its national average productivity was about 8 t ha^{-1} in the 2011 main cropping season, which was far below the productivity (40 t ha^{-1}) of improved varieties achieved in research trials (APHRD, 2009). The average productivity of potato in the production systems with local varieties in Chencha and Dita highlands (> 2500 meter above sea level) is only about 2.4 t ha^{-1} (Mesfin *et al.*, 2014).

One of the major factors attributed to the low productivity of potato is access to improved varieties. The main constraints to accessing improved varieties are lack of availability of healthy seed tubers and poor seed tuber quality (Hirpa *et al.*, 2010; Gebremedhin *et al.*, 2008; Berga and Gebremedhin, 1994). Adoption of improved varieties is hindered by awareness of the availability and use of improved technologies (Hirpa *et al.*, 2010), shortage of land (CSA, 2011a) and the high prices of healthy seed tubers (Agajie *et al.*, 2013). Thus, the majority of potato growers in the country use local cultivars and poor quality seed tubers. Out of the total land allotted to potato production, only 0.5% of the land was covered by improved varieties in the 2011 main season (CSA, 2011a). The seed shortage can be more aggravated in remote potato growing areas, such as Chencha woreda, which are far from the major seed sources.

Productivity of potato is also affected by different bacterial, fungal and viral diseases. Late blight followed by bacterial wilt, potato leaf roll virus, and potato virus Y (PVY) are the most important of these (Berihun and Gebremedhin, 2013). Virus diseases cause degeneration of planting materials and yield loss (Nascimento *et al.*, 2003). According to Schulte-Geldermann (2013), the high incidence of these diseases in Eastern Africa is due to lack of a good seed system, inappropriate use of chemicals to control fungal diseases, lack of proper sanitation, crop rotation and varietal resistance, among other factors. Most farmers in Ethiopia do not use pesticides and only a quarter of the potato farms were sprayed in the 2011 main season (CSA, 2011a).

Suboptimal agronomic practices - other than lack of crop protection - further depress yields (Berihun and Gebremedhin, 2013). Due to limited access to training, most farmers use the same, traditional crop management practices for ware and seed potatoes. Potato has a high demand for soil nutrients; however, soil fertility has been declining due to erosion, continuous cropping and mining of nutrients. Only half of the potato farms in 2011 were fertilized with DAP (35%), urea (2%) and DAP and urea together (14%), while the rest were treated with organic fertilizer only (27%) or did not receive fertilizer at all (12%) (CSA, 2012). An increase in the price of fertilizer (Endale, 2011; Abush *et al.*, 2011), adverse climate and illiteracy (Daniel and Larson, 2010) hinder fertilizer adoption in the country.

Generally, the above constraints are important in all potato production areas of the country, with little variation across locations. Chencha is one of the potato production areas of southern Ethiopia facing these typical constraints. These constraints should be resolved to increase the productivity of potato to its potential, thereby playing a role in improving the livelihoods of smallholder farmers. These diverse constraints need diversified research and development solutions at the local level because of the large biophysical and socioeconomic variations across locations. Hence, the Chencha project was initiated with the overall objective to develop sustainable seed potato systems in Chencha.

This part of the study has three objectives: (1) to create a baseline of the potato production system in the highland areas of Chencha, (2) to quantify the variation in household and farming types on a scale from ‘closed’, self-sufficient systems to ‘open’, commercial systems, and 3) to identify and rank constraints to improving potato yield as perceived by farmers and to relate these to farm/household type.

2. Materials and Methods

2.1. Description of the study area

Chencha is one of the districts of North Omo Zone of southern Ethiopia. The total area of the district is 373.5 km^2 with a human population density of 388 persons per square kilometre (CSA, 2011b). The altitude ranges from 2000 to 3000 meter above sea level (m asl). The agroecology is classified as highland (>2500 m asl), which accounts for 82% of the total area, and midland (2000 - 2500 m asl) accounting for 18%. The minimum air temperature ranges from 11 to 13 °C, whereas the maximum ranges from 18 to 24 °C. Based on eight years (2002 - 2009) data from the Office of Agriculture, the average annual rainfall is 1172 mm with a peak in April followed by a second peak in September. As a result of this bimodal rainfall pattern, there are two cropping seasons locally known as *belg* (March to May) and *meher* (June to October). The district has 45 administrative units which are locally known as kebeles (the smallest administrative unit, similar to a ward, which each consists of, on average, 395 households in the case of Chencha). While potato is produced in all these kebeles, 33 (73%) can be earmarked as potential prime production areas.

2.2. Site and farmer selection

Among the potential potato production kebeles, five kebeles were selected for the survey in consultation with experts of the District Office of Agriculture; these were: Losha, Gendogembela, Yuera, Laka, and Tegecha. These kebeles were selected because, together, they represented the distribution of the agro-ecological conditions of the 33 potential potato production kebeles. A total of 21 villages were randomly selected from all kebeles and each kebele was represented by at least two and at most six villages. Lists of names of farmers registered by each kebele administration were used to select every tenth farmer in the list. Care was taken to make sure that different household characteristics, mainly gender and wealth classes, were included although not proportionally. As a result, a total of 57 households were selected from the five kebeles, i.e. nine to fourteen households from each of the five kebeles. However, for the purpose of this paper, we considered only the data from 47 households of the first four kebeles, which represent the highland agro-ecology that covers the largest part of the district with similar cropping systems.

2.3. Data collection

A questionnaire was used to collect the data, employing individual interviews with household heads. Whenever necessary, open-ended questions were also used for clarification. The interviews were conducted from October to November 2012. The data collected included household characteristics and practices related to overall crop and livestock farming as well as use of inputs and outputs (input/output) and constraints specific to potato production. The household characteristics collected were gender of the household head, wealth status based on local classification (poor, medium and rich), age of the household head, education level of the household head (uneducated, elementary school level [Grade 2 to 6], junior school level [Grade 7 to 8], senior or high school level [Grade 9 to 12]), family size and potato technology adoption level of a household (adopter or non-adopter). Adoption of potato technology refers to adoption of one or more of the improved potato technologies: improved variety (high yielding and resistant to diseases), row planting (at spacing of 75 cm by 30 cm), fertilizer use (195 kg DAP ha^{-1} and 165 kg Urea ha^{-1}), crop rotation (≥3 years break), triple ploughing and earthing up, pesticide use and diffused light storage. Wealth status and adoption level of households were determined by the local administrators together with Development Agents of the Office of Agriculture. The criteria used to determine the wealth status of participating households were: (1) type and number of houses; (2) number of cattle and horses; (3) size of land holding; (4) age of owned enset plants; and (5) number of bamboo and eucalyptus trees. The input/output management practices specific to potato were use of inorganic fertilizer (DAP and/or urea), improved variety, hiring-in labour, access to training, and sale of surplus potato produce. Data were also taken on the practice of off-farm income generation.

2.4. Data analysis

Descriptive statistics (frequency, percentage, mean standard deviation and cross tabulation) were computed on most of the data using SPSS version 20. Pearson Chi-square was used to test significance. The degree of 'openness' of farms vis-à-vis input/output was evaluated by accounting for the total number of inputs/outputs practised per household. Principal component (PC) analysis was computed to derive the degree of association of household characteristics to input/output and production constraints using XLSTAT 2014. Class intervals were used to analyse descriptive statistics for age, education level and family size, whereas their actual values were used to compute PC analysis.

3. Results

3.1. Baseline of production system

3.1.1. Households' characteristics

Most of the sample households (n=47) were headed by men (Fig. 1). The ages of the household heads varied from young to old with an average of about 44 years. The average family size was nearly seven persons per household. Based on the local classification, most of the sample households were of medium wealth status and the proportions of poor and rich households were nearly equal. Most of the households had land holding less than 1 ha with an average of about 1.4 ha per household. The variation in farm size was associated with the wealth status of households. Generally, the farm of a household was fragmented over different locations. The majority of the households were adopters of at least one improved potato technology. Most of the household heads were not educated while others had attended schools at a range of levels (Fig. 2).

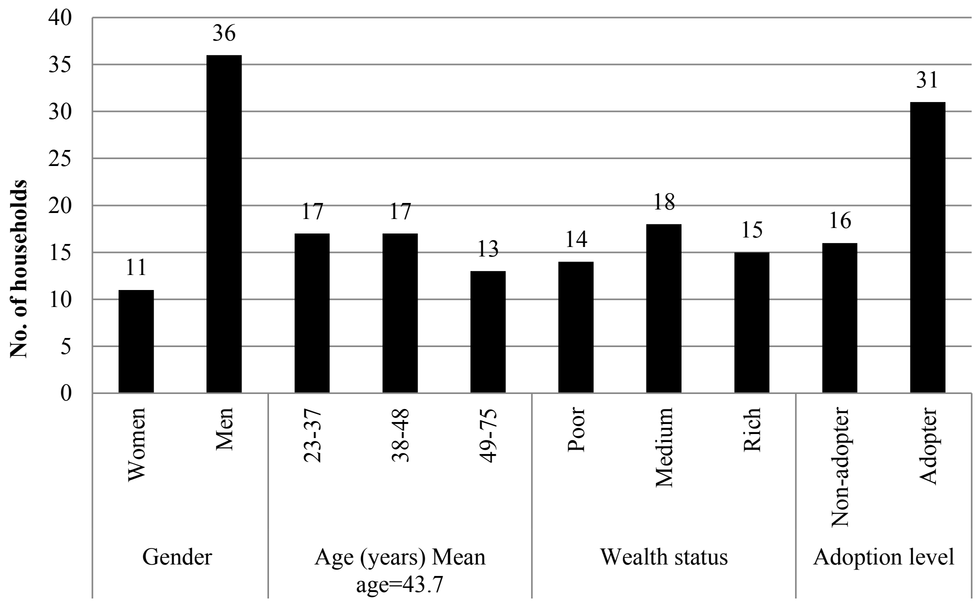


Fig. 1. Number of sample households against gender, age, wealth status and potato technology adoption levels

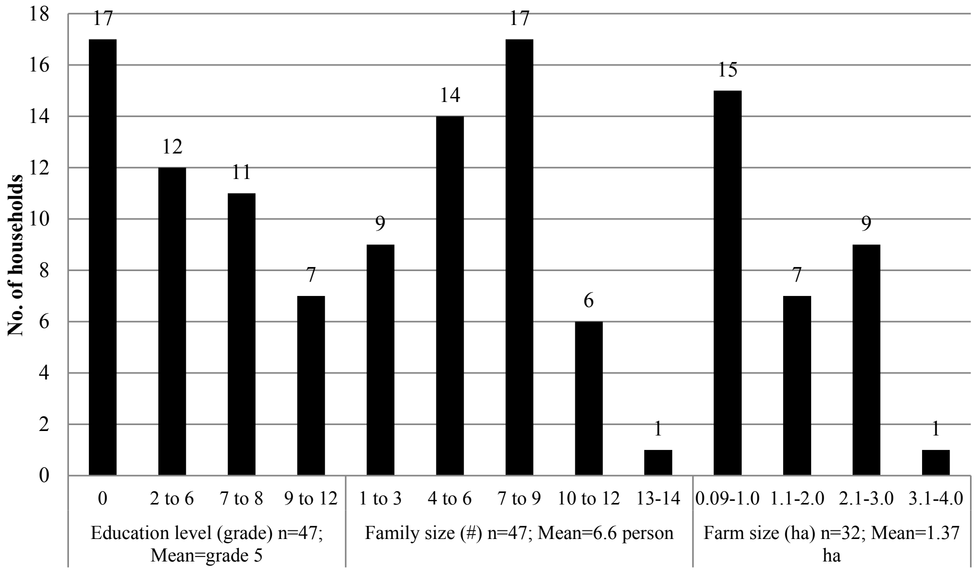


Fig. 2. Number of households against education level of the household head, family and farm size

3.1.2. Crop production

Different crops were grown in two cropping seasons, which received different amounts of rainfall. Common crops included cereals, pulses, root and tuber crops, vegetables, fruit crops and oil crops. On average, about nine crops (range: 5 - 13) were grown per household. The most widely cultivated crops were enset (*Enset ventricosum* [Welw.] Cheesman), barley (*Hordeum vulgare* L.), potato (*Solanum tuberosum* L.), wheat (*Triticum aestivum* L.), kale (*Brassica oleracea* L.), faba bean (*Vicia faba* L.) and apple (*Malus domestica* Borkh.). The former four crops were grown by all households. Improved varieties were used for production of mainly potato and wheat and in a few cases for barley whereas local varieties were used for the other crops. Sole cropping and double cropping (growing two crops on the same land in a year) were commonly practised in the area. The most common crops grown in the *belg* season were potato and barley which could also be grown in the *meher* season, along with other annual crops.

Land preparation was implemented largely by hand, as were other farm operations. An ox ploughing was also used by some households. For potato production, hand and oxen ploughing was practised by 83 and 17% of households, respectively. The majority (77%) of farmers used triple ploughing for potato. Potato fields were commonly weeded three times whereas wheat and barley fields were weeded once.

Inorganic and organic fertilizers were commonly used in the area. For potato production, the majority (57%) of the households used inorganic fertilizers only, whereas 17 and 26% of the households used only organic fertilizers or a combination of both types of fertilizers, respectively. The common inorganic fertilizers were DAP and Urea, which were used by about 76% and 73% of the households, respectively, irrespective of crop type. The most widely used organic fertilizer was farmyard manure, while compost was used by a few households.

The average amount of potato produced per household was 5.8 tons (range: 0.3 to 28.5) per year. Disaggregating the data by wealth class, the average amount produced by poor, medium and rich households was 2.3, 4.4 and 10.7 tons, respectively. Non-adopters produced 1.7 tons, while adopters produced 7.9 tons. The amount of potato produced per household was significantly ($p<0.01$) correlated ($r=0.61$) with the farm size of the households. Most of the households sold their produces to the local market as ware and/or seed and the number of households which sold potato produce varied over household characteristics (Table 1). Generally, the amounts of potato sold as seed ($r=0.90$) and ware ($r=0.72$) were significantly ($p<0.01$) correlated with the amount of produce per household.

3.1.3. Livestock production

The main livestock types reared in the highlands of Chencha were cattle, sheep, chicken and horses, which were reared by about 98, 75, 38, and 26% of the households, respectively. Rich households had relatively more of all of the above animals, while horses were kept only by medium and rich households. Generally, the number of animals decreased from year to year, mainly due to feed shortage and disease. The most common animal feed types were enset leaves, weeds, crop residues and grasses from private pasture. Croplands were generally grazed by the livestock after harvest. Based on farmers' ranking, enset leaves were the primary fodder source for rich and medium households, whereas weeds were the major source for poor households. Private pasture (natural grass grown on private land) was an important feed source for rich households. Communal grazing areas are grazed by livestock, which are attended by all members of a family, but particularly by children.

Table 1. Number of households which sold their potato as seed and ware against household characteristics

Household characteristics		Number of households					
		As seed and/or ware		As seed		As ware	
		No	Yes	No	Yes	No	Yes
Gender	Female (n=11)	6	5	6	5	9	2
	Male (n=36)	10	26	16	20	13	23
Wealth	Poor (n=14)	9	5	10	4	9	5
	Medium (n=18)	5	13	9	9	7	11
	Rich (n=15)	2	13	3	12	6	9
Adoption level	Non-adopter (n=16)	11	5	14	2	11	5
	Adopter (n=31)	5	26	8	23	11	20
	General (n=47)	16	31	22	25	22	25

3.1.4. Income sources

Farmers usually received their income from both on-farm and off-farm sources. Common on-farm sources were crop and livestock products. The off-farm sources included weaving, small trading, hiring out labour and remittances. Based on farmers' overall ranking, crop products were the most important income source followed by weaving and small trading. For poor male headed households, hiring out labour was an important source of income, whereas remittance was an income source only for female headed households, mainly from their children and spouses. In general, on-farm income sources were more important for most households than off-farm income sources. On-farm income sources were specifically important to rich and medium households whereas off-farm income sources were important to poor ones.

3.2. Degree of openness of potato farms to input and output

3.2.1. Total number of inputs and outputs per household

The inputs considered were improved variety, inorganic fertilizer, training, hiring-in labour, income from off-farm source and sale of potato produce. Most households used four inputs, but this number was significantly influenced by wealth status and adoption level of the households (Table 2). The average number of inputs/outputs used by the rich households was twice that of the average used by poor households. Similarly, the mean number of inputs/outputs used by adopter households was much higher than that used by non-adopter households.

3.2.2. Degree of association between input/output use and household characteristics

Principal component analysis on input/output use and household characteristics showed that the first three principal components (PCs) had eigenvalues greater than one and they explained about 61% of the total variance while each of them contributed about 33%, 14% and 14%, respectively. The first principal component (PC1) was strongly and positively correlated with seven of the ten original variables having correlation coefficient values of ≥ 0.65. However, PC1 correlated most with wealth status, adoption level, use of inorganic fertilizer, improved variety and selling of products with similar loadings suggesting that PC1 was characterized primarily by these variables. The association among these variables is easily depicted in the loading plot (Fig. 3a). The second principal component (PC2) was loaded by large negative values of gender and large positive values of hiring-in labour and they are located on the opposite sides in Fig. 3a. Bi-plot of PC1 versus PC2 showed that households or farms were not clustered among themselves and to practices of certain input/output and household characteristics (Fig. 3b).

3.3. General constraints of potato production

Principal component analysis related to production constraints revealed that the first seven principal components had eigenvalues greater than one and they explained about 73% of the total variance. However, the first three PCs accounted for about 44% of the total variation. PC1 was characterized by relatively large positive values of wealth status, adoption and education levels and market constraints. Fig. 3a clearly shows this strong and close mutual association. PC1 was also characterized by large negative value of cash shortage. Cash problem and insufficient quantities of produce were positively correlated and both were negatively correlated with wealth, adoption and education levels in PC1. In PC2, constraints of access to improved varieties and training and to some extent fertilizer were positively correlated mainly with age and family size and to some extent with gender. Pest, land shortage and labour shortage were cross-cutting constraints for all households (Fig. 4a). The distribution of farms over PC1 and PC2 showed that there was no clear clustering of farmers and few farms were outliers in both PC1 and PC2 (Fig. 4b).

Table 2. Percentage of households within household characteristics against number of inputs/outputs used per household

Household characteristics		Total	Number of input/output used per household							Pearson Chi- square	Mean # of input	SD *[1]
		N	0	1	2	3	4	5	6			
Gender	Female	11	0	9	9	27	27	9	18	3.5 (p=0.745)	3.73	1.6
	Male	36	3	3	11	17	33	25	8		3.83	1.4
Wealth	Poor	14	7	14	36	21	7	14	0	40.4 (p<0.000***)	2.50	1.4
	Medium	18	0	0	0	33	50	17	0		3.83	0.7
	Rich	15	0	0	0	0	33	33	33		5.00	0.8
Age (years)	22-37	17	6	0	18	18	24	12	24	19.0 (p=0.088)	3.82	1.7
	38-48	17	0	0	6	18	29	41	6		4.24	1.0
	49-75	13	0	15	8	23	46	8	0		3.23	1.2
Education level	Uneducated	17	6	12	18	29	24	6	6	19.1 (p=0.381)	2.94	1.5
	Elementary	12	0	0	8	25	25	33	8		4.08	1.2
	Junior	11	0	0	9	9	27	36	18		4.45	1.2
	Senior	7	0	0	0	0	71	14	14		4.43	0.8
Household size	1-3	9	0	22	11	11	33	11	11	21.1 (p=0.628)	3.33	1.7
	4-6	14	7	0	7	21	29	29	7		3.79	1.5
	7-9	17	0	0	18	12	29	24	18		4.12	1.4
	10-12	6	0	0	0	33	50	17	0		3.83	0.8
	13-14	1	0	0	0	100	0	0	0		3.00	.
Adoption level	Non-Adopter	16	6	13	25	31	13	13	0	18.7 (p<0.005**)	2.69	1.4
	Adopter	31	0	0	3	13	42	26	16		4.39	1.0
Total households	N	47	1	2	5	9	15	10	5			
	%	100	2.1	4.3	10.6	19.1	31.9	21.3	10.6			

**Significant at p<0.01; ***Significant at p<0.001; *[1]Standard deviation

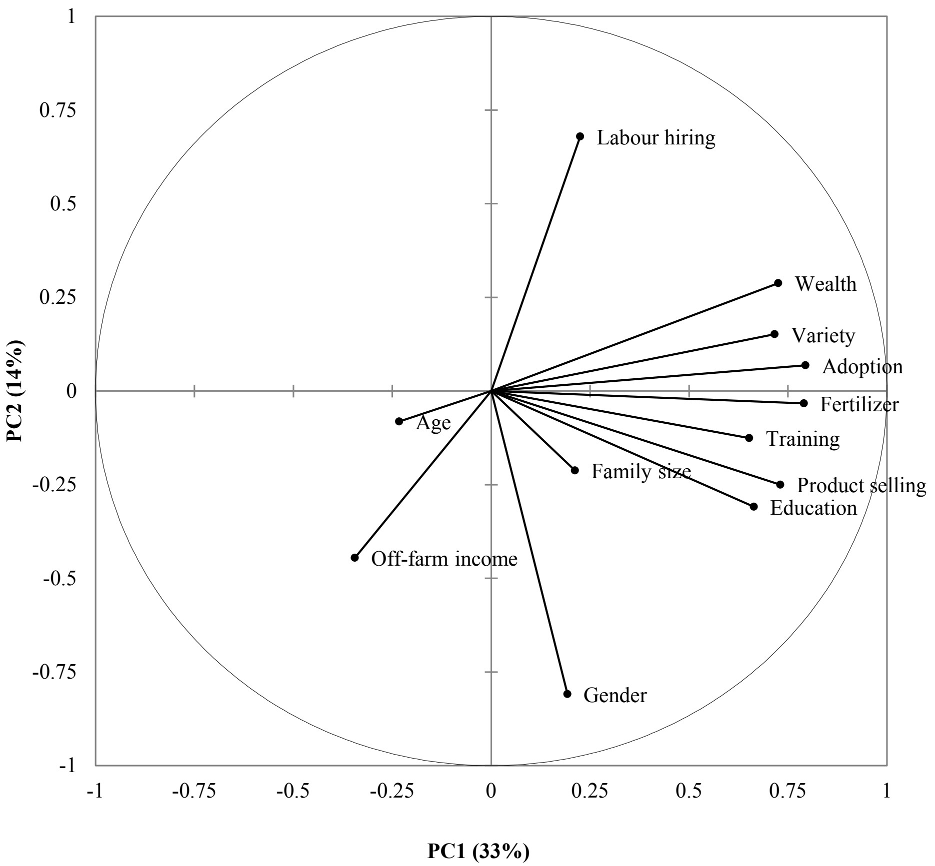


Fig. 3a. Loading plot showing the relationship among individual input use and household characteristics over two principal components. PC1 refers to the left and right sides of X-axis whereas PC2 refers to the upper and bottom sides of Y-axis

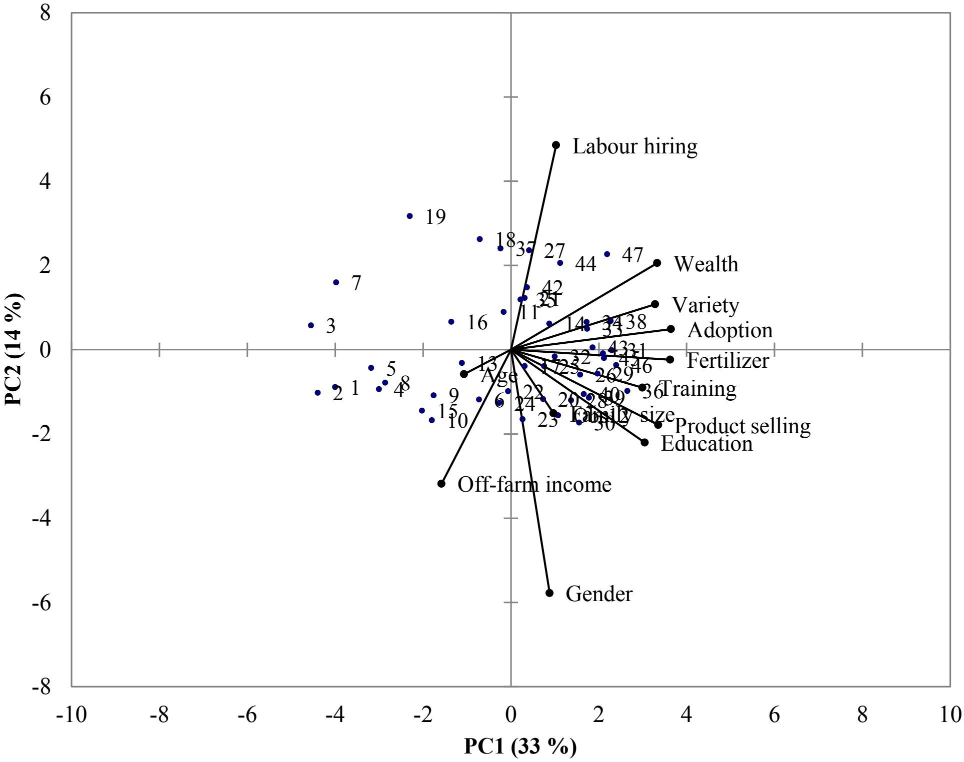


Fig. 3b. Bi-plots showing the association of farms with individual input use and household characteristics. PC1 refers to the left and right sides of X-axis whereas PC2 refers to the upper and bottom sides of Y-axis

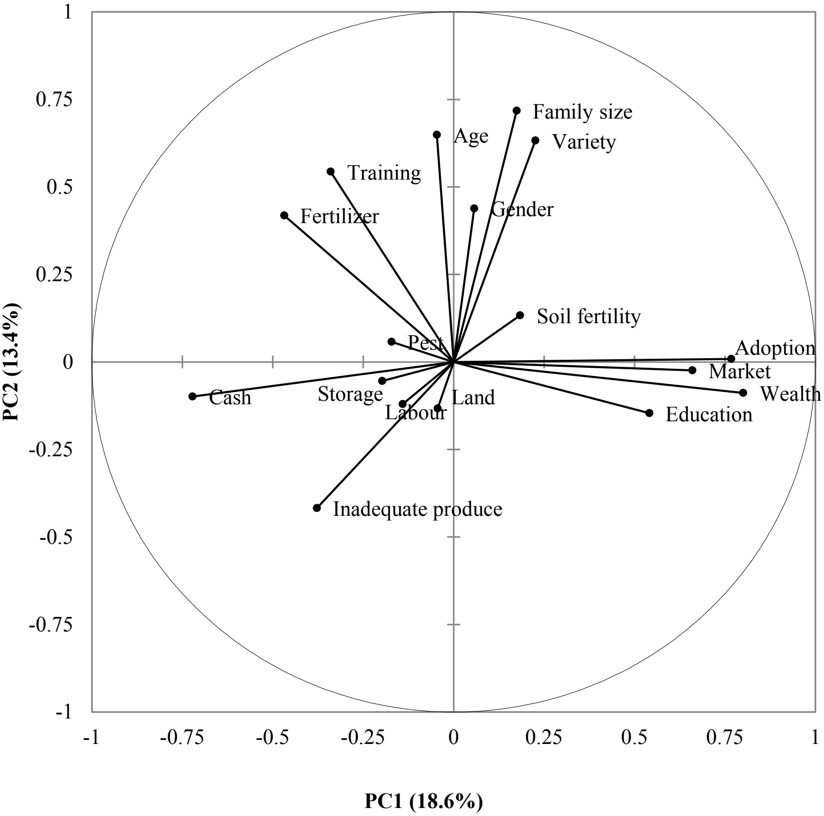


Fig. 4a. Association among constraints and household characteristics over two principal components. PC1 refers to the left and right sides of X-axis whereas PC2 refers to the upper and bottom sides of Y-axis

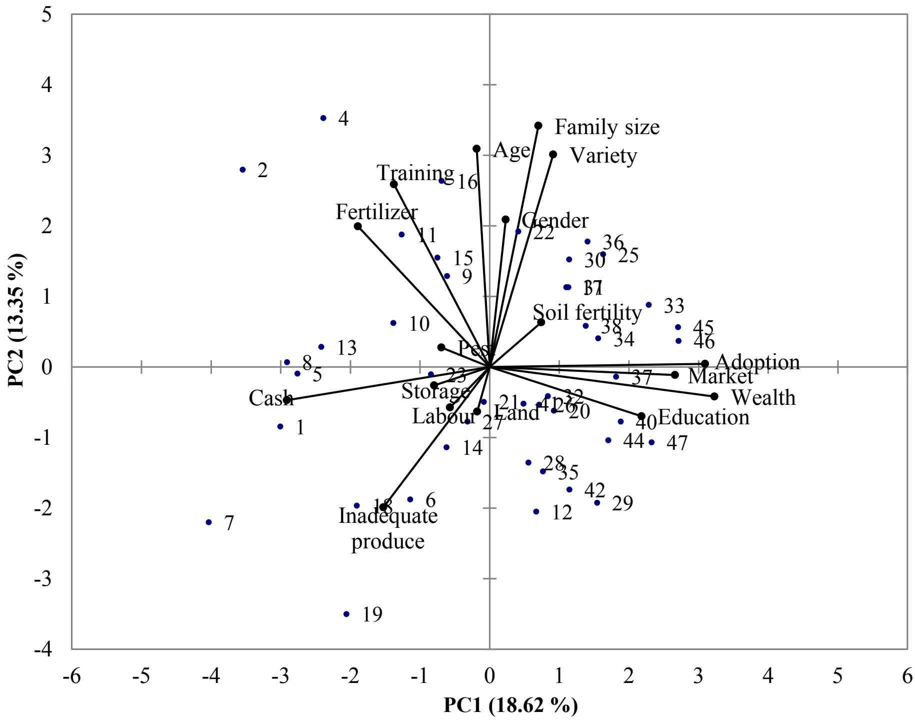


Fig. 4b. Distribution of farms in relation to constraints and household characteristics over two principal components. PC1 refers to the left and right sides of X-axis whereas PC2 refers to the upper and bottom sides of Y-axis

4. Discussion

The farming system of the study area was a mixed farming system where crops and livestock husbandry occurred simultaneously. Similar farming systems are practised by the majority (82%) of rural households in the country (CSA and World Bank, 2013). Highland areas of southern Ethiopia with farming systems similar to the ones in Chencha include highlands of Gamo Gofa, Bule, Hagereselam, Geta, Gumer and Duna. Diverse crops and livestock are grown in these areas with predominantly traditional management practices. These areas are also characterized by a high population pressure resulting in land shortage.

4.1. Hierarchy of constraints

The multiple constraints facing the smallholder farmers can be categorised into a hierarchical order, shown in Fig. 5. The first constraint relates to the limited availability of land, which is a base for crop production without which any of the other constraints are irrelevant.

Subsequently, for farmers who have overcome this constraint, resolving cash shortages emerges as the next constraint, as cash is a primary input to obtain essential inputs for production. Then labour shortage should be alleviated as most of the farm operations use human labour. For farmers who have land, cash and labour available, access to training becomes a relevant constraint to effectively planning and using the available inputs. Trained farmers can further improve productivity by using improved varieties, using quality seeds. Once productive crops are grown, pest control measures are required. If these conditions are fulfilled, it is likely that farmers harvest enough produce to sell: only for these farmers, access to market becomes the main constraint. The following discussion section follows this hierarchical order in Fig. 5 from bottom to top. The hierarchy does not match with the number of households identifying the constraints because farmers' responses were on the degree of importance of constraints but not on their hierarchical order.

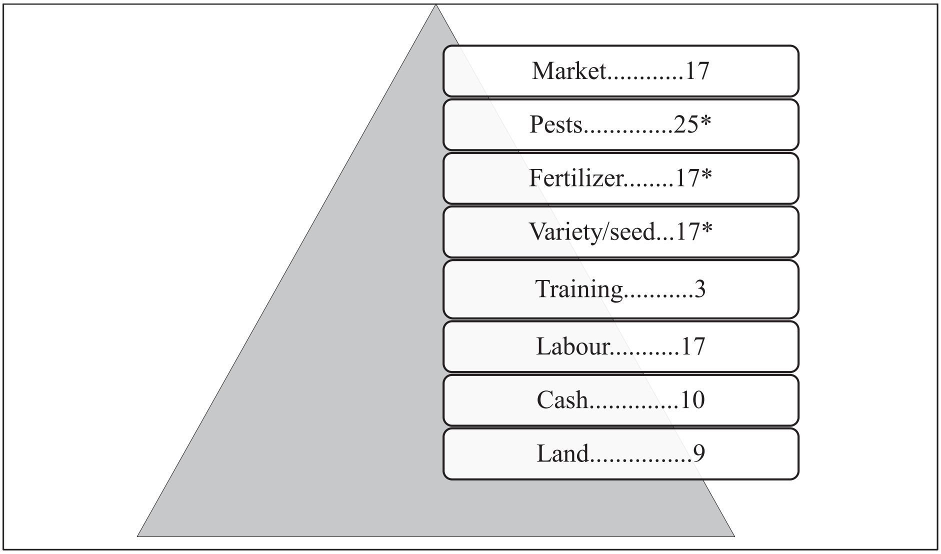


Fig. 5. Hierarchical order of contraints from bottom to top and number of households constrained (*N = 47; for others N = 43)

4.2. Land availability

Land shortage was a cross-cutting constraint raised by some of the interviewed households. Farmers specifically associated land shortage to the large amount of land required to meet the recommended rotation (≥ three-years) of potatoes. Land shortage is a common constraint in the high population density areas of the country (Josephson *et al.*, 2014). It is one of the constraints that hinder the full implementation of the extension packages for other crops, too (CSA, 2011a). The size of land holding positively influences the adoption of potato technologies (Beliyu *et al.*, 2013). To solve their general land problems, some farmers in the study area hire land from other farmers who experience a shortage of inputs (cash, labour, seed and fertilizer) and/or whose fields are too far away to manage effectively by themselves.

4.3. Cash availability

The strong negative association of cash shortage with wealth, adoption and education level in PC1 (Fig. 4a) indicates that cash shortage is a main constraint to poor, non-adopter and uneducated households. Most of the non-adopter (71%) and uneducated (57%) households were poor and cash shortage was mainly associated to their inability to purchase inorganic fertilizer and labour. Moreover, the positive correlation between cash shortage and inadequate produce in PC1 (Fig. 4a) indicates a vicious poverty cycle where lack of cash results in inadequate productivity and *vice versa*. Shortage of cash is the most important reason why farmers in Ethiopia do not implement the extension packages for different crops (CSA, 2011a). At national level, the potato extension package was fully implemented on only 15% of the potato farm area during the 2011 main season. Most farmers do not use financial credits for two reasons: (1) because they expect that they will not be able to pay off loans and (2) because of the unavailability of credit services.

4.4. Labour availability

Labour is a cross-cutting constraint associated with the high labour requirement of potato production. The opposite relationship between practices of hiring-in labour and off-farm income generation in PC1 (Fig. 3a) indicates that households that were engaged in off-farm activities had little experience with hiring-in labour and *vice versa*. This may be related to the household's capacity to hire-in labour, as most (86%) of the households which were engaged in off-farm income activities were poor, whereas most of those which relied on hired-in labour were rich. This contradicts findings by Belete (2006), who found that most households which are engaged in weaving prefer to hire-in labour for agricultural activities so that they have sufficient time for weaving. In our results, the large negative correlation values of gender and positive values of hiring-in labour in PC2 (Fig. 3a) implies that hiring labour was more dependent on the gender of the household head. Accordingly, most of female-headed households had more experience with hiring-in labour, compared to the male-headed households and this may be attached to the local tradition that tillage is the responsibility of men (Belete, 2006). The cost of labour, which includes the daily meals of the laborer, is increasing over time and is becoming unaffordable for most of the households.

4.5. Access to training

The positive association of reduced access to training with age, family size and gender in PC2 (Fig. 4a) suggests that access to training was related to age, larger family sizes and male-headed households. The reason why none of the female-headed households considered lack of access to training to be a constraint may be due to lack of awarenes on its importance. Some farmers in the country do not get adequate advisory service (Bezabih and Mengistu, 2011) and lack of awareness about the availability and use of improved technologies and management practices has hampered adoption of potato technologies (Hirpa *et al.*, 2010). Conversely, access to training positively influences the adoption of potato technologies (Beliyu *et al.*, 2013).

4.6. Use of improved varieties

The use of improved varieties was predominantly governed by the households' wealth, adoption and education levels (PC1 in Fig. 3a). This is consistent with other research from Ethiopia that has shown that education level and access to extension service significantly influence the adoption of improved potato varieties (Beliyu *et al.*, 2013; Gumataw *et al.*, 2013; Teklemariam, 2014). Wealthy households have better opportunities to access education; in turn educated farmers have better opportunities to access training on new technologies.

On the other hand, lack of access to improved varieties was related to age, larger family sizes and male-headed households (PC2 in Fig. 4a) and applied to all improved varieties including the most recently released ones which are more productive and resistant to diseases (e.g. late blight). Male farmers (particularly the rich ones and the adopters) who already had access to different improved varieties and training considered access to the most recently released varieties a constraint, because they were aware of such varieites. However, female-headed and poor households who had no information on the importance and presence of the recent varieties had interest in accessing any improved variety. Schulte-Geldermann *et al.* (2013) noted that lack of demand for seeds of new varieties may be the result of inadequate information about their advantages; thus awareness is an important element in the adoption of new varieties. This constraint of limited access to varieties in the study area is indicative of other parts of the country (Tewodros *et al.*, 2014) which explains why improved varieties were used on only 0.5% of the potato cropping area in 2011 (CSA, 2011a).

4.7. Fertilizer use

Inorganic fertilizer use was largely influenced by the households' wealth, adoption and education levels (PC1 in Fig. 3a). Inorganic fertilizers were used mostly by wealthy, educated and adopter households. Wealthy households have the financial capacity to buy fertilizers and have better access to education which improves their awareness of the importance of fertilizers. This is consistent with other studies in Ethiopia that have shown that fertilizer adoption is positively influenced by education levels of the household heads (Endale, 2011; CSA, 2011a). Many poor households identified inadequate access to inorganic fertilizers a constraint, citing high prices and cash shortages, whereas timely delivery of fertilizer was a more prominent constraint for wealthy households. This shows that poor households may not adopt fertilizers due to their low financial capacity. Indeed, an increase in the price of fertilizer (Endale, 2011; Abush *et al.*, 2011) and adverse climate and illiteracy (Daniel and Larson, 2010) have been a main constraint of fertilizer adoption in the country. Moreover, some farmers in the country cannot purchase available fertilizers, due to the large pack size (IFDC, 2012).

4.8. Pests

The presence of pests was a cross-cutting constraint for all households. Pests included diseases, arthropods (millipedes) and vertebrates. The major potato diseases were late blight and bacterial wilt, whereas the major arthropod pests were millipedes. Vertebrate pests were porcupines, monkeys and mole rats which were more prevalent on farms in the vicinity of shrub vegetation. Most of the farmers do not know the causes or preventive and control measures of diseases; this may be due to lack of awareness as a result of limited training services. Bacterial wilt is a relatively recent phenomenon and needs special attention to prevent its expansion. Pesticides are not locally available and seeds of resistant varieties are not easily accessible.

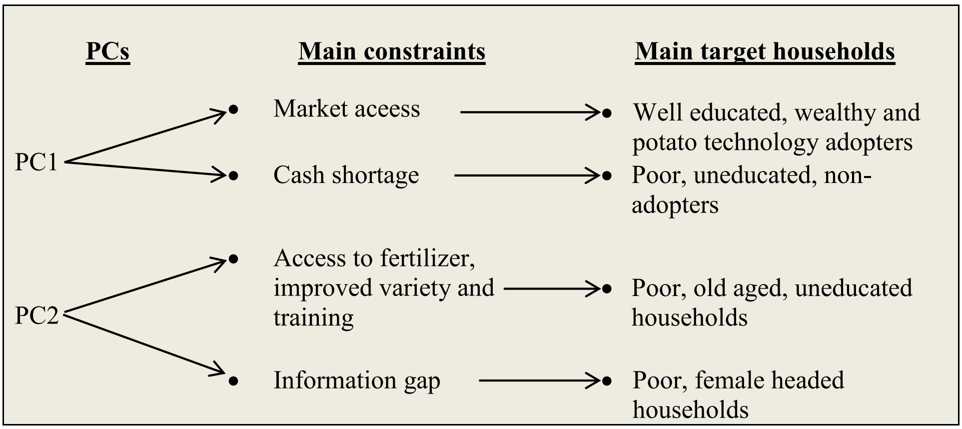
4.9. Product use and access to market

The practice of selling surplus produce was largely confined to rich, well-educated and adopter households. This demography cited inadequate access to market as their main constraint (PC1 in Fig. 4a). All of the farmers in the area harvest their potato nearly at the same time and immediately sell the produce in the nearby local markets at lower prices as a result of temporary oversupply. Farmers have a low capacity to access markets outside their vicinity to sell their produce at a better price. Moreover, most of them have a low financial and technical capacity to construct improved storage to store and sell their produce when prices improve. Low prices of ware potato was also reported as a constraint in Oromiya and Amhara regions (Agajie *et al.*, 2013).

Box 1 shows a summary of the main potato production constraints and their linkage to main target households more affected by these constraints.

We found in our study that there are three drivers of constraints which are related to: (1) access to inputs for willing producers most of whom are self-sufficient; (2) poverty trap for the poorest and uneducated households whose farms are closed to most of the inputs and are characterized by a critical shortage of cash and produce for consumption; (3) market access for proficient producers whose farms are open to most of the inputs and have surplus produce. Therefore, there is a need to have a pluriform advisory model, which recognizes and builds on alleviating the diversity of constraints in the highland areas of Chencha. These findings have implications for the optimization of extension services to farmers. The current extension service

Box 1. Linkage between production constraints and target households from two principal components



in Chencha is inclined towards a certain portion of the farming community. Fertilizers are supplied through direct purchase, limiting their availability to farmers who have sufficient financial means. Seeds of improved varieties accompanied by training are usually supplied to wealthy farmers who have sufficient resources to grow these varieties and to educated farmers who are expected to easily understand trainings. In addition, the formal extension systems (FES) prioritize specific cereal and pulse crops because the seeds of these crops are easily transportable and produced in relatively larger quantities compared to tuber crops. However, the FES do not put enough effort into using the opportunity of producing tuber crops at local level without the support of nongovernmental organizations (NGOs), nor they have aimed to address land and labour shortages. Moreover, FES have focused exclusively on primary production and do not include training on the post-harvest handling and the marketing aspect of the products, which is a concern of mainly the wealthier farmers. As our study shows that constraints differ over household characteristics, the following suggestions may contribute to developing a more pluriform extension service:

- Additional income generation activities that require less land and labour, such as bee keeping, could be promoted where farmers are constrained by land and cash shortages.
- The Chencha Office of Agriculture (COoA) in collaboration with NGOs should facilitate the introduction of recently released disease (late blight) resistant varieties and scale out local level seed tubers production to address the needs of different social categories. In-kind seed credit, which is being implemented by local development projects (such as the Vita project), should be promoted to equitably address the constraints of the poor households too.
- The Chencha Office of Agriculture and Cooperatives could facilitate timely delivery of fertilizers. In addition, the COoA and microfinance institutes could facilitate access to credit. Some farmers are not sure whether they can produce enough to repay their loans; they require training on how to maximise the effectiveness of their production systems.
- Cooperatives could facilitate better access to markets. The COoA, in collaboration with NGOs, could promote improved storages for ware potato to reduce post-harvest losses and to enable long-term storage to avail of better prices and increased consumption.

5. Conclusions

In this study, we uncovered the variations of input use in relation to household characteristics and identified important bottlenecks for potato production in the highlands of Chencha. The main constraints were related to access to inputs for willing producers, to the poverty trap for the poorest and uneducated households and to market access for proficient producers. Therefore, there is a need to develop a pluriform advisory model, which recognizes and builds on alleviating the diversity of constraints faced by farmers from contrasting demographies. The following suggestions need be given due emphasis:

- The promotion of additional income generation activities that require less land and labour;
- The introduction of recently released disease resistant varieties and scale out local level seed production activities;
- Facilitation of the timely delivery of fertilizers and access to credit;
- Improving access to market and promoting improved storage facilities for ware potatoes;
- The limitation of the current study is the small sample size. Thus, validation of the findings is necessary; and
- Similar studies may be required for the midland part of Chencha, which has a different agro-ecology and cropping system.

Acknowledgements
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Chapter 4

The Agronomic and Socioeconomic Sustainability of Farming Systems in Chencha, Southern Ethiopia

This Chapter is based on the article: Dersseh, W.M., Schulte, R.P.O, Groot, J.C.J., Schulz, S. and Struik, P.C., The Agronomic and Socioeconomic Sustainability of Farming Systems in Chencha, Southern Ethiopia. Submitted.

Abstract

In Ethiopia, there is limited information on combined analysis of soil nutrient and animal feed balances and agronomic and socioeconomic efficiencies at farm level. Therefore, a farm system level study was conducted in Chencha, Southern Ethiopia, to analyse the agronomic practices, feed self-sufficiency and soil nutrient balance and status, to quantify labour use and economic efficiencies, and to identify constraints for sustainable intensification. Twelve farms were surveyed largely from January to December 2013. Data on crop and livestock husbandry and socioeconomic data were collected. Composite soil samples were taken from plots of each farm and laboratory analyses were carried out for texture, bulk density, pH, N, P, K, organic carbon and organic matter. Weather data were collected using an automatic weather station. Soil nutrient balance and flow, labour balance, gross margins, operating profit and feed balance were computed using the whole-farm bio-economic model FarmDESIGN. Labour and economic efficiencies of crop production were calculated manually. The results revealed that the sustainability of the farming system is constrained by low agricultural productivity, soil fertility, labour efficiency and economic return associated with improper crop rotation, inappropriate soil fertility management practices, shortage of animal feed, labour- and economically inefficient farm practices and labour shortage. Therefore, implementation of appropriate crop rotation, proper management and use of farm yard manure is needed, as well as facilitating access to improved food and feed crop varieties, upgrading the productivity of local cattle breeds and introducing labour- and economically efficient farm practices.

Key words: crop rotation, economic efficiency, feed self-sufficiency, labour efficiency, mixed farming, soil nutrient balance

1. Introduction

The United Nations (2012) projected that the world population will grow to about 9.6 billion people in the year 2050, with much of the increase taking place in Africa and about one third being rural population. Food security will remain a challenge (The Economist, 2014). As a result of population growth, land is becoming scarce and thus the opportunities of extensive farming are becoming less and in most areas untenable. Many populous regions, like the highlands of Ethiopia, will already soon exhaust their land frontiers (Jayne *et al.*, 2014). Therefore, increasing production through sustainable intensification of agriculture will be crucial to achieve both food security and sustainability (Struik *et al.*, 2014). While sustainable intensification may not be synonymous with food security (Garnett *et al.*, 2013), and can even be considered an oxymoron (Struik *et al.*, 2014; Kuyper and Struik, 2014), it is part of a strategy for the food system to optimize productivity and a range of environmental and possible other outcomes (Garnett and Godfray, 2012).

The challenge of achieving sustainable food security is particularly prominent in Ethiopia where 85% of the population depends on agriculture, which consists mainly of subsistence farming. By 2050, the population is expected to increase to about 188 million, about twice the current population. Therefore, producing more food on incrementally smaller and fragmented farms will be double-edged challenges. Although agricultural outputs are growing (Dorosh and Thurlow, 2009), the production is not enough to ensure household food security. Low production is generally caused by land degradation (Gashaw *et al.*, 2014; Jolejole-Foreman *et al.*, 2012), low levels of input (Taffesse *et al.*, 2011), low efficiency of fertilizer use and erratic rainfall (Bekabil, 2014). Land degradation is partly associated with erosion (Gashaw *et al.*, 2014), unsustainable farming techniques (Meshesha *et al.*, 2012), inappropriate land use, the use of crop residues and dung for fuel (Taddese, 2001) and overstocking of grazing lands (Berry, 2003), resulting in deficiencies of soil nutrients in most cultivated areas. Soil erosion accounts for the major portion of loss of N, P and K (Haileslassie *et al.*, 2005) and other soil nutrients and it is most manifested in highland areas like Chencha. The productivities of both crops and livestock remain low and based on 2011 data, the average productivities of cereal, pulse, and root and tuber crops were about 2, 1 and 8 Mg ha^{-1}, respectively (CSA, 2012). The average cow lactation yield is 524 litres (Ketema and Tsehay, 1995) and in some areas it is 383 and 1251 litres for local and crossbred, respectively (Mulugeta and Misaye, 2014). Feed shortage and low producing local breeds have resulted in low productivity of livestock (Kuria *et al.*, 2014).

The government has prioritized the agricultural sector, as a major portion (47%) of the Gross Domestic Product is derived from this sector. Efforts are made to improve access to chemical fertilizers, improved varieties and seed, better agricultural practices and expert advice. Because potato gives higher yield, more calories, vitamins and nutrients per unit area (Knapp, 2008) compared with cereals, it has a vital role to ensure food security in land scarce areas like Chencha. Although potato is one of the most important crops cultivated by the majority of farmers in Chencha, its productivity is lower than the national average (Mazengia *et al.*, 2015). Some of the major factors affecting the productivity and production of potato in the area are lack of access to improved variety seeds and fertilizer, shortage of labour, land and cash, pests (Dersseh *et al.*, 2016) and decline in soil fertility (Mazengia *et al.*, 2015). The livestock sector has received less extension services in the country and the productivity remains low (ERSS, 2013), while a better integrated livestock and crop production system significantly improves resource use efficiency (Mussa *et al.*, 2012).

Various local research findings have shown the opportunities in crop and livestock production. Many improved varieties of wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), potato (*Solanum tuberosum* L.), faba bean (*Vicia faba* L.) and field pea (*Pisum sativum* L.) have been released with appropriate production packages (MoARD, 2009). Crop residues are the main feed resource in the country but due to inappropriate management they are poorly digestible (Birhan and Adugna, 2014), while maximum benefit from meat and milk production is attained by using high quality feeds, through a storage and carry-over system (Abegaz *et al.*, 2007). On the other hand, intensive dairy production with indigenous tropical breeds (Ethiopian Boran) is not economically feasible (Haile *et al.*, 2007) suggesting the need for cross breeding. Due to population pressure, land scarcity is common in the highlands (Josephson *et al.*, 2014) and the rapid decline in farm sizes emphasizes the need for agricultural intensification in Ethiopia (Headey *et al.*, 2013). Moreover, the evidence that smaller farms apply more fertilizer, improved seeds, pesticides, and herbicides implies an opportunity to intensify land use (Headey *et al.*, 2013). In such land scarce areas, there is a need to look into the economics of intensification and determine the carrying capacity of land for sustainable production (Kuria *et al.*, 2014). According to Haji (2006), economic efficiencies in smallholders' mixed farming system are influenced by endowment, crop diversification and farm size. Labour-substituting inputs, such as herbicides and tractors are less explored in the country but can be important for intensification when family sizes continue to decline (Headey *et al.*, 2013). Sustainable agricultural practices are important but their adoptions are influenced by many factors including household wealth, labour availability and social capital and little is known about their associated effects on productivity under smallholder farmers' conditions (Teklewold *et al.*, 2012).

Although the farming systems in Ethiopia are predominantly mixed farming systems (CSA and World Bank 2013), most of the research in the country focuses on individual constraints and thus there is limited research experience to demonstrate the interrelations between crop and livestock management practices in improving sustainability of production. There is also not enough evidence on combined analysis of soil nutrient and animal feed balances and agronomic and socioeconomic efficiencies at farm level. Moreover, most of the research concentrates mainly on the central parts of the country and areas such as Chencha receive limited attention. Thus the current study was initiated as part of a joint research led potato development project in Chencha (Mazengia *et al.*, 2015) to bridge this information gap.

In this paper, we identified at farm level the main obstacles and constraints to sustainable intensification using the Chencha district as a case study. The specific objectives were to: (1) understand the frequency of potato rotation, (2) evaluate animal feed self-sufficiency at farm level, 3) understand the existing soil nutrient balance and status, and (4) quantify the labour use and economic efficiencies at plot and at farm level.

2. Materials and methods

2.1. Description of the study area

Chencha is one of the districts of the North Omo Zone of southern Ethiopia, consisting of 45 administrative units, which are locally known as *kebeles*. The total area of the district is 373.5 km^2 with a human population density of 388 persons km^{-2} (CSA, 2011). The altitude ranges from 2000 to 3000 meter above sea level (m asl). The agro-ecology is classified as highland (>2500 m asl), which accounts for 82% of the total area, and midland (2000 – 2500 m asl) accounting for the remaining 18%. About 65% of the landscape is steeply sloped while the slopes of the study farms range from 6 to 60%. The minimum air temperature ranges from 11 to 13 °C whereas the maximum ranges between 18 and 24 °C. Based on eight years (2002 -

2009) data from the Office of Agriculture, the average annual rainfall is 1172 mm with a peak in April followed by one in September. The rainfall pattern is bimodal as a result of which there are two cropping seasons locally known as *belg* (March to May) and *meher* (June to October). Crops cover about 35 and 65% of the farmlands in the two seasons, respectively. The majority of the arable land is in use and currently about 6000 ha cultivable land is remaining. The majority of the remaining land is used as communal grazing area. Most plots have been cultivated for many years and the soils are degraded. Most soils have a reddish brown colour and clay loam texture. Land is the property of the state and the people and sale and exchange of land is prohibited. Individual farmers have holding right to use, lease and bequeath the land. Subsistence mixed crop-livestock farming is the major farming system. The major crops grown are enset [*Enset ventricosum* (Welw.) Cheesman], wheat (*Triticum aestivum* L.), potato (*Solanum tuberosum* L.) and barley (*Hordeum vulgare* L.). Cattle, horse, sheep and chicken are the major livestock (Dersseh *et al.*, 2016). The majority of the households rear cattle and sheep. Crop products are the most important income sources followed by weaving (Mazengia *et al.*, 2015).

2.2. Farmer selection

Farms of 12 potato growers (5 women and 7 men) with an average age of 44 years were selected and surveyed representing the highland areas. To select these farmers (based on local classification 33% with high endowment, 58% medium wealthy and 8% with low endowment), we used purposive and stratified random sampling methods. First, we selected six "shared farmers" (shared among three PhD studies carried out simultaneously) on the basis that each of these six farmers had Diffused Light Storage for seed potato, also had uniform plots without potato crops in the last three years, and represented contrasting altitudes/agro-ecological zones. Secondly, we used stratified random sampling to select an additional 6 farmers, following a preliminary survey of 57 farmers (Mazengia *et al.*, 2015). We did this by examining 10,000 automated random sets of 6 additional farmers from the population of 57 farmers, stratified by *kebele*, to ensure that three farmers were selected from each of the four *kebeles* in each of the 10,000 sets. For each of the 10,000 sets of 12 study farmers (consisting of the 6 shared farmers and the 6 additional farmers), we evaluated the extent to which these 12 farmers reflected the larger population of 57 farmers, based on the following criteria: intervention experience, gender, age, education level, household size, wealth class, experience with potato growing, off-farm income levels, mineral fertilizer usage, diversity of livestock and diversity of crops. For each of these criteria, we calculated the chi-square goodness-of-fit test between the 12 study farmers and the population of 57 farmers. We subsequently computed an overall goodness-of-fit statistic as follows: Goodness of fit = $\Pi^{11}_{i=1}\ [1-\chi^2(criterion\ i)]$.

Of the 10,000 sets of 6 additional farmers, we examined the five sets that gave the best overall goodness of fit, and made the final selection from these five sets, based on practical considerations.

2.3. Data collection

To facilitate data collection, plots were identified, assigned codes and hand sketched for each farm. Following the data requirement of the FarmDESIGN model (Groot *et al.*, 2012), seasonal field and household data were collected nearly every two weeks from January to December 2013 while crop rotation per plot was recorded in 2013 and 2014. Agronomic data included types of crops and area coverage, seed rate, fertilizer type and rate, economic (grain, root or tuber) and straw yield with their destination. Straw yield (S) was estimated from harvest indexes (HI) of respective field crops as: S = (G/HI)–G; where G is economic yield. Secondary data were collected on effective organic matter input, humification coefficient, nutrient content, feed value, and N fixation by crops (Groot and Oomen, 2011). Livestock related data were type, number and age of the animal, number of days on farm and yard per year, number of hours animals stayed in yard and pasture per day, and amount of products (mainly milk) and their use. Secondary data and experts' knowledge were used to estimate animal weight, carcass percentage, growth rate, and feed requirements. Chickens (*Gallus domesticus*) were not considered in the farm component because the number of chicken per household was small and thus their relative role in the farming system was negligible.

Socioeconomic data were collected on regular (family) and casual labour inputs by interviewing each of the farm owners while average prices and costs of inputs (fertilizer, seed and labour) and products (crop and livestock) were estimated through key informant group discussions. For crop production, labour data per plot were collected for tillage, seedbed preparation, sowing, weeding, harvesting, threshing, and manure transport and application. Labour hours spent for general crop guarding (policing and fencing) per year was also estimated. For livestock production, labour data per farm were collected for keeping animals, feed collation, milking and pen maintenance. Land and veterinary service costs, which were considered as general costs, were recorded per household.

Composite soil samples (on average 5 samples per plot) were taken from all plots of each farm and laboratory analyses were carried out for texture, bulk density, pH, available N, P and K, and organic matter (OM). Bulk density was determined as mass of oven dry soil core divided by volume of soil core (Black, 1965). Texture was analysed using hydrometer method 1:20 soil/water (W/V). Chemical analyses were made using the standard procedure set by Teagasc (Massey *et al.*, 2013). pH was determined using a glass electrode in a 1:2.5 (volume fraction) suspension of soil in water. Morgan's extraction solution was used to analyse available P and K. Loss on ignition was used to determine OM content (BS EN 13039:2000). LECO elemental analysis was used to analyse total N and organic carbon (LECO Corporation, 2002). For texture and bulk density, mean results of three plots (one from homestead area and the others from outer field) per farm were considered to represent each of the twelve farms. Contrastingly, N, P, K and organic matter were established for all plots of each of the twelve study farms. The amount of soil eroded per year was taken from a secondary source (Belay and Bewket, 2010).

Weather data were collected hourly using an automatic weather station (Campbell Scientific PC200W 4.1) installed at a central position of the study site. Average temperature of the year 2013 was used for the study.

2.4. Data analysis

FarmDESIGN (Groot *et al.*, 2012) is a model that serves as a farm diagnosis and exploratory tool to generate alternative management options in search of improved farm performance. The model is used as an interactive application which supports iterative cycles of learning and adaptation of the structure of a mixed farm. The model was used in the current study to analyse most of the data for each farm independently. Using the model, estimations were made on farm gate nutrient balances (the differences between input and output of nutrients), cycles and losses from soils. Depending on the nutrient type, inputs considered in the nutrient balances were nutrients imported into the farm mainly through crop products, manures and fertilizers and symbiotic and non-symbiotic nitrogen fixation, whereas outputs were export of nutrients through exported crop products and excreta by the households. Losses of nutrients from the soil were through erosion, leaching or volatilization and for carbon through the degradation of soil organic matter and manure after application.

The labour balance was calculated as the difference between required and available labour per farm whereas labour use efficiency (LUE) of crop production was manually calculated as monetary values of crop products divided by cost of labour at farm and plot levels. Operating profit was calculated by subtracting total costs of crop and animal production and fixed costs for assets such as buildings and equipment from gross return from crop and animal production. The economic efficiency of crop production was manually calculated as monetary values of crop products divided by the sum of the cost of seed, fertilizer and labour at farm and plot levels. The feed balance was calculated by subtracting the total available feed from crop products and other feeds from the total feed required for animal maintenance and production. Feed self-sufficiency (FSS) was manually calculated as $FSS = (1–D) \times 100$, where D is the estimated amount of imported grass divided by the total mass of dry matter fed to animals.

3. Results

3.1. Frequency of potato rotation

Farmers practised different cropping sequences in the two seasons of a year or rotation over years. The frequency of successive growing of potato in two years over 64 fields of 12 farmers is presented in Fig. 1. In the majority (73%) of the fields, potato was grown with a break of $\geq$1.5 years whereas in about a quarter of the fields it was grown in one year break. Most households grew potato in the first season followed by cereals, mainly wheat and barley. When potato is grown in the second season, it is grown mostly on previously fallow plots. In the study farms, potato, wheat and barley covered the majority of crop areas per farm respectively and enset and apple (*Malus domestica* Borkh.) were among the dominant perennial crops. Pulse crops appeared less frequently in the cropping systems.

3.2. Feed self-sufficiency

There was imbalance between the available on-farm feed resources and required quantities of feed to cover livestock energy and protein demand, and therefore all farms depended on external sources for feed mainly through free gazing out of the own farm. The degree of feed self-sufficiency of farms ranged from 7 to 41% with an average of 28%. External feed sources included communal grazing areas, grazing over others' plots and purchased feeds, which were practised by 6, 8 and 10 of the 12 farms, respectively. Communal grazing areas were overgrazed throughout the year and became unproductive. Feeding animals with enset leaves and weeds from crop plots was practised by all farms. The feed shortages were relatively high in Farms 7, 8, 9 and 11 which were female-headed households from the poor to medium endowment classes. To express the magnitude of feed shortage, the farmers stated that feed shortage was one of the main reasons for the reduction in number of animals kept per household over time. The land areas allotted to grass in most farms were small (72 to 784 m^2) and 40% of the farms had no grassland at all. The area allotted to grass was positively correlated with the number of animals kept per household (r=0.89).

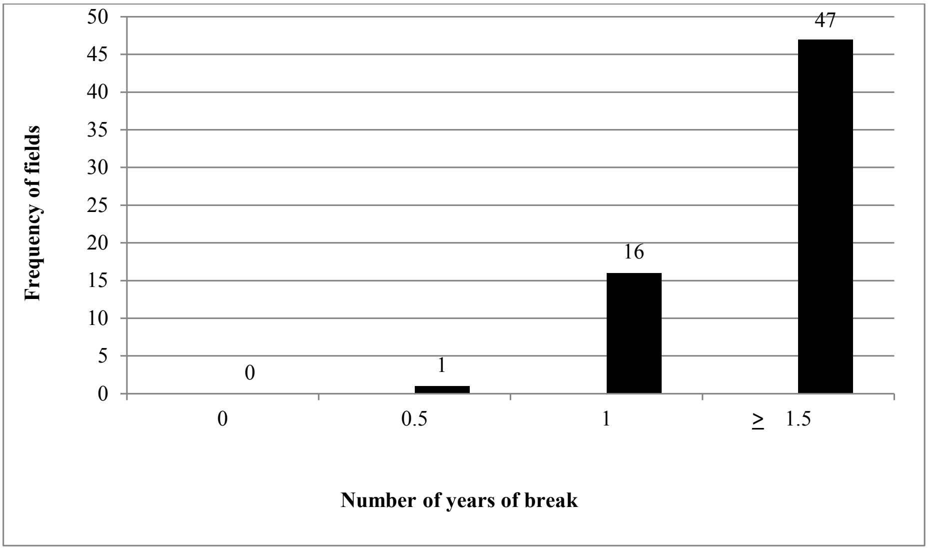

Fig. 1. The frequency of fields with different durations of the break period between successive crops of potato on the same field in four seasons of two years (2013 and 2014).

3.3. Soil nutrient balance and status

The farm gate nutrient balances (the differences between input and output) were positive for most nutrients across farms except for three farms for K balances (Table 1). A positive balance means that there is a net gain in nutrients. The average soil balance for organic matter was 998 kg ha^{-1}. The average balances for N, P and K were 139, 60 and 33 kg ha^{-1} while the medians were about 144, 58 and 35 kg ha^{-1}, respectively and the majority of the farms had values below the averages for P and K. A considerable portion of the nutrients came to the soil through farmyard manure. Most of the animal feeds were from external sources implying that significant portions of the above nutrients were imported from external sources. The nutrient balances were negatively correlated with farm size, particularly for N, meaning the larger the farm, the smaller the nutrient gains per ha, probably because the imported resources were diluted over a larger area and the animal density was lower on large farms.

Table 1. Soil balance of soil organic matter (SOM), farm-gate nutrients balances (N, P and K; input minus output) and model-calculated nutrient losses (or mining in case of negative values) across twelve farms.

Farm	Household characteristics†	Farm size (ha)	SOM balance (kg ha^{-1})	Farm-gate balance (kg ha^{-1})			Soil nutrient loss or mining (kg ha^{-1})		
				N	P	K	N	P	K
Farm 1	M-R-S	1.11	694	117	35	34	34.4	35.3	29.2
Farm 2	M-M-E	0.30	648	130	84	-32	39.3	83.9	-36.9
Farm 3	M-R-J	1.22	2197	158	42	61	85.3	42.3	56.8
Farm 4	F-R-J	0.97	517	109	82	-14	54.3	81.7	-16.5
Farm 5	M-M-S	0.70	905	71	61	-3	15.4	61.0	-6.6
Farm 6	M-R-S	4.26	110	60	35	6	3.6	34.7	2.9
Farm 7	F-M-E	1.59	744	166	41	76	66.4	40.5	70.1
Farm 8	F-M-I	0.82	443	152	50	64	69.1	49.4	55.5
Farm 9	F-M-I	0.33	1423	200	81	78	97.8	80.9	72.4
Farm 10	M-M-S	0.89	2012	182	95	32	97.8	94.8	28.8
Farm 11	F-P-I	0.57	1406	187	60	53	102.1	60.2	49.4
Farm 12	M-M-E	0.61	874	136	55	36	63.2	55	27.6

†Gender of household head (F=female, M=male); wealth endowment (P=poor, M-middle, R=rich); education level of household head (I=Illiterate, E=elementary, J=junior, S=senior)

Modelled soil nutrients losses, particularly for N and K, were variable across farms. The average losses of N, P and K were 61, 60 and 28 kg ha^{-1} year^{-1}, respectively. An example of detailed nutrient flows in a farm is provided in Fig. 2 for the case of N flows in Farm 1.

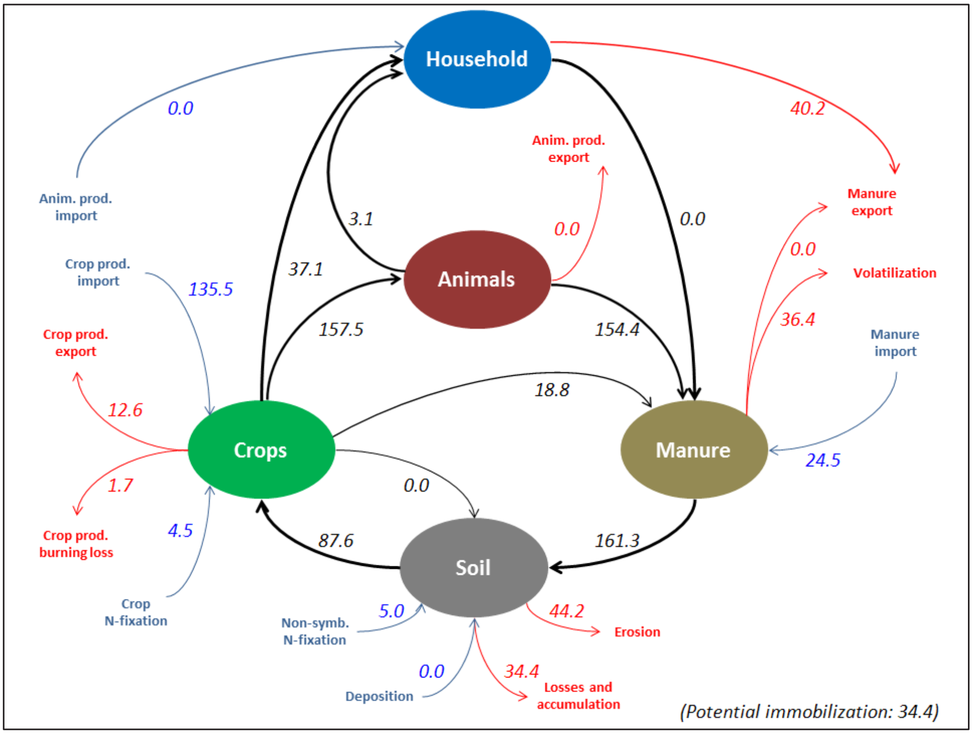

Fig. 2. Nitrogen cycle in Farm 1 (kg ha^{-1}) generated by the FarmDESIGN model. The inward and outward arrows show the incoming and outgoing of the nutrient from the farm components, respectively. A major portion of nitrogen comes to soil through manure and goes out mainly through crops.

Table 2 shows large differences in soil fertility between homestead and outer fields in one farm, particularly in relation to P and K. Table 3 shows that this relationship also holds for all farms. The common crops grown within the homestead were enset and apple. This might indicate that soils in most homestead areas were relatively severely fertilized with cattle manure and house refuse compared with the outer field although with some exceptions (Farms 5, 7 and 8). However, the overall average showed that differences in organic matter and carbon contents between homestead and outer field soils were small. The acidity of soils from outer field plots was high compared with the acidity from homestead fields which might be the consequence of more manure application in the homestead.

Table 2. Detailed soil test results over plots of one farm in Losha area (Farm 1).

Crops grown per plot per year	Site of the plot	C %	N %	Available P, ppm	Available K, ppm	Available Mg, ppm	pH
Grass	Outer field	2.40	0.26	0.12	214	294	5.7
Bamboo	Outer field	2.99	0.28	0.12	58	186	4.9
Enset	Homestead	3.89	0.34	15.8	1638	577	7.0
Apple/plum//beans/peas/kale	Homestead	2.49	0.25	0.36	304	500	5.9
Potato-Barley	Outer field	2.44	0.25	0.36	245	294	5.7
Fallow-Barley	Outer field	2.44	0.25	0.12	227	595	5.2
Fallow-Potato-1	Outer field	2.68	0.29	0.24	176	334	5.0
Fallow-Wheat-1	Outer field	2.46	0.25	0.12	241	517	5.6
Fallow-Potato-2	Outer field	2.15	0.22	0.36	243	450	5.9
Fallow-Potato-3	Outer field	2.03	0.21	0.12	284	670	5.5
Fallow-Potato-4	Outer field	2.30	0.23	0.12	309	386	5.7
Fallow-Wheat-2	Outer field	2.74	0.27	0.49	218	321	4.9
Apple seedling	Outer field	2.43	0.25	0.24	161	477	5.4
Eucalyptus	Outer field	4.50	0.42	1.46	152	542	5.9
Potato	Outer field	2.42	0.25	0.12	266	310	5.5

Table 3. Detailed soil test results of twelve farms averaged for homestead and outer field plots

Farms	Site of the plot	C %	N %	Available P, ppm	Available K, ppm	Available Mg, ppm	pH
Farm 1	Homestead	3.19	0.30	8.07	971	539	6.4
	Outer field	2.61	0.26	0.31	215	413	5.5
Farm 2	Homestead	2.81	0.27	7.60	819	481	6.2
	Outer field	2.60	0.26	0.43	266	388	5.4
Farm 3	Homestead	2.67	0.27	0.85	323	387	5.8
	Outer field	2.36	0.25	0.31	240	444	5.4
Farm 4	Homestead	2.76	0.31	0.12	148	189	5.1
	Outer field	1.68	0.20	0.66	173	471	5.5
Farm 5	Homestead	2.21	0.25	8.01	244	641	5.8
	Outer field	1.67	0.20	3.73	180	620	5.7
Farm 6	Homestead	3.21	0.32	2.91	402	535	6.3
	Outer field	1.91	0.21	0.53	188	415	5.4
Farm 7	Homestead	2.37	0.26	0.25	284	397	5.9
	Outer field	2.89	0.29	2.93	341	331	5.8
Farm 8	Homestead	2.21	0.24	1.40	367	339	6.0
	Outer field	2.61	0.26	0.25	515	389	6.0
Farm 9	Homestead	3.38	0.33	11.72	408	516	6.1
	Outer field	2.82	0.29	2.81	316	352	5.9
Farm 10	Homestead	2.66	0.27	12.41	483	872	6.4
	Outer field	2.33	0.23	0.23	121	494	5.7
Farm 11	Homestead	2.18	0.23	3.80	339	496	6.3
	Outer field	2.17	0.23	0.38	200	422	5.7
Farm 12	Homestead	3.37	0.33	77.84	1326	656	6.9
	Outer field	2.15	0.23	0.53	261	386	5.7
Overall mean	Homestead	2.75	0.28	11.25	510	504	6.1
	Outer field	2.32	0.24	1.09	251	427	5.6

Note: Homestead crops were mainly enset and apple

3.4. Labour use and efficiency

At farm level, the labour balances (the differences between required and households' own labour) showed that there was labour shortage for the entire farms for crop and animal production. There was high variation in labour use efficiency (LUE; USD gross return/USD labour costs) over farms for crop production in general, ranging from less than two to more than 15. Labour use efficiency was high for production of some crops like apple seedlings (Table 4) and relatively low for cereal based cropping systems. Labour use efficiencies were also variable within the same cropping systems across farms (Table 5). The variation was very high particular for fallow-potato followed by fallow-barley systems.

Table 4. Plot level labour use efficiencies (LUE) for major crop production systems averaged across farms

Dominant crop types or system	Crops per plot in two seasons: *Belg*	*Meher*	# of farms	Average labour hours ha^{-1}	Average labour cost, USD ha^{-1}‡	Average gross return, USD ha^{-1}	LUE per plot
Enset	Enset	-†	12	6755	1326	2900	2.19
Trees	Bamboo	-	6	3437	675	4596	6.81
	Eucalyptus	-	4	824	162	14808	91.50
Apple seedling	Apple seedling	-	3	5915	1161	208674	179.70
Apple trees	Apple tree and plum	-	2	4847	952	8263	8.68
Vegetables	Vegetables		3	7923	1556	2748	1.77
Potato-cereal	Potato	Barley	6	6855	1346	2821	2.10
	Fallow	Potato	6	4028	791	2226	2.81
	Potato	Triticale	4	8109	1592	2873	1.80
	Potato	Wheat	7	7555	1483	4207	2.84
Cereal-pulse	Fallow	Barley	10	2976	584	866	1.48
	Fallow	Wheat	10	2970	583	1003	1.72
	Fallow	Triticale	4	3610	709	949	1.34
	Barley	Faba bean	3	3820	750	906	1.21
	Barley	Wheat	5	3777	742	1100	1.48
	Fallow	Faba bean	4	1152	4318	18775	4.35

†not practised in that farm; ‡annual costs and returns were considered for all crops including trees

3.5. Economic return and efficiency

Gross margin and economic efficiencies of crop and animal production differed among farms. The gross margin and economic efficiencies of crop production were larger than 1 indicating larger returns than costs in all and most farms, respectively. The gross margins from farms that grew apple were over four times higher than those of the other farms. The average gross margin from annual crops production was 1,882 USD ha^{-1} and this was considerably lower than the gross margin from perennials (4,772 USD ha^{-1} $year^{-1}$ on average). Gross margins from animal production were very low (on average 170 USD ha^{-1}) and a quarter of farms had negative returns. The overall operating profits for crop and animal production were positive for most farms except for Farm 8, which had low crop productivities of some crops due to high incidence of pests and low nutrient use. The average economic efficiencies of crops per farm ranged from 1.01 to 3.19 and they were positively correlated (r=0.68) with labour use efficiency.

Economic efficiencies of crop production were highest for eucalyptus, followed by bamboo and apple-plum production, all of which had economic efficiencies higher than four indicating the economic gain was four times higher than the cost of production (Table 6). Contrastingly, most other cropping systems had economic efficiencies less than two or even one. More inefficiency was observed in potato-cereal and cereal-pulse based cropping systems. The average efficiency of potato-cereal and cereal-pulse cropping systems were 1.18 and 1.38, respectively. Economic efficiencies of a particular cropping system differed between farms (Table 5). The variations were strongly correlated with labour use efficiencies for enset (r=0.85), fallow-barley (r=0.88), fallow-wheat (r=0.98) and fallow-potato (r=0.93). Farmers considered enset as the most important crop for food security and thus its value as a hunger-breaking crop might outweigh its gross margin.

4. Discussion

4.1. Inappropriate potato rotation practice

Although the majority of farmers maintained duration of the break period between successive potato crops of ≥1.5 years, they did not know the advantage of rotation from the point of

Table 5. Variation in labour use (LUE) and economic (EE) efficiencies across farms for the most frequent cropping systems

	Enset (n=12)		Fallow-Barley (n=10)		Fallow-Wheat (n=10)		Fallow-Potato (n=6)	
Farm	LUE	EE	LUE	EE	LUE	EE	LUE	EE
Farm 1	2.94	2.64	3.77	3.39	3.57	2.65	4.87	1.90
Farm 2	3.18	1.65	-[†]	-	-	-	3.36	1.65
Farm 3	3.01	1.61	0.35	0.34	1.12	0.89	-	-
Farm 4	2.14	1.74	1.56	1.10	0.48	0.30	1.62	0.64
Farm 5	1.70	1.53	-	-	1.31	1.02	-	-
Farm 6	2.70	1.99	2.71	0.98	2.45	1.93	6.99	1.92
Farm 7	4.60	3.18	2.23	1.65	1.70	1.35	-	-
Farm 8	2.27	1.81	0.51	0.38	1.45	1.03	0.25	0.12
Farm 9	1.89	1.22	0.95	0.85	2.46	1.62	-	-
Farm 10	1.77	1.43	1.81	1.55	2.72	1.93	-	-
Farm 11	1.64	1.41	1.61	1.31	-	-	-	-
Farm 12	1.38	1.08	1.93	1.41	2.20	1.68	1.03	0.55

[†]not practised in that farm

Table 6. Plot level economic efficiencies of crop production averaged over different numbers of farms.

Dominant crop types or system	Crops per plot in two seasons: *Belg*	*Meher*	# of farms	Average total cost/ plot, USD ha^{-1}	Average gross return/plot, USD ha^{-1}	Economic efficiency per plot[†]
Enset	Enset	-	12	33898	55396	1.63
Trees	Bamboo	-	6	13314	87775	6.59
	Eucalyptus	-	4	3377	282827	83.75
Apple seedling	Apple seedling	-	3	1471282	3985670	2.71
Apple trees	Apple tree and plum	-	2	31716	157831	4.98
Vegetables	Vegetables[‡]	-	3	35018	52495	1.50
Potato- cereal	Potato	Barley	6	45637	53882	1.18
	Fallow	Potato	6	35248	42509	1.21
	Potato	Triticale	4	60245	54869	0.91
	Potato	Wheat	7	57549	80350	1.40
Cereal-pulse	Fallow	Barley	10	14698	16536	1.13
	Fallow	Wheat	10	14988	19149	1.28
	Fallow	Triticale	4	17282	18130	1.05
	Barley	Faba bean	3	18489	17313	0.94
	Barley	Wheat	5	19178	21006	1.10
	Fallow	Faba bean	4	6834	18775	2.75

[†]Economic efficiency per plot = Monetary values of crop products or gross return per plot /sum of cost of seed, fertilizer and labour; [‡]cabbage, carrot, beet root, kale, onion and garlic

disease management and pulse crops were insufficiently included in the cropping systems. Studies in southern Ethiopia have shown that most farmers lack knowledge and follow traditional practices for almost all crops and some farmers who have the knowledge could not practise proper rotation due to land shortage (Bymolt, 2014; Dersseh *et al*., 2016). Overall, the rotation practices have no systematic pattern and may result in decline in soil fertility, disease development and consequently low productivity. This will particularly affect the long-term stability of potato production on which most farmers in the highland areas depend and which is among the most important crops given priority by the government to ensure food security. The productivity of potato was very low (0.8 Mg ha^{-1}) in a farm where pest damage was extreme. Therefore, increasing farmers' levels of understanding of rotation from the point of crop protection and the need for integrated pest management is essential. However, in an area where land is scarce, it may prove difficult to convince farmers about such practices, when their effects are seen only in the long term. Nevertheless, the effects of events like the outbreak of potato bacterial wilt (as observed in most of the study areas recently) can be easily observed and traced in a short period and may be used in the formal extension programme to convince farmers. Generally, potato production may not be sustainable with the current management practices and thus practising proper and efficient agronomic and pest management practices appears to be indispensable.

4.2. Soil nutrient status and uneven fertility management

Nutrient depletion through crop biomass harvesting, uneven farmyard manure (FYM) application and insufficient use of fertilizers might be key to the low and variable soil fertility status. According to Horneck *et al*. (2011), P levels of all farm soils were in the low category. The harvesting of crops like barley by uprooting, as well as the burning of crop residues of crops like faba bean and triticale are likely to contribute to the ongoing depletion of soil organic matter and soil fertility. Product harvest has been reported as one of the important causes of nutrient depletion in Ethiopia (Haileslassie *et al.*, 2005). Farmers have developed the good practice of using FYM for soil fertility (Mazengia *et al.*, 2015) as opposed to the practice in other parts of the country where FYM is used as fuel. However, most of the FYM and house refuses are applied on plots and crops that are near the homestead, in most cases to the enset crop. Most nutrient balance studies in Africa also showed that plots located close to homesteads usually presented higher balances than plots located relatively farther away (Cobo *et al.*, 2010).

Amede and Taboge (2007) have reported higher N, P and K contents in the homestead soils compared with in the outer field particularly for P similar to the current study. This indicates that there is a need to improve distribution of the available organic matter sources over plots. One of the challenges to implement this practice is the difficulty of transporting FYM to plots that are far away from the sources and that have steep gradients. One solution would involve the practice of manure banking, where farmers mutually collaborate and share their FYM and labour. However, there is shortage of FYM to cover all plots and thus efficient use of the available FYM will be important. Due to lack of awareness, urine from livestock, an untapped source of nitrogen, has not been used for crop production in the area.

The low crop productivities can partly be explained by the low nutrient use and low rates of fertilizer application, which in turn is a result of cash shortages. Fertilizers are supplied to farmers by the government through cooperatives in direct cash payments, which may not be affordable for all households. According to Spielman *et al.* (2009), this approach reduces the quality of input services to smallholders and incurs many hidden costs to the government.

4.3. Trend of labour shortage and the need for efficiency

Labour shortage has been reported as a cross-cutting constraint in Chencha (Mazengia *et al*., 2015). The current agronomic practices developed in a time when there was plenty of labour available. This has changed in recent times, with the onset of labour migration to towns for economic opportunities. Economic migration to towns has been also reported by Bymolt (2014). The migration is mostly by men and in some areas like Dorze, the percentages of female headed households are higher than the male headed households. In addition, children are less involved in farm operation as they nowadays go to school. These changes might have aggravated labour shortage particularly for female-headed households which hire-in labour in most cases (Dersseh *et al*., 2016). Previously, there was a culture of working together among neighbours at labour peak periods. This culture is now less practised because the farm owner has to feed the labourers, which has become unaffordable with the current increasing food prices.

Tillage, harvesting and threshing of cereals are commonly conducted manually and they are labour demanding operations (Dersseh *et al*., 2016). Moreover, harvesting of barley is commonly done by uprooting and thus it consumes much labour and increases workload on women who are mostly involved in the operation. Thus, there is a need for alternative approaches to improve the labour efficiency of farm operations to alleviate the effects of the labour shortage. Such approaches may include the introduction of small machinery for farm operations like tillage, harvesting and threshing. Such mechanizations are labour saving but can be capital demanding and their costs may be unaffordable and not feasible for most individual farmers whose farms are small and fragmented. However, such an introduction may become feasible by involving cooperatives or private businesses. In some African countries, hiring-out services to small-scale farmers was a better approach towards sustainable mechanization (Diao *et al.*, 2014) and this can be applied by cooperatives and private businesses in the study area to reach smallholders. The adoption of such new technologies would be more effective by conducting participatory evaluation and adaptation prior to wider expansion of the technologies. Previous evaluations on hand operated ploughing machine through the South Agricultural Research Institute have shown that the machine had shortcomings of design on operation and plough strength and thus was not adopted.

4.4. Low return from animal production

The low gross margin from animal production is mainly due to low productivity and high feed costs from external sources. The low productivity of the indigenous cattle breeds and the inadequate feed quality have been major factors limiting dairy productivity in Ethiopia (Ahmed *et al.*, 2004). The majority of the cattle reared in the study farms were indigenous breed and the milk productivity (1.75 litre per cow per day) was very low and used for home consumption similar to most farms practising mixed farming system in Ethiopia (Ahmed *et al.*, 2004). This partly contributed to the reduction of the gross margin, which is seven times lower than that from the cross-breeds (Ahmed *et al.*, 2004). However, animals have additional benefits that include draught power, transport, provision of farmyard manure and as an asset for the household. Animal feed (and hence conversion by animals) is the main source of nutrients into the farms. The land shortage forces all study farmers to use weeds, mainly from crop fields, as main feed source. Therefore, weeds are allowed to grow in crops (particularly in barley grown in *belg*) to get adequate feed, at the expense of crop yields.

Studies have shown that improving feed quality and adjusting herd sizes could result in higher livestock production (Abegaz *et al.*, 2007). Therefore, one of the options to alleviate feed shortages may be the introduction of improved feed varieties. Scarcity of land is likely to be a constraint to the adoptions these varieties. However, some of the feed varieties can be planted on unused lands such as boundaries of house compounds, peripheries of crop farms and on conservation bunds without competing for land for crops. However, the free grazing of these feeds will remain a significant challenge for successful implementation. Therefore, it might be important to introduce the feeds at community level rather than individual level. Alternatively, there may be merit in cross breeding the local cattle breeds with exotic, more productive breeds, with a view to reducing the number of animals required to maintain production.

In general, we identified in this study that the sustainability of the farming system is constrained with various agronomic and socioeconomic challenges resulting in lower agricultural productivity, soil fertility, labour efficiency and economic return. Although the government is working on alleviating the challenges, the following still need high attention: 1) potato production is characterized by low productivity and economic returns with the current management practices unless proper and efficient agronomic and pest management practices are in place; 2) the soil fertility is low and there is uneven distribution of nutrients over plots with high concentration in the homestead areas; 3) the current trend of economic migration of labour to towns results in labour shortage and this calls for: a) transition from full manual labour dependency to small scale mechanized farming systems at least for operations like harvesting and threshing; b) facilitating credit access and training for such machineries; c) organizing farmers to solve labour demanding operations, such as transporting of farm manure to distant plots and steep slopes, collectively; 4) considering the direct return from animal production, most of the farms had very low gross margin with the current management system and this requires improving access to quality feed and productive animal breeds.

Although there are solutions to these four constraints, most of these are not within the grasp of individual farmers. As a result, they are stuck in their existing systems. A level of community organization may be required to make the quantum leap to more efficient systems. The main actors who could potentially play a role in this are: Office of Agriculture (OoA), Cooperative, Research and Non-Governmental Organizations (NGOs). We will frame our recommendations accordingly:

A) For the district OoA and NGOs, opportunities exist to:

- Create awareness for farmers on the benefits of practising systematic crop rotation for soil fertility and disease management;
- Facilitate access to improved food crops through in-kind credit and feed crop varieties at community level to improve their productivities;

- Train farmers on proper management and use of FYM to ensure the quality and distribution of FYM over plots by facilitating farmers to establish manure banking;
- Scale out the existing programme to crossbreed the local with exotic cattle through artificial insemination.

B) For the OoA and Cooperatives, opportunities exist to facilitate access to financial credit from local institutions such as Omo and Wisdom Micro Finances.

C) For research institutes there are opportunities to play a leading role in:

- Improving the quality of crop residues as feed and identify proper niches to grow different improved feed varieties;
- Breeding more productive animals and determine optimum stocking rate per farm;
- Determining labour efficient and economical farm management practices including crop choice and alternative farm configuration.

5. Conclusions

We identified in this study that the sustainability of the farming systems of Chencha district in southern Ethiopia is constrained by various agronomic and socioeconomic challenges resulting in low agricultural productivity, soil fertility, labour efficiency and economic return. These are improper crop rotation, inappropriate soil fertility management practices, shortage of animal feed, labour- and economically inefficient farm practices and labour shortage. The following are important considerations to alleviate the constraints:

- Design improved crop rotation practices targeting both crop soil fertility and disease management;
- Design proper management and use systems for farm yard manure;
- Improve access to improved food and feed crop varieties;
- Improve the existing feed quality and the productivity of local cattle breeds;
- Conduct research and introduce labour- and economic efficient farm practices;
- The sample size used in this study is small to represent the whole district. Therefore, future studies need to include more farms from different agro-ecologies and farming systems.

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Chapter 5

Exploring synergistic solutions for major constraints of sustainable agricultural production in Chencha, Southern Ethiopia

This Chapter is based on the article: Dersseh, W.M., Schulte, R.P.O, Groot, J.C.J., and Struik, P.C., Exploring Synergistic Solutions for Major Constraints of Sustainable Agricultural Production in Chencha, Southern Ethiopia. Submitted.

Abstract

Several constraints affect the performances of the farming system in Chencha, Southern Ethiopia, suggesting the necessity of adjustments in the farm components. Therefore, an exploration was made to simultaneously optimize operating profit and labour and soil organic matter balances. Data from twelve representative farms and secondary data on improved technologies for possible intervention were used as bases for the exploration. Using the multi-objective model FarmDESIGN, the optimization was conducted for two scenarios for the twelve farms, i.e., optimization based on the currently existing farm components and practices and by introducing new technologies and practices to amend the current farm management options. The results revealed that the farm operating profit, labour balance and organic matter balance were not yet optimized with the current farm configurations of all farms. But there is ample scope to improve and simultaneously optimize both the economic, social and environmental sustainability either through optimization of management within current farm resources, or through using improved technologies. However, the highest improvement could be made through optimally combine management optimization and introduction of improved technologies. The major factor that influenced the optimization was the cropping plan, which might be associated with the management practices applied for a particular crop. However, adjusting areas of crops and implementation of some other optimized solutions may be difficult for individual farmers and requires advice through agricultural extension programmes. Therefore, there is a need to improve the awareness of farmers to wisely manage: crop area and associated crop and soil management practices, land use for eucalyptus, straw use and storage of farm yard manure. Moreover, it is important to diversify off-farm income sources, introduce alternative threshing machineries and improve market access for farm products.

Key words: Farm design, labour balance, operating profit, optimization, organic matter balance, sustainability

1. Introduction

The world population is estimated to reach about 9.6 billion people in 2050 (United Nations, 2012) and food security will remain a global challenge (The Economist, 2014). The increase in agricultural production should match population growth. However, agricultural production is constrained worldwide by several factors including land scarcity due to population pressure and effects associated with climate change. Achieving sustainable food security is a challenge particularly in Ethiopia where the population growth is rapid (3.02%) (United Nations, 2015), the majority (85%) of the population depend on subsistence farming characterized by low productivity of crops (CSA, 2012) and livestock (Mulugeta and Misaye, 2014) and food price hikes faster than non-food items given the double digit economic growth of the country (Haji and Gelaw, 2012). Constraints to agricultural production in Ethiopia include land scarcity in the highlands (Josephson *et al.*, 2014), land degradation (Gashaw *et al.*, 2014; Jolejole-Foreman *et al.*, 2012), low levels of input (Taffesse *et al.*, 2011), low efficiency of fertilizer use and erratic rainfall (Bekabil, 2014). Recent reports indicate that due to the weather shocks in the year 2015, millions of people need food assistance in different parts of the country (USAID, 2015).

Potato gives higher yield and more calories, vitamins and nutrients per unit area compared with cereals. Therefore, it has a vital role in ensuring food security in land scarce areas like Chencha. Potato is one of the most important crops cultivated by the majority of farmers in Chencha and it is used as source of food and income (Mazengia *et al.*, 2015). However, its productivity is low compared to the national average (Mazengia *et al.*, 2015). Some of the factors affecting the productivity and production of potato in the area are lack of access to improved variety seeds and fertilizer, shortage of labour, land and cash (Dersseh *et al.*, 2016), and decline in soil fertility (Mazengia *et al.*, 2015), which affect also other crops in the farming system. Although mixed farming is the dominant farming system in Ethiopia and constraints of production are diverse, most of the research in the country focuses on addressing individual constraints.

Improvements in farm productivity can be achieved through increased yields of products of individual crops and animals, or by reconfiguration of existing or new components at the farm level (areas of crops, numbers of animals, allocation of products, amounts of applied manures and fertilizers, etc.) to close the farm productivity gap (Cortez-Arriola *et al.*, 2014). Components of a farming system are interrelated and solutions to certain components may positively or negatively affect the other components in the system and this necessitates optimized solutions. Moreover, agricultural production is influenced by different biophysical, socioeconomic and climate factors and thus redesigning the current farming systems is important. Martin *et al.* (2013) have identified two categories of farming system design approaches: i. optimization approaches in which emphasis is placed on exhaustive computational exploration of the solution space by a problem-solving algorithm; and ii. participatory and simulation-based approaches in which problem situation analysis and exploration of the solution space rely on the creativity of humans. Optimization is the task of finding one or more solutions which correspond to minimizing (or maximizing) one or more specified objectives and satisfy all constraints (Branke *et al.*, 2008). To simultaneously address two or more problems, methods with multi-objective optimization are required. A multi-objective optimization results in a set of alternatives with different trade-offs, called Pareto optimal solutions, or non-dominated solutions among which usually a single most preferred is to be chosen. Such methods serve different objectives and have been reported by different authors (Dogliotti *et al.*, 2005; Maringanti *et al.*, 2011; Groot *et al.*, 2012). FarmDESIGN (Groot *et al.*, 2012) is a model that serves as a farm diagnosis and exploratory tool to generate large sets of Pareto optimal alternative management options in search of improved farm performance. The model is used as an interactive application which supports iterative cycles of learning and adaptation of the structure of a mixed farm. The model has demonstrated its usefulness for multi-objective optimization in the design of mixed farming systems (Groot *et al.*, 2012). Flores-Sánchez *et al.* (2014) and Cortez-Arriola *et al.* (2016) have used the model to simultaneously improve income, labour and soil organic matter.

In Ethiopia, there are limited experiences in exploring solutions for constraints using optimization (Adane, 2014; Yihun, 2015) and multi-objective optimization (Awulachew *et al.*, 2009; Hassaballah *et al.*, 2012; Saliha, 2012; Seitz and Torre, 2014) and most of them focus on water productivity and use. Yirga and Hassan (2010) have worked on optimization of soil nutrients. Amede and Delve (2008) used an optimization model to address food security and cash income. However, approaches that simultaneously address multiple production constraints related to biophysical (crop, livestock, soil) and socioeconomic (labour and farm income) issues are rare.

In our previous study, we identified a number of constraints in the performances of the farming systems in Chencha, indicating the necessity of adjustments in all farm components (Dersseh *et al.*, under review). The cropping systems were constrained by narrow rotations and low crop yields, primarily caused by lack of improved cultivars, low nutrient supply, and pests and diseases. Inappropriate management of on-farm produced manures and incorrect amounts and application methods of purchased fertilizers impaired soil fertility and caused nutrient losses to the environment. Although land holdings are small, livestock is present on most farms but their productivity is low due to lack of feed resources and low animal production potential. Many aspects of farm management are constrained by large labour demands due to prevalence of manual cultivation practices combined with limited labour availability. The current study aims at optimizing operating profit, labour and organic matter balances. We identify management practices and technologies that could resolve these issues, and conduct model-based tests of these potential innovations in a whole-farm context. Moreover, we explore how further reconfiguration of current and newly introduced practices and technologies can contribute to better production, socio-economic and environmental performance of farms.

2. Materials and methods

2.1. Description of the study area

Chencha is a district in the North Omo Zone of southern Ethiopia. It has a total area of 373.5 km^2 and a human population density of 388 persons km^{-2} (CSA, 2011). The altitude ranges from 2000 to 3000 meter above sea level (m asl). The agro-ecology is classified as highland (>2500 m asl), which accounts for 82% of the total area, and midland (2000 – 2500 m asl) accounting for the remaining 18%. About 65% of the landscape is steeply sloped. The minimum air temperature ranges from 11 to 13 °C and the maximum ranges from 18 to 24 °C. Based on eight years (2002 to 2009) data from the Office of Agriculture, the average annual rainfall is 1172 mm with a peak in April followed by one in September. Due to this bimodal rainfall pattern, there are two cropping seasons locally known as *belg* (March to May) and *meher* (June to October). Crops cover about 35 and 65% of the farmlands in the two seasons, respectively. Mixed farming is the major farming system.

2.2. Farm selection and data collection

The majority of the data used for this study were adopted from our previous farm surveys conducted in 2013 on twelve farms selected using stratified sampling (Dersseh *et al.*, under review). The main criteria used to select the farms were the farm owners' gender, age and education level, household size, wealth class, off-farm income levels, mineral fertilizer usage and diversity of livestock and crops. The data were collected mainly through interviewing the farm owners, taking samples and reviewing secondary sources. The data were related to crop, animal, soil and socioeconomic aspects of the farms and the households. Additional data were collected on management practices and technologies from secondary sources.

2.3. Characteristics of the original farm configurations

Each farm had a total land area ranging from 0.3 to 4.3 ha (on average 1.1 ha), divided over, on average, 10 plots planted with different annual and perennial crops. Sequential double-cropping was practised on most plots. In different farms, a total of fifteen food crops, one feed crop (natural grass) and two tree species (eucalyptus and bamboo) were grown. Enset, potato and barley were grown in all farms and wheat and vegetables were grown in 92 and 67% of the farms, respectively. The most common cropping system was sole enset grown by all farms followed by Fallow-Barley, Fallow-Wheat and Fallow-Potato each practised by 83, 83 and 50% of the farms, respectively. Average plot sizes ranged from 0.01 ha of apple or vegetables to 0.51 ha of eucalyptus, respectively, with a median of 0.075 ha. Crop products were used partly for home consumption (particularly enset and barley) while the remaining were exported from the farm through sale (particularly fruits and vegetables). Depending on the crop type, straws were used for animal feed and bedding, fire wood or other home uses or, in a few cases, for sale.

Average fertilizer rates used to produce different crops per farm were 94, 57 and 5608 kg ha^{-1} diammonium phosphate (DAP), urea and farm yard manure (FYM), respectively. Rates varied across farms from 30 to 201 kg ha^{-1} for DAP, 20 to 158 kg ha^{-1} for urea and 457 to 20929 kg ha^{-1} for FYM. Only FYM was applied to enset and fruit trees plots whereas no fertilizer was applied to eucalyptus and grass plots.

The animal herd consisted of mainly cattle, horse and sheep. All farms had cows and the majority (92%) of the cows had calves. About 33, 17 and 42% of the farms had heifers, bulls and oxen, respectively. Most (67%) of the farms had sheep whereas a lower percentage (33%) of the farms had horses. Average numbers of cattle, sheep and horses (including young) kept per rearing farm were about 5, 6 and 1.5, respectively, whereas the average numbers of the adult ones were about 2, 5 and 1, respectively. All farms had animal feed shortage and the average feed self-sufficiency was only 28%. Animals grazed for 8 hours during the day throughout the year. Animals, particularly the young ones, were used for sale while nearly all of the milk products were used for home consumption. FYMs were used only for crop production in all farms.

2.4. Modelling improved management practices and technologies

Multi-objective optimization was used for the twelve farms to explore possibilities to improve farm performance on the basis of only the currently existing farm components and practices or resources (Scenario 1) and by introducing new or improved technologies and practices to amend the current or existing farm management options (Scenario 2). The proposed interventions are described below and Table 1 shows the specific changes made for one farm.

Frequency of potato in the rotation: In all farms, the maximum frequency of potato was set at 0.66 so that potato appears in a plot utmost once in every one and half years (or once in every three growing seasons) which is practised by most farmers as demonstrated in our previous study. The frequency can also be related to the proportion of plot area of potato relative to the total farm area.

Improved crop varieties: Improved varieties with associated management practices were considered for annual crops including potato, wheat, barley, faba bean, field pea and grass. The average yields of the improved crop varieties attained on farmers' plots at national level were considered as interventions (MoARD, 2009). Interventions were proposed for farms mainly where the productivities of crop varieties were less than the average on-farm yields of the improved varieties. In one farm (Farm 6), the productivity of an improved potato variety in one plot was below the average potential due to management problems. Therefore, proper management practices, including fungicides, were considered as intervention. Generally, for six farms, 75 to 100% of the above mentioned crops were replaced by improved varieties and practices, whereas in the remaining farms, 20 to 71% of the plots were replaced by improved varieties and practices.

Table 1. Proposed introductions (interventions) of improved technologies and their productivities or efficiencies relative to the current practices in Farm 11

Plot, practice, animal	Type of introduced technology	Productivity (kg ha^{-1}) /efficiencies		Seed rate, kg ha^{-1}		DAP, kg ha^{-1}		Urea, kg ha^{-1}	
		Current	Introduced	Current	Introduced	Current	Introduced	Current	Introduced
	No					0		0	
	No					0		0	
Potato-Triticale	Potato variety*	2667	20000	1333	1900	220	195	220	165
	No for triticale	2000		120		20		10	
Fallow-FB	Variety	1000	3100	170	275	41	100	0	50
Potato-Wheat	No for potato	19048	2000	1667	2000	119	195	95	165
	No for wheat	3571	2770	238	175	0	100	0	150
Barley-Wheat	Barley variety	560	2600	80	125	0	50	0	50
	Wheat variety	2400	2770	80	175	0	100	0	150
Fallow-Barley	Variety	1875	2600	128	125	0	50	0	50
Barley-FP	Barley variety	208	2600	100	125	0	50	0	50
	FP variety	1042	2900	150	150	0	100	0	50
Barley-FB	Barley variety	450	2600	100	125	0	50	0	50
	FB variety	759	2770	100	275	0	100	0	50
Potato-Barley	Potato variety*	9167	20000	1800	1900	133	195	100	165
	Barley variety	833	2600	100	125	0	50	0	50
Potato rotation	Frequency	The highest frequency was set at 0.66							
FYM storage	Plastic cover	Fraction of mineral N storage loss in aerobic condition = 0							
Cereal threshing	Machinery	The machine threshes 400 kg hr^{-1} wheat and 500 kg hr^{-1} barley							
Lactating cow**	Cross breed	1.75 l day^{-1}	5.2 day^{-1}						

Farm yard manure management: To improve management of on-farm produced manure, covering farm yard manure (FYM) with impermeable plastic sheet was assumed to create anaerobic condition to reduce N loss (Shah *et al.*, 2012; 2013). Therefore, the originally used fraction (0.27) of mineral N loss during storage in aerobic conditions was adjusted to 0 in the model for all farms.

Improved cattle breed: For all farms, the productivity of the current lactating cow breed was replaced by a cross-breed (cross between indigenous and exotic breed) which produces about three folds more milk per day and has a longer lactation period compared with the local breed (Mulugeta Ayalew and Misaye Badasso, 2014).

Machine threshing: To reduce labour requirement, manual threshing of wheat, barley and triticale was assumed to be replaced by threshing with a small machine (Asella multi-crop thresher) which is being promoted in the country (Girma Moges and Dawit Alemu, 2014). The time saved, compared with manual threshing of the same product, was calculated and the total hours of labour required to produce respective crops was adjusted accordingly in the model. The cost of machine threshing (on hiring basis) was considered as cost of contract work in the model.

2.5. Variables and steps for optimization

The main production constraints identified by our previous studies (Dersseh *et al.*, 2016; Dersseh *et al.*, under review) were considered as objectives in the model. These constraints were cash and labour shortages and low soil fertility. Accordingly, the objectives of the optimization were to maximize the operating profit to generate sufficient income, to maximize the farm labour balance (decrease labour requirement) and to maximize the soil organic matter balance.

The decision variables that were changed to attain the above objectives were crop land area, fertilizer (DAP, Urea and FYM) amount, animal number and amount of fresh grass to feed animals. The minimum value for each of the decision variables was set to zero except for the plot areas of permanent crops and trees (enset, apple, plum, eucalyptus and bamboo), which were fixed at the original plot sizes of respective farms, as well as the number of cows, which was fixed at one. The maximum values for permanent crop areas and amount of fertilizer and fresh grass to feed animals were set to about twice the original values of the respective farms. The maximum areas of annual crops were set at the total area of the farm minus the sum of the areas of permanent crops while the maximum numbers of animals were set to four times higher than the original values.

The constraint variables in the model were total farm area, percent feed balance [percent deviation between required and available dry matter intake (DM), energy (EN) and protein (CP) for maintenance and production] and soil nutrient (N, P and K) losses. The minimum allowed nutrient loss was zero to avoid mining, except for farms that originally showed mining for K (farms with negative values for K losses).

The exploration was conducted using the FarmDESIGN model (Groot *et al.*, 2012). Pareto-based Differential Evolution (DE) was used as selection strategy in the exploration. For each of the twelve farms, the model was run to explore alternative solutions relative to the original farm configurations with 1000 iterations. The parameters for the evolutionary algorithm (DE) were F=0.15 (mutation amplitude) and CR=0.85 (crossover probability). The number of solutions generated depended on the number of decision variables and multiplication factors (MP). MP were adjusted so that the number of solutions for each optimization was ca. 700 (varying from 690 to 726 with an average of 714).

3. Results

3.1. Optimized solutions and their relationships

A number of optimized solutions were generated simultaneously for the three objectives for each farm (Fig. 1). The relationships between the optimized solutions for the objectives were different across farms. The relationships between the optimized solutions for organic matter (OM) and labour balances (the difference between available and required labour) were negative in half of the farms in both the current farm management (Scenario 1) and introduction of improved technologies (Scenario 2) (Figs 1 a and b). However, the degree of association varied across farms. Similarly, the relationships between the optimized solutions for OM balance and operating profit were negative in the majority (75%) of the study farms in the two scenarios (Figs 2 a and b) although the degree or strength of their association varied across farms and scenarios.

Contrastingly, the relationships between the optimized solutions for labour balance and operating profit were positive in 50% and 58% of the farms in Scenario 1 and Scenario 2, respectively (Fig. 3), indicating that an increase in labour balance (i.e., a decrease in labour requirement of the farm) is associated with an increase in profit. The degree of association was relatively high in Scenario 2 in the majority of the farms.

3.2. Deviation of mean optimized values from original

The mean optimized estimates and original values of the OM balance in the two scenarios are presented in Fig. 1(c). Optimizations of the current farm configurations increased OM balance by 108 to 351 kg ha^{-1} yr^{-1} or by 5 to 319% (average: 59%) compared to the original values. On the other hand, technological intervention alone increased OM balance by less than 1% compared to the original values in the current management practices (Scenario 1) for all farms. In contrast, optimizations of farm configurations in Scenario 2 brought OM balance increments ranging from 10 to 387% (average: 78%) compared to the original values in Scenario 1.

Likewise, optimizations of the current farm configurations decreased labour balance by 120 to 315 hr ha^{-1} yr^{-1} or by -9 to -137% (average: -35%) compared to the original values (Fig. 1(d)). Technological intervention alone decreased labour balance on average by -16% compared to the original values in Scenario 1. Optimizations of farm configurations in Scenario 2 decreased labour balance by -15 to -106% (average: -51%) compared to the original values in Scenario 1.

On the other hand, optimizations of the current farm configurations increased operating profit by 928 to 8373 BR ha^{-1} yr^{-1} (1 Br = 0.05 USD) or by 7 to 742% (average: 149%) compared to the original values (Fig. 2(c)). Technological intervention alone increased operating profit by 13519 to 29055 BR ha^{-1} yr^{-1} compared to the original values in Scenario 1, whereas optimizations using improved technologies increased operating profit by 32729 to 373451 BR ha^{-1} yr^{-1} compared to the original values using the current management system. One farm that had the lowest and negative initial operating profit showed the highest percent increment in operating profit.

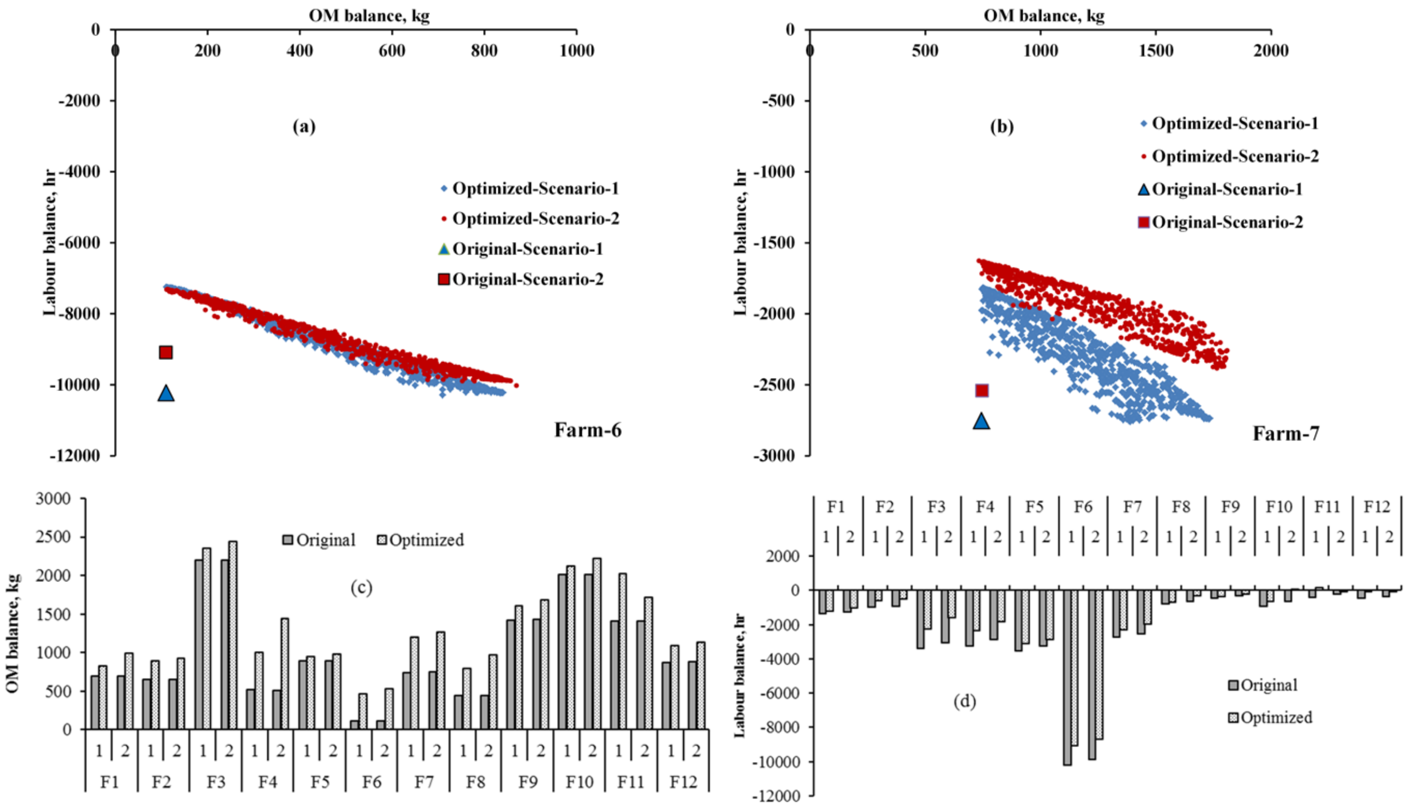

Fig. 1. Relationship between optimized solutions of organic matter (OM) and labour balances and their mean optimized estimates compared to their original values in Scenario 1 (1) and Scenario 2 (2) across farms (F)

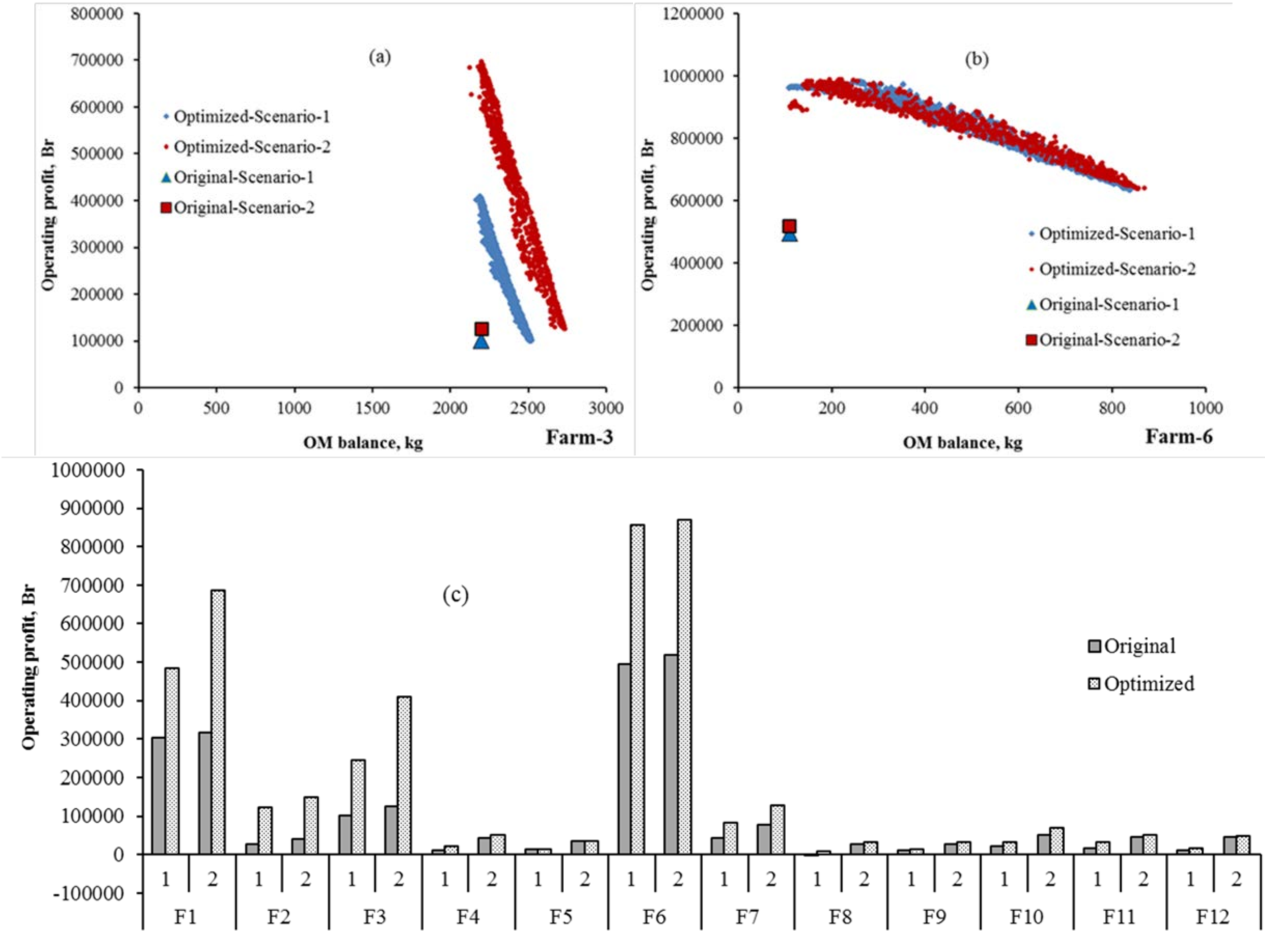

Fig. 2. Relationship between optimized solutions for organic matter (OM) balance and operating profit and mean optimized estimates of operating profit compared with the original values in Scenario 1 (1) and Scenario 2 (2) across farms (F)

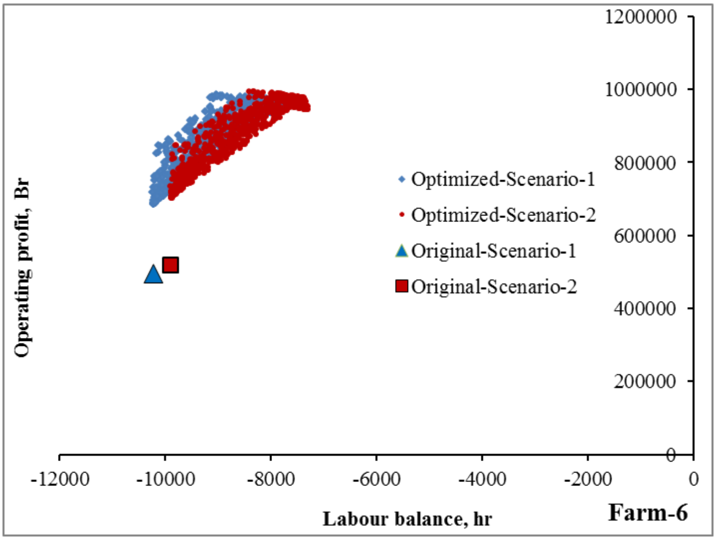

Fig. 3. Relationship between optimized values of labour balance and operating profit in Scenario 1 and Scenario 2 for Farm 6

3.3. Relationship between management practices and optimized solutions

3.3.1. Crop areas and organic matter balance

The model uses "crop area" as proxy for "contribution to the cropping plan" and thus as the plot area of one crop increases, the plot areas of other crops automatically decrease. The relationships between plot areas and optimized solutions for OM balance in Scenario 2 varied among crop types (Fig. 4). For barley, the relationships were positive with change in areas of the majority of plots although the relationship varied across plots (Figs 4(a) and (b)). On the other hand, adjusting the areas of potato resulted in mixed responses of the OM balance (Figs 4(b) and (c)): the relationship was negative when potato was grown in mono-cropping (Fallow-Potato), whereas it was positive when potato was double cropped with triticale, wheat and barley in most farms. In most cases the OM balance was negatively associated with the areas of faba bean, vegetables, apple seedling, grass and eucalyptus (Figs 4(c) and (d)).

3.3.2. Crop areas and labour balance

The relationship between optimized solutions for labour balance and plot areas in Scenario 2 varied based on crop types and cropping systems (Fig. 5). In most plots, the labour balance

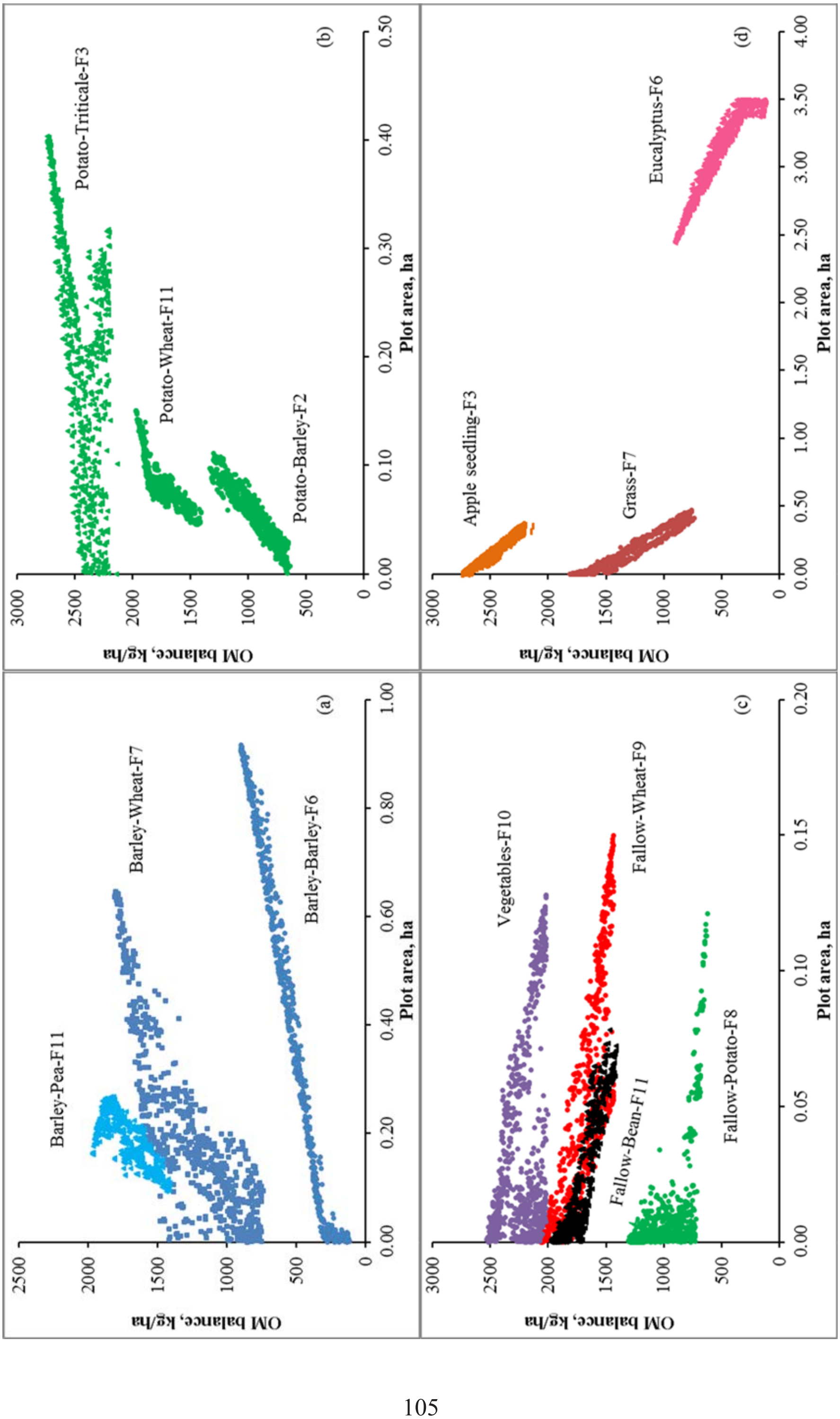

Fig. 4. Relationship between crop area and optimized organic matter (OM) balance in Scenario 2 across farms (F)

was negatively associated with the areas of mainly barley grown particularly in double-cropping (Figs 5(a) and (b)). Labour balance was also negatively associated with the areas of potato when it was double cropped with other crops. Labour balance, however, was mostly weakly and positively associated with areas of potato in mono-cropping and with plot areas of mono-cropping of wheat (Fig. 5(c)) and triticale (data not shown). Generally, mono-cropping had a positive association with labour balance for most crops. In addition, the labour balance was strongly and positively associated with plot areas of grass and eucalyptus in almost all farms where they were grown (Fig. 5(d)).

3.3.3. Crop areas and operating profit

Operating profit was negatively associated with the areas of barley (Figs 6(a) and (b)). It showed a weak and varied relationship with the areas of most potato plots across farms. However, it had a positive association with plot areas of potato particularly in a mono-cropping system. In contrast, operating profit had a strong and positive association with the areas of apple seedling, vegetables and eucalypts in the majority of the farms where they were grown (Figs 6(c) and (d)).

3.3.4. Improved FYM storage and N loss

In all farms, improved storage of FYM reduced the amount of N loss (Fig. 7). The reduction in N loss between the current and introduced improved storage methods ranged from 4 to 16 kg ha^{-1} $year^{-1}$ equating to 26 to 32%. The relative reduction in N loss was weakly and positively correlated with the total amount of FYM used per farm.

3.3.5. Other management practices

On the majority of farms, other management practices had only weak associations with the objective variables with the exception of the amount of fresh grass to feed to animals (Fig. 8), which had a relatively strong positive relationship with the organic matter balance and negative relationship with the operating profit on some farms.

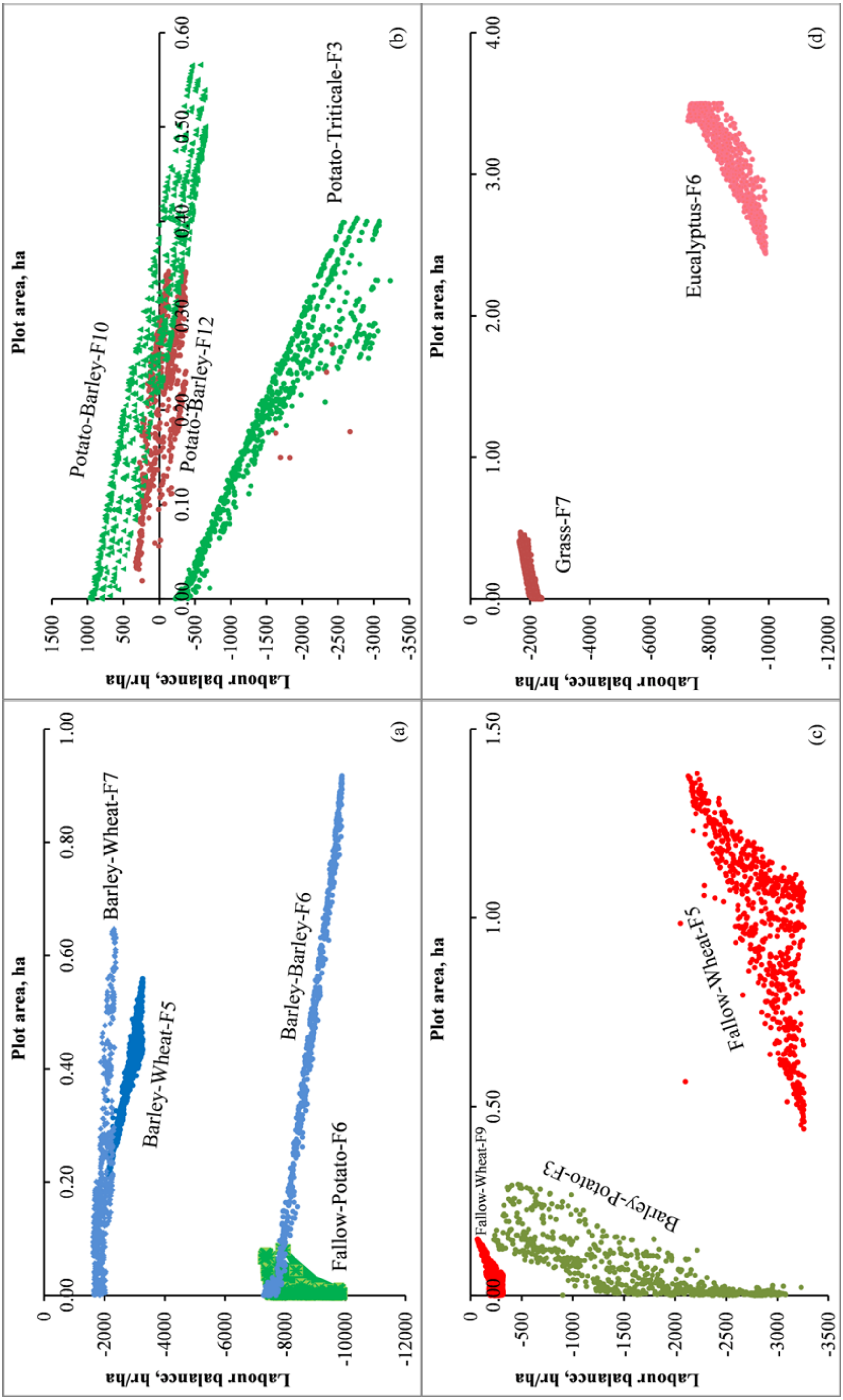

Fig. 5. Relationship between crop area and optimized labour balance in Scenario 2 across farms (F)

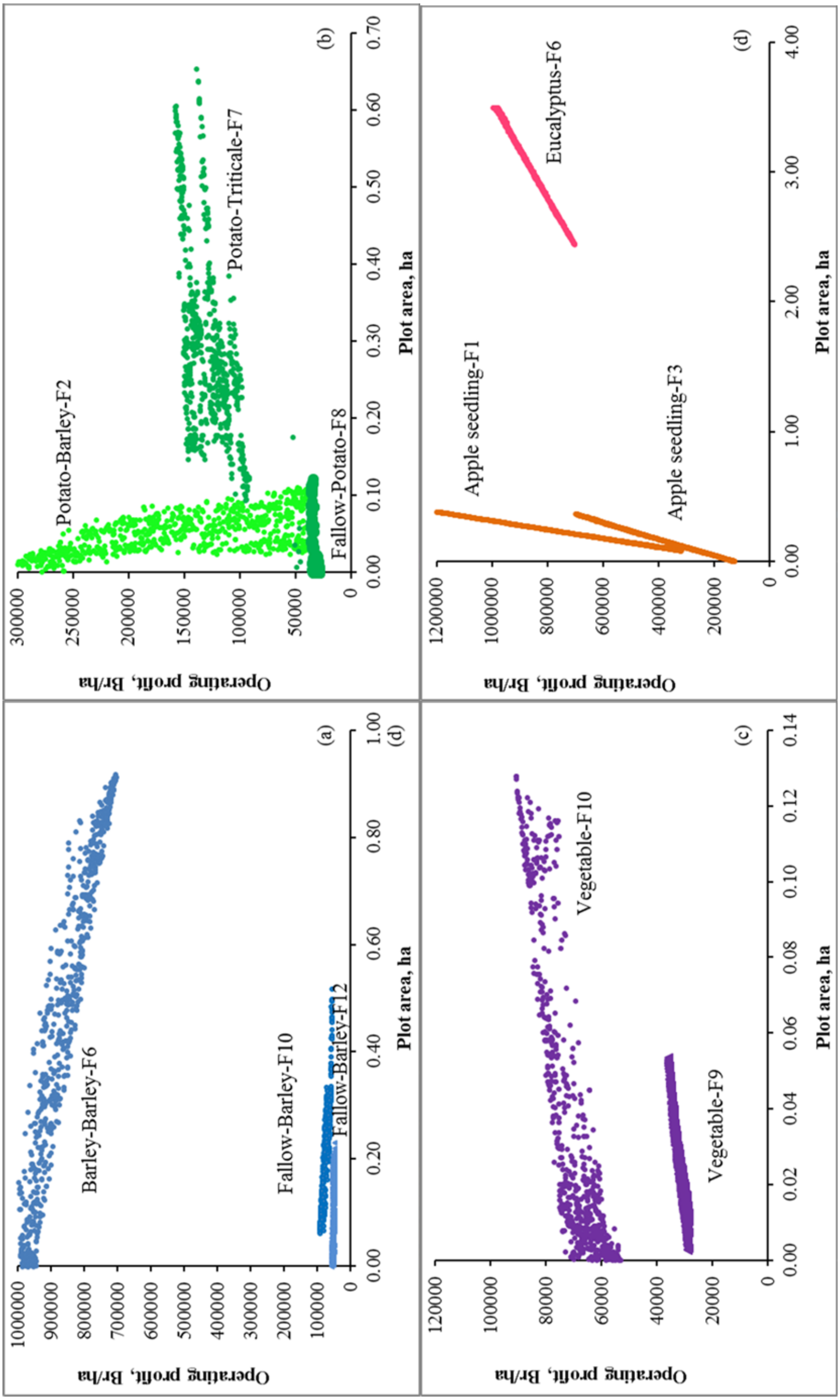

Fig. 6. Relationship between crop area and optimized operating profit in Scenario 2 across farms (F)

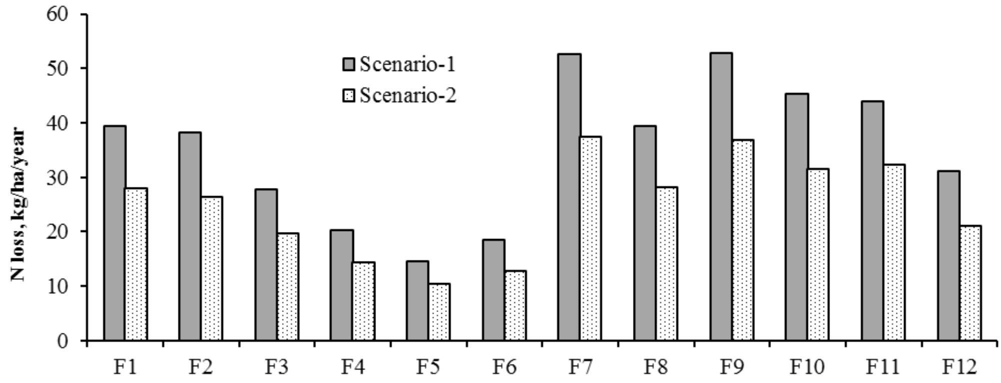

Fig. 7. Comparison of estimated N loss through volatilization from FYM with the current (Scenario 1) and improved (Scenario 2) storage method across farms (F)

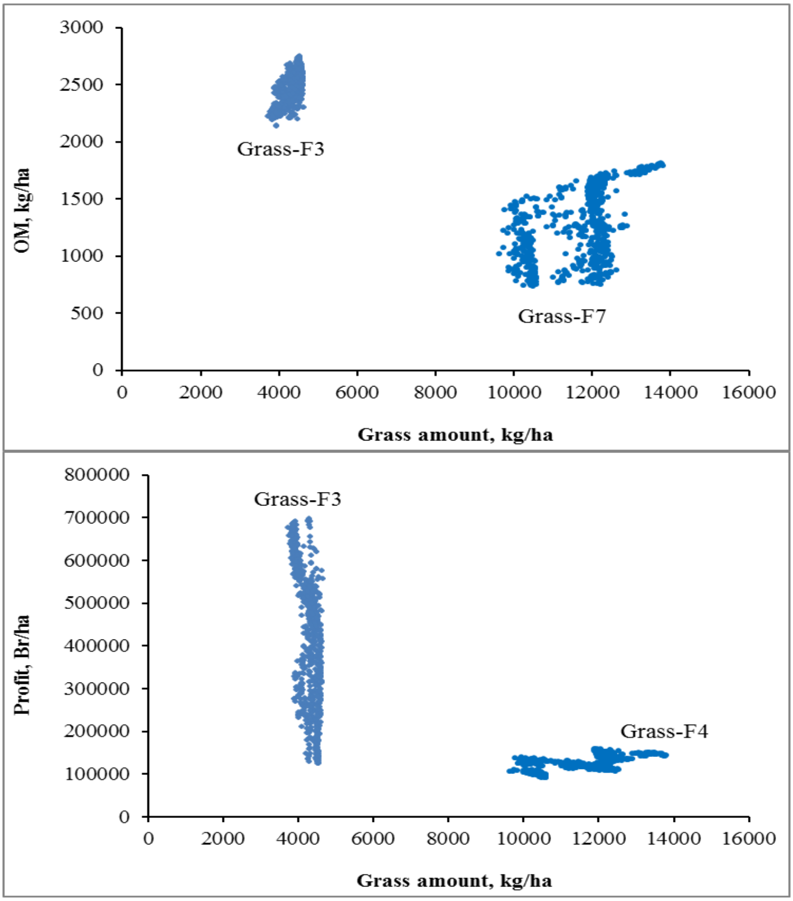

Fig. 8. Relationship between amount of fresh grass to feed animals with organic matter (OM) balance and optimized operating profit in Scenario 2 across farms (F)

4. Discussion

4.1. The need to optimize the current farm configuration

The differences between the optimized solutions and the original values for the objective variables in the current systems (Scenario 1) imply that the current farm configurations of all farms are not yet optimized and this signifies the room and the need for simultaneous, synergistic improvements for the three objectives. Therefore, the solution spaces that were explored in the current study suggest that each farm can have a wide range of options from which farmers can select based on their needs.

4.2. Role of adjusting plot area for optimization

Depending on crop type and associated management practices, adjusting the crop composition, by changing the plot areas of individual crops, played a major role in optimizing the three objectives. The positive association of the plot area of barley with OM balance might be related to the prevailing soil fertility and straw management practices for barley production. In most farms, barley is produced using FYM with little or no chemical fertilizer. In addition, the majority of the straw yield of barley is used for animal bedding and feed in most farms; this reflects common practice in other parts of the country (Brink and Belay, 2006). Barley straw is not used for fire or burned on the field like the straw of some other crops. Therefore, the portion of the straw product used as bedding material and for animal feed is returned to the soil with and through FYM and might increase the OM balance. In contrast, OM had a negative association with an increase in areas of crops of which the straw products are mainly burned, as observed with faba, or the products of which leave the farm through sale, such as apple seedling, vegetables and eucalyptus. Moreover, it is not common to apply fertilizer to eucalyptus and little or no fertilizer is applied to faba bean, as it is a nitrogen fixing crop. Therefore, one way to improve the soil OM balance might be by increasing the area of barley plots that might attract FYM and increase the availability of feed and bedding material. However, an increase in the plot area of barley was associated with high labour demand and low operating profit as evidenced in most farms. Thus, improving labour use and economic efficiency of crop production, particularly for barley, and adjusting the destination of crop straws would be important. It might be important to distribute the available FYM to other crop plots too.

Increasing the areas of plots with relatively less labour requirement played an important role in the optimization of labour balance. This was demonstrated by the positive association between eucalyptus and grass plots with labour balance. Based on the local practice, cultivation of eucalyptus requires less labour, which is mainly for land preparation and planting, whereas minimum labour input is required for grazing grass. Thus it appears that labour requirement of farms could be minimized by expanding the areas of primarily eucalyptus and grass. However, optimization of the labour balance was associated with reduction in OM balance which might be due to the removal of OM from the farms through the biomasses of mainly eucalyptus and to some extent grass. Moreover, increasing the area of grass plots might not be practical due to land scarcity and its negative association with operating profit. Therefore, it might be important to improve both labour and economic efficiencies of farms focusing on food crops that proved to contribute more to OM. One of such crops was barley, but increasing the areas of barley plots was associated with high labour demand in most farms. This suggests that threshing of barley using a machine did not bring significant reduction in the overall labour requirement for barley production for some farms. This in turn implies the presence of labour inefficiencies in other management practices which might include weeding and harvesting of barley by uprooting. In a previous study in Chencha, the labour and economic efficiencies of barley production were lower than for other crops (Dersseh *et al.*, under review). In addition, collecting weeds for animal feed in the fields of cereals (mainly barley) is a common practice in the area and this might require extra labour. Therefore, improving the method of harvesting of barley and feed management may also be crucial to improve the labour balance.

The positive association of plot areas of some crops with operating profit may be related to the productivity, input and product use of such crops which included eucalyptus, apple seedling, vegetables and fallow-potato. Eucalyptus requires less labour and fertilizer inputs and it gives a high-value product which is used mainly for sale. As a result, it has high labour and economic efficiency (Dersseh *et al.*, under review) and this might be a reason why eucalyptus plantations are expanding fast throughout the country. Matthies (2013) reported that the equivalent annual income of eucalyptus exceeds that of other crops. However, expanding the area of eucalyptus may not be practical due to land scarcity in Chencha. In addition, eucalyptus is considered by the government as a threat for competing crop land and exhausting soil fertility and thus some regional states have banned eucalyptus tree planting on farm-lands (Jagger and Pender, 2000). Apple seedlings also require fewer inputs, including land, and the majority of its produce is used for sale. A small increase in an area of apple may generate high profit and may not have much effect on the overall OM balance on the farm. However, access to the market may be a potential challenge for apple production. Although Chencha was known to be the major source for apple seedling in the country, currently there is less market for apple seedlings in the area which may be caused by the emerging competition among growers within and outside the district. Thus investigating the challenge and improving market access are essential.

The majority of the products of vegetables (cabbage, carrot and beet root) are used for sale and thus had a positive association with operating profit. However, vegetables are currently grown in a small area per farm and may not generate adequate income to the household. But there is a possibility of increasing the areas of vegetables with proper soil fertility management to maintain OM balance as vegetables showed negative association with OM balance. On the other hand, the negative association of operating profit with other crops might be related to the use of all or most of the products of these cops for home consumption. A good example is barley which was produced by the majority (67%) of the farms only for home use. This might be one reason why operating profit had negative relationship with the plot areas of barley in mono- or double-cropping with other crops such as potato. Overall, the positive association of operating profit with the plot areas of several crops shows that there are many options to improve the operating profit. However, most of the crops were associated with a negative OM balance and this means that optimized crop management is conditional on proper soil management practices being in place. Alternatively, augmenting off-farm income generating activities could play a role in improving profit.

4.3. Sources of improvement for optimization

Our scenario analyses consider two sources of improvement in the exploration. The first one is management optimization within the current farm resources, which was demonstrated by the wide variation between the mean optimized solutions and the original values of the three objective variables in Scenario 1. The wide variation indicates the possibility and the extent of improvement that can be made in each farm by redesigning the current farm management within the current resources. However, the scale of the potential improvements varied across farms, and may be associated to certain farm characteristics for each objective. The percent improvement in OM balance was related to the original OM balance and the total areas of the farms. Therefore, the improvement was relatively large for farms having a low original OM balance and a large area. Farms of most of the wealthier households were low in OM balance and this might be related to the tendency that such households use more inorganic than organic fertilizer for crop production (Mazengia *et al.*, 2015). Moreover, the farms of most of the rich households were relatively large and might be constrained with insufficient organic material to cover the whole farm. Similarly, the improvement in labour balance was high for farms originally having high ratio of family labour and farm size suggesting that such farms had low original labour use efficiencies which were the characteristics of most of the farms of households of low to medium wealth (Dersseh *et al.*, under review). On the other hand, the improvement made in operating profit had no clear relationship with farms although there was a tendency that farms with low original profit had relatively high improvement indicating that farms of relatively most rich households were already optimized.

The second source of improvement is through using improved resources or practices. This is the improvement made as a result of intervention or introducing improved farm practices and technology. It is the difference between the original values of the three objectives in Scenario 2 and Scenario 1. The percent improvement in OM balance, arising from these improved technologies, was low and had no significant variation across farms. In Scenario 2, inorganic fertilizers were used to amend soil fertility and thus might not have significant effect in changing the OM balance. The use of a machine thresher for cereals was the only introduced practice used to improve the labour balance. Therefore, the variation in improvement across farms could be partly associated with the proportion of cereals in each farm. Similarly, farms with a high proportion of introduced technologies had a relatively high percentage of improvement in operating profit. Generally, the improvements made on the three objectives using this method were relatively low suggesting that use of improved practices/technologies with the current farm configuration alone cannot bring enough change and reconfiguring the farms is essential to further maximize benefits.

Finally, we considered the potential of ‘double optimization’ in Scenario 2, i.e. the combined effects of Improved Technologies and subsequent Optimized Management. In this scenario, the scope for improvements, quantified as the difference between the mean optimized values in Scenario 2 and the original values, was quite high compared to the improvements made by Optimized Management or Improved Technologies in isolation. This suggests that combined use of improved technologies and reconfiguring farm structure is indispensable to maximize benefits. However, the scale of the improvements varied across farms, for the same reason as those described in the above two sources of improvement.

4.4. Importance of potato intervention

Potato is one of the most important food and cash crops in Chencha (Mazengia *et al.*, 2015) and it is an important crop to ensure food security. In the current study, the impact of intervention of potato in the production system could be seen from its role in environmental and socioeconomic sustainability across farms. The negative association of potato production in mono-cropping with OM balance in most plots suggests that it played a less positive role in environmental sustainability. This might be because potato is mostly produced using inorganic fertilizers (Mazengia *et al.*, 2015) which have no direct role in maintaining OM. Moreover, potato has a very high harvest index and small root system and thus less biomass remains in the farm leading to OM depletion. However, the positive association of OM balance with potato in double cropping with other crops shows the importance of crop rotation in soil fertility management and the possibility of reducing the nutrient mining effect of potato in ensuring sustainable production.

On the other hand, the positive relationship between potato production and labour balance particularly in mono-cropping signifies the social importance of potato intervention in reducing labour demand. In a previous farm survey, to the contrary, high labour requirement of potato production has been identified as a constraint mainly for female headed households (Dersseh, *et al.*, 2016). In the current study, the positive association of potato production with operating profit in most farms shows the relative economic importance of potato which covers the largest portion of the land allotted for food crops. This will create an opportunity to improve the incomes of most households constrained with cash shortage. Therefore, along with improved farm practices, optimizing the current farm configuration can improve the role of potato production in improving farm labour requirement and profit.

In summary, the current study revealed that there is ample scope to improve and simultaneously optimize both the economic, social and environmental sustainability (as indicated by the organic matter balance, labour balance and operating profit) for each farm. Improvements could either be achieved through optimization of management within current farm resources, or through using improved technologies. However, the highest improvement could be made through optimization combination of management optimization and improved technologies. Depending on the management practices used per farm, the solutions for each objective can either be antagonistic or synergistic. The major important factor that influenced the optimization was the cropping plan, which might be associated with the management practices applied for a particular crop. However, adjusting areas of crops and implementation of some other optimized solutions may be difficult for individual farmers and requires advice through agricultural extension programmes. Therefore the following may be considered to enhance the practical implementations of solutions for the three objectives:

- Although eucalyptus played an important role in improving profit and labour balance, its expansion might not be practical with the current land scarcity and for it exhausts organic matter unless proper land use is in place.
- The current soil fertility management and straw use of barley improves the OM balance and this role of barley might be sustainable if the current productivity and labour efficiencies of barley are improved.
- The implementations of most of the optimized solutions will be practical if the current labour use and economic efficiencies of production are improved.
- Expansions of the areas of apple seedling and vegetables with proper soil fertility management practices can play an important role in improving income if access to market is facilitated.

The district Office of Agriculture (OoA) of Chencha, supported by research institutions, has been working on multisector extension service to improve the livelihoods of the farming communities. The following considerations may accelerate the ongoing development work in the district, by creating awareness on:

- The pros and cons of optimizing the cropping plan and their management practices from the perspective of improving OM, labour requirement and profit;
- Planting eucalyptus where it is not suitable for other crops or where it has less competitive impact on crops;
- The role of using crop straws for animal bedding and feed in improving organic matter and the disadvantages of burning crop residues;

- Improving the storage of FYM using plastic cover;
- The distribution of FYM across different crops similar to barley plots;
- Strengthening the introduction of improved crop (food and feed) varieties with their improved management practices;
- In collaboration with cooperatives and NGOs, facilitate introduction of small threshing machineries and easy methods for harvesting of cereals;
- Improving market access for vegetables and apple seedlings;
- Introducing or strengthening different off-farm income generating activities that do not require much land.

Research institutes need to implement the following:

- Determine economic and labour efficient management practices for crop production;
- Evaluate and adapt threshing machineries to the local situation.

5. Conclusions

The current study showed that the farm operating profit, labour balance and organic matter balance were not yet optimized with the current farm configurations of all farms. It also showed that there was room to simultaneously optimize the three objectives through:
(1) optimization within resources as demonstrated by the variation between the mean optimized solutions and the original values in Scenario 1;
(2) introducing improved farm practices and technology as evidenced by the difference between the original values in Scenario 2 and Scenario 1; and
(3) optimization using introduced improved practices/technologies which was shown by the difference between the mean optimized values in the Scenario 2 and the original values in Scenario 1.

Depending on the management practices used, the solutions for each objective could be antagonistic or synergistic. The major important factor that influenced the optimization was optimizing the cropping plan, which may be associated with the management practices applied for a particular crop. However, adjusting the cropping plan and implementation of some other optimized solutions may not always be practical. The following considerations may facilitate the practical implementation:

- Creating awareness for farmers on pros and cons of adjusting crop area and management practices;
- Allocating proper land for eucalyptus;
- Using straws for animal bedding and feed;
- Improving the storage and use of FYM;
- Introducing improved crop varieties, off-farm income generating activities and threshing machineries;
- Improving market access for vegetables and apple seedlings;
- Improving economic and labour efficiencies for crop production.

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Chapter 6

General discussion

1. Introduction

Potato is one of the most important crops in Ethiopia where nutrition and food security are major concerns. It is an integral component of the farming system in the country and its production is increasing from year to year. In view of the multiple benefits of potato to society, a research-for-development project was launched in 2012 with the aim of creating a potato centre of excellence and sustainable production in Chencha (Vita, 2015). This PhD study is a part of the components of this research-for-development project. The study analysed the baseline and sustainability of the farming systems in Chencha, giving special emphasis to potato production. In the beginning, a household survey was conducted to understand the major crop production systems and bottlenecks in general (Chapter 2) and to assess a baseline of production system, to quantify the variation in input and output and to identify constraints for potato production in particular (Chapter 3). Chapter 3 elucidated the degree of association of household characteristics to input/output use and production constraints which were computed using principal component analyses (PCA). The main findings (of Chapters 2 and 3) were used as criteria to select the farm/households for the follow-up study (Chapter 4). Understanding of the constraints of the existing farming systems is a base to search for solutions that ensure sustainable agricultural production. In this study, an effort was made to evaluate the sustainability of the farming systems at farm level (Chapter 4). The main indicators used to evaluate the sustainability of the farming systems were soil nutrient status and balance, and labour use and economic efficiencies which were analysed using the FarmDESIGN model. Moreover, the potato rotation pattern was assessed at plot level for two years. Because the constraints of the farming systems were different, searching for optimized solutions for the major constraints was an important question for this study. Reconfiguration of the existing or new components of a farm has been one of the strategies used to improve farm productivity (Cortez-Arriola *et al.*, 2014). In Chapter 5, we explored synergistic solutions for the major constraints of the farming systems, using most of the data from Chapter 4. Two scenarios (existing or new components) were used as bases to search for optimized solutions.

Therefore, this thesis used various approaches that included lab analysis, household surveys, group discussions, experts' estimates, visual observation, and farm surveys. The different chapters of this thesis investigated the constraints and possible solutions for sustainable farming system. This chapter (Chapter 6) brings the findings of the different chapters together and reflects on the implications for the sustainability of the current farming system in general and prospects of improved, sustainable potato production in particular.

2. Prospects of potato production

The potato crop has a high potential of expansion in Ethiopia because most of the arable land throughout the country is suitable for cropping with potato. It can potentially be grown on about 70% of the 10 million hectare of arable land (mainly in the highland areas where 90% of the population resides), indicating that Ethiopia has possibly the greatest potential for potato production in Africa (FAO, 2008). Its area of cultivation and amount of production/productivity are increasing from year to year (Fig. 1). Compared to the main cropping season in the year 2001/02, the areas of cultivation and amount of production in 2014/15 have increased by about 83 and 139%, respectively (CSA, 2015). The increase in production has been mainly due to an increase in the area of production. Similarly, its productivity has increased by about 30% with an average of 9.3 t ha^{-1}. The increase in productivity was mainly due to diffusion of improved varieties and increased inputs. However, in some areas, such as Chencha, the average productivity of potato remains very low (Chapter 3) in spite of the potential to yield up to 40 t ha^{-1} in Ethiopia (APHRD, 2009). Potato has a short crop cycle and it is suitable for double cropping with other crops: several areas in the country (including Chencha) have two cropping seasons within a year. This improves the productivity of the land and has an important role in boosting production in the highland areas of the country where land scarcity is a constraint for agricultural production. Potato can be intercropped with maize which is a common practice in the north-western part of the country (Berihun and Woldegiorgis, 2013).

However, the production of potato is constrained by various socioeconomic and biological factors (Chapters 2, 3 and 4). The constraints are related to access to inputs (land, labour, seed, fertilizer, and training), the poverty trap (cash shortage) and access to the market (Chapter 3). Potato production is also constrained by improper and inefficient agronomic and pest (mainly bacterial wilt and late blight diseases) management practices (Chapters 2, 3 and 4). Most of these constraints affect the production of other crops too (Chapter 2). These constraints are also countrywide challenges affecting the amount of potato production upon which millions depend to ensure household food security.

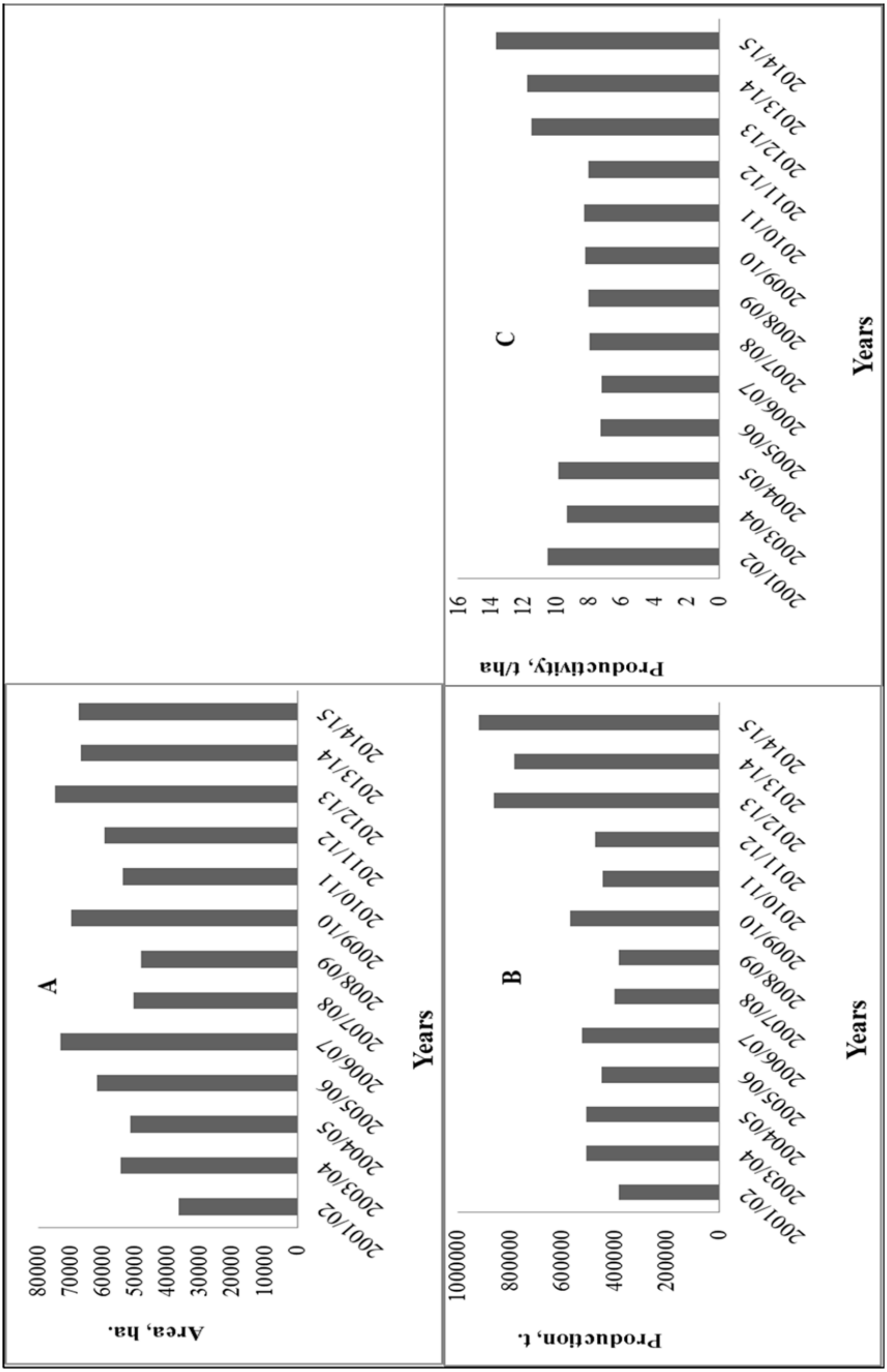

Fig 1. Area, production and productivity of potato in Ethiopia across years (Adapted from CSA, 2015)

Therefore, solving the aforementioned constraints is essential and should be a priority for the regional and/or national government and other development actors in the country. Some of the constraints, such as land shortage, may need policy intervention at higher levels. Some can be resolved through provision of equitable training and creating awareness for farmers in different social categories (gender, age, and education level). Others, such as access to the market and improved storage, are not given adequate emphasis by the current formal extension service. Solving such problems and improving resource (land, labour, fertilizer) use efficiencies will make potato production more repaying and encourage farmers to enhance and sustain potato production. There are very good prospects for value addition with increasing numbers of urban consumers willing to diversify their potato consumption patterns to include branded and packed fresh potatoes in supermarkets, chips and crisps (Haverkort *et al.*, 2012) which are not widely consumed in the country yet. Potato disease management should get special consideration as the majority of farmers do not know their causes and management strategies. One of the reasons why farmers practised improper potato rotation is due to lack of awareness about diseases (Chapter 4). Therefore, bacterial wilt disease, in particular, may easily disseminate over locations and adversely affect the fate and expansion of potato production in the country at large. Currently, the disease has been found distributed throughout the country ranging from low to high altitudes (Berihun and Woldegiorgis, 2013). Evidence in the early 1980s has shown that the widespread infestation of late blight has contributed to the decline of potato cultivation in Ethiopia (Tesfahun *et al.*, 1985).

Overall, addressing the abovementioned constraints will enhance and sustain the productivity and production of potato and play an important role in ensuring food security at household and national level.

3. Evaluation of the sustainability of farming systems

Sustainable agriculture integrates plant and animal production practices having a site-specific application (USDA, 2007) and sustainability in agriculture can be best evaluated against a range of environmental, economic, and social goals that reflect the views of diverse groups in society (NAP, 2010). Sustainability of a farming system can be evaluated at different spatial scales. In this study, analyses were made on the agronomic practices, feed self-sufficiency, soil nutrient balance and status, labour use and economic efficiencies to evaluate sustainability of the farming system mainly at farm level (Chapter 4). Considering the major constraints identified in this study as indicators, the sustainability of the farming systems will be discussed below in line with the findings of the study and related outcomes of other studies.

3.1. Soil nutrient management

The farm-gate nutrient balances were positive for most nutrients across farms except for some farms for K balances (Table 1 in Chapter 4). This indicates that most of the farms have net gain in nutrients. This can be an indicator for sustainability of production in terms of soil fertility maintenance on the respective farms. The use of nearly all of the farmyard manure (FYM) produced on farm for crop production might have an important role contributing to the positive balance. Farmyard manure is a good way of recycling nutrients in all farms. Thus, a portion of the biomass harvested on the farms returns to the soil. Feed from external sources can also come to the soil through FYM. The great majority (97%) of farmers in Chencha use farmyard manure for crop production (Chapter 2). This shows that farmers have a good understanding of the role of FYM to amend soil fertility. Besides enriching soil nutrients, FYM helps also to reduce the soil acidity (Citak and Sahriye, 2011). Therefore, the practice of applying FYM will help to improve the soil acidity which ranges from slightly acidic to strongly acidic in Chencha (Chapter 4). To sustain soil fertility and increase production, farmers from other parts of the country, who use FYM mainly for other purposes, need to be advised to follow the experiences of Chencha farmers.

However, farmers lack the awareness and skill of improved management and storage of FYM resulting in high losses of nutrients. Therefore, to exploit the full benefit from FYM, much has to be done in improving the management and use of FYM by the extension and research institutes in the country.

Laboratory analysis, on the other hand, showed that the values of some of the soil nutrients ranged from low to medium in most farms (Table 2 in Chapter 4). Most of the plots of the different farms analysed have low available P (<20 ppm) and low organic carbon (<2%) which is an indicative of the status of the soil organic matter. The contradicting results from the nutrient balance (positive farm-gate nutrient balance) and lab analyses (low soil nutrient contents) may indicate the presence of nutrient losses due to different factors including poor management of FYM, burning of crop biomass and erosion which also contribute to environmental pollution. In most cases, FYM is stored in an open space near the homestead exposed to the sun and rainfall which cause nutrient losses through volatilization and leaching. In addition, there are high nutrient losses during application of FYM on the field due to poor incorporation into the soil. Application of relatively much FYM on plots in and around the homestead has resulted in high soil fertility in the homestead area while plots far away from the homestead are characterized by a low soil fertility status (Table 3 in Chapter 4). Nutrient losses can also occur through the burning of the straws of some crops, which is a common practice in the area. Moreover, water erosion may cause large nutrient losses as the majority of the topography of the area is steeply sloped and subject to high rainfall. Furthermore, there is no appropriate crop rotation in the area (Fig. 1 in Chapter 4), despite the known role of crop rotation in maintaining sustainability.

Most farmers use low amounts of chemical fertilizers due to a shortage of cash (Chapters 2 and 3). Overall, the impact of low soil nutrients coupled with other constraints in the farming system was directly reflected in the low productivity of the cropping system and indirectly and partially in the low productivity of animal rearing which all affect the sustainability of the farming system (Chapter 4). An increase in crop production was associated mainly with an increase in area of cultivation rather than using improved crop technologies. This implies that with the current soil fertility management practices, the sustainability of crop production in the area and in the majority of the highlands of Ethiopia is in question unless integrated soil fertility management and conservation practices are in place resulting in healthy soil which is a key component of sustainability.

3.2. Labour efficiency

Ethiopia has a large labour force engaged in agriculture indicating that the country has a huge potential of human labour to foster sustainable economic development (CSA, 2014). Therefore, one of the basic premises of the government strategy is accelerated and sustained growth through labour-intensive production methods envisioning to use a heightened productive capacity of the agricultural labour force to the fullest extent possible (MoFED, 2003). However, the results of the current study showed that there was labour shortage for all of the surveyed farms (Chapter 4) and most of the interviewed households stated that labour shortage was one of the major production constraints in the area (Chapter 3). This indicates that the farming system is not sustainable in terms of labour use. The main possible reasons for labour shortage include the use of inefficient agricultural management practices, labour demanding operations, labour migration to towns for economic reasons, and fragmentation of farm lands. Most of the crop and livestock management practices are traditional and labour demanding as nearly all field operations are conducted manually. For instance, the practice of harvesting of barley by uprooting, which is not common in most other parts of the country, takes much time and labour to accomplish (Chapter 4) and the field management of crops such as potato is labour demanding (Chapter 3), both resulting in low labour use efficiency. The findings in Chapter 5, however, showed that the labour requirement of a farm can be reduced through increasing the areas of plots with relatively less labour requirement and/or using labour efficient management practices. On the other hand, the labour efficiency could be influenced by the culture of the society and land fragmentation. According to the local culture, farm activities such as transporting of farm yard manure and harvesting of barley are performed by females whereas activities such as tillage are implemented by males only; labour efficiency could be improved if both gender classes could do these tasks jointly. This inefficiency particularly affects female-headed households whose spouses have migrated to towns. Labour migration to towns is a common phenomenon throughout the country and is expected to continue, following the development of the country.

Culturally, land is inherited from a parent by dividing all plots of the farm, which are usually scattered in different geographical locations, among children. Successive sharing of plots has reduced the farm size per household and the plots of a farm remain located far apart. Travelling to such far plots to carry out routine farm operations consumes time and labour and this further affects labour efficiency. Although there is land scarcity in the area, some farmers (particularly aged and female farmers) hire out some plots because they are far away from homes. Labour efficiency can be improved by technologies and crop choices. According to the government policy, however, such technologies and farming methods should not have a labour-displacing nature (MoFED, 2003).

3.3. Economic performance

Ethiopia has adopted agricultural development led industrialization (ADLI) as a strategy to bring fast change in the development of the country. Agricultural development led industrialization is a development strategy that aims to achieve initial industrialization through robust agricultural growth and close linkage between the agricultural and the industrial sectors (Ohno, 2009). It is the Government's overarching policy response to Ethiopia's food security and agricultural productivity challenge (ECOSOC, 2007). Therefore, agriculture continues to be a driving force for the economic development of the country. A sustainable agro-system should maintain or improve the economic viability of agricultural production (Lescot *et al.*, 2007) and a farming system is said to be economically sustainable when it generates a net income per work unit higher or equal to the reproduction threshold (Canali and Segre, 2007). In the current study, the combined operating profits from crop production and livestock rearing were positive for the majority (92%) of the surveyed farms (Chapter 4). This is a good indication that the majority of the farms are economically sustainable. However, there was a very large profit variation across farms and some of the farms had low operating profit to cover household needs. The large profit variation across farms suggests that most of the farms have the potential to further increase their profits. The profit variation could partly be attributed to the types of farms. Crop farming resulted in by far higher profit compared to animal rearing. About a quarter of the study farms showed negative returns from animal rearing and this impacted negatively on the overall operating profit. The positive operating profits of the majority of the farms were due to the high returns from crop production. While animals showed negative return, they are essential for sustaining the cropping systems through bringing in nutrients from outside the cropping areas indicating the role of mixed farming system in sustaining agricultural production. The profit variations between crop and livestock production might occur partly because of the influence of the extension system which is skewed towards crop production. In the country in general, much effort has been exerted in the crop husbandry and thus relatively more improved crop technologies and training services have been provided. This indicates that the extension service for the livestock sector needs to be strengthened to improve the productivity and profitability of livestock in the country.

The variation in the profitability of crop production was influenced by the types of crops, management practices, and the access to the market (Tables 4, 5, and 6 in Chapter 4). In general, crops that are mainly cultivated for cash generation were more profitable compared to those produced mainly for home consumption. Such cash crops included perennial trees of eucalyptus, bamboo, and apple. These crops were more profitable because they were produced with low costs (because they require low inputs) and had very high labour efficiencies.

The variation in the economic efficiencies of the other crops (annuals) was associated mainly with the productivity of the respective crops. The productivity of these crops was in turn influenced by the efficiency and type of inputs used (labour, variety, fertilizer, etc.) and the incidences of pests. The labour use efficiencies of each farm had an important role in determining the economic efficiencies of respective farms indicating the positive role of improving labour use efficiency on economic performance. Unimproved varieties were used for most crops and the amounts and types of fertilizer used were not adequate (Chapter 2); this could significantly reduce the productivities of the crops. The economic inefficiency of potato production in some farms was mainly due to disease problems (Table 5 in Chapter 4) and such diseases can be a potential challenge for potato production because most of the farmers do not know their causes and control measures due to lack of awareness as a result of limited training services (Chapter 3).

As evidenced for potato, low price of products due to inadequate access to the market (Figure 4 in Chapter 3), particularly during the harvesting period, had impact on its economic return.

The above all suggest that in order to sustain the economic sustainability of the farming systems, proper choices of crops and improving access to inputs (improved varieties/breeds, fertilizers, pesticides, improved animal feeds and training) and markets are among the very important concerns. Moreover, use of labour efficient methods, determination and use of optimum fertilizer rate and plant population (seed rate) can have important roles in improving economic efficiency of crop production which is the main component of the current mixed farming system.

4. Synergistic options to sustain farming systems

Exploring optimized solutions is an important approach for simultaneously searching harmonized and improved solutions for two or more constraints in a farming system. Different models are in use to explore such solutions in several countries and the results help not only to address the constraints under consideration but also to sustain production, resource use and protect environment, among others. In Ethiopia, however, there is limited experience in using optimization as a means to simultaneously explore solutions for different constraints. Several studies in the country have merely focused on solving individual constraints while additional constraints could simultaneously be addressed and save time and resources. In this study, various constraints were identified challenging agricultural production in Chencha (Chapters 2, 3 and 4) which formed the basis to explore synergistic solutions for low soil fertility and shortages of cash and labour, by simultaneously optimizing the organic matter balance, operating profit and labour requirements (Chapter 5). The findings of the exploration revealed that all of the farms were non-optimized within the current farm configuration. This implies that the sustainability of the farming system in the area is in question unless balanced solutions are sought and implemented. The current study showed that each farm can have a wide range of optimized solutions: adjusting the crop composition, by changing the plot areas of individual crops, played a major role in optimizing the above three constraints. Improvements could be made for all farms in different ways - by redesigning the current farm management within the current resources, by introducing improved technologies, or through the combined effects of improved technologies and subsequent redesigning. Much improvement can be made by simply reconfiguring the existing farm management. However, the improvement made through the combined effects of improved technologies and subsequent redesigning was higher suggesting that introduction of improved technologies alone is not enough to maximize benefits. Currently, the government of Ethiopia is trying to transform the agriculture sector mainly by improving the productivity of smallholder agriculture through increased use of improved agricultural technologies. Based on the current study, however, redesigning the farm management should be part of the plan so as to achieve more improved and sustained agricultural production.

5. Conclusions

This study evaluated the sustainability of the farming systems in Chencha by assessing the constraints to crop production in general and potato production in particular (considering that it plays an important role to ensure food security) and by evaluating agronomic and socioeconomic performances at farm level. We explored optimized solutions for the main constraints that affect the sustainability of the farming systems. In general, the findings showed that the potato production was challenged by a number of constraints that varied between farms. At farm level, the sustainability of the farming system was constrained by low agricultural productivity, low soil fertility, low labour efficiency, and low economic returns associated with improper crop rotation, inappropriate soil fertility management practices, shortages of animal feed, labour- and economically inefficient farm practices and general labour shortages. There is ample scope to improve and simultaneously optimize the major constraints at farm level. We can draw the following insights from the findings of the study:

1. The current potato production is characterized by low productivity and economic returns, due to various socioeconomic, agronomic and biological factors. The main constraints were primarily related to access to inputs (seeds of improved varieties, fertilizer, and training) for willing producers, to the poverty trap (cash shortage) for the poorest and uneducated households and to market access for proficient producers. Land and labour shortages and pests were cross-cutting constraints. Therefore, there is a need to develop a pluriform advisory model that recognizes and builds on alleviating the diversity of constraints faced by farmers from contrasting demographies. The above constraints affect the production of other crops too. Therefore, integrated solutions are required to alleviate the constraints and different organizations should get involved. The Office of Agriculture, in collaboration with other governmental and nongovernmental organizations, needs to introduce additional income generation activities that require less land and labour and facilitate access to disease resistant varieties, fertilizers, financial credits, improved ware potato storages, and markets. In addition, awareness creation for farmers on the benefits of practising systematic crop rotation (where potato comes not more often than once in three years and pulse crops are purposely included in the rotation) for soil fertility and disease management is essential.

2. Based on lab analyses, the soil fertility is low and there is uneven distribution of nutrients over plots with high concentration in the homestead areas. The low soil nutrient contents might be caused due to loss of nutrients through several factors including loss of nutrients from farm yard manure as a result of mismanagement (during storage and application), burning of crop biomass and water erosion. Moreover, there is no appropriate crop rotation and commonly inadequate amounts and types of chemical fertilizers are used. However, farmyard manure had an important role in recycling and maintaining soil fertility. To reduce nutrient losses from farm yard manure, the farm yard manure should be covered (e.g. by plastic sheet) and stored under a shed and incorporated into the soil immediately after field application. It is also important to distribute farm yard manure across plots. Therefore, providing training to farmers on proper management and use of farmyard manure is very important to ensure the quality and distribution of farmyard manure over plots. In addition, research institutes need to determine economical rates of chemical fertilizers (mainly N and P sources) integrated with and without farm yard manure. Office of Agriculture and Cooperatives should facilitate the timely supply of these chemical fertilizers through credit with low initial payment.

3. The current labour shortage can be attributed to mainly inefficiency of agricultural management practices and labour migration to towns for economic reason indicating that the traditional farming system is not sustainable in terms of labour use. Therefore, research is required to improve labour efficiency of management practices from land preparation to threshing. In addition, the extension service should improve farmers' access to proven technologies that improve labour efficiency. Resolving the challenges related to land fragmentation may require policy intervention.

4. Considering the direct returns from animal production, most of the farms had very low gross margin for their current animal management systems and this has reduced the overall operating profit of farms. The low return from animal rearing was offset by the relatively high profit from crop production. Animals are essential for sustaining the cropping systems through bringing in nutrients from outside the cropping areas. To improve livestock productivity, improving access to quality feed and productive animal breeds are mandatory. Research is required to improve the existing feed quality and the productivity of local cattle breeds. To materialize this, the roles and responsibilities of research, higher learning and development institutions are indispensable.

5. The entire farms were not optimized with the current farm configuration. However each farm can have a wide range of optimized solutions mainly through introduction of improved technologies (varieties, breeds, fertilizers, etc.) and subsequent redesigning of the farm management (adjusting crop composition, herd type and number, etc.). Adjusting the crop composition, by changing the plot areas of individual crops, played a major role in exploring optimized solutions. The optimized cropping plan showed that increasing the plot areas of barley, grasses and apple seedlings, for example, can improve OM and labour and economic efficiencies, respectively. However, adjustment of the cropping plan and the implementation of some other optimized solutions might not always be easy to implement. For instance, some regional states have banned planting of eucalyptus trees on farm-lands assuming that eucalyptus trees compete for food crops' land and exhaust soil fertility. Moreover, because most farmers are uneducated the implementation of the approach might be difficult for individual farmers unless they get advice through the agricultural extension programme. Therefore, it will be fundamental to educate farmers and create awareness among them on pros and cons of adjusting crop areas and management practices.

In general, Ethiopia has diverse agroecologies and agricultural production systems. Most of the agricultural practices are traditional and natural resources are becoming scarce while the population growth is escalating. Therefore, it is high time and worthwhile to assess the sustainability of agricultural production in different farming systems and agroecological zones of the country. Based on the results of our assessment, the introduction of agricultural technologies, coupled with a reconfiguration of farm management should be considered as one of the most important approaches to increase and sustain agricultural production in different parts of the country.

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Summary

Potato is one of the most important crops grown in many parts of Ethiopia. Its production is increasing from year to year. There is a high potential to expand the cultivation area of the potato crop, as most arable land is in principle suitable for cropping with potato. The potato grows quickly, has a high yield, and produces more energy and protein per unit area than any cereal crop. Therefore, it can play a vital role in ensuring food security, which is a major concern for the country. However, its national average productivity is much below the productivity of improved varieties achieved in research trials due to several factors including access to improved varieties, pests and suboptimal agronomic practices.

As a result of population growth, land is becoming scarce globally and thus the opportunities of extensive farming are becoming less and in most areas untenable. Many populous regions, like the highlands of Ethiopia, will already soon exhaust their land frontiers. Therefore, increasing production through sustainable intensification of agriculture will be crucial to achieve both food security and sustainability. The challenge of achieving sustainable food security is particularly prominent in Ethiopia where the majority of the population depend on agriculture, which consists mainly of subsistence farming. The population grows rapidly and thus producing more food on incrementally smaller and fragmented farms will create double-edged challenges. Although agricultural outputs are growing, the production is not enough to ensure household food security in the country. Low production is generally caused by land degradation, low levels of input, low efficiency of fertilizer use and erratic rainfall. Various reports in literature indicate that improvements in farm productivity can be achieved through increased yields of products of individual crops and animals, or by reconfiguration of existing or new components at the farm level to close the farm productivity gap.

The farming systems in Ethiopia are predominantly mixed farming systems. Components of a farming system are interrelated and solutions to certain components may positively or negatively affect the other components in the system and this necessitates optimization which is the task of finding one or more solutions which correspond to minimizing (or maximizing) one or more specified objectives and satisfy all constraints. However, most of the research in Ethiopia is focused on individual constraints and thus there is limited research experience to show interrelation between crop and livestock management practices in improving sustainability of production. There is also not enough evidence on combined analysis of soil nutrient and animal feed balances and agronomic and socioeconomic efficiencies at farm

level. Moreover, most of the research concentrates mainly on the central parts of the country and areas such as Chencha receive limited attention. The overall objectives of the current study were therefore to understand the production constraints and agronomic and socioeconomic sustainability of the farming systems of the study area and explore synergistic options to alleviate major constraints.

The introduction in Chapter 1 presents an overview of Ethiopia's geographical location, land use and population. It also provides descriptions of the country's economy, agroecology and crop diversity, concepts of farming system and sustainability, and the rational of the study. Moreover, it describes the general and specific objectives and the methods and approaches used in the study.

Chapter 2 assesses the diversity of farming systems in the potential potato production areas of Chencha. Household surveys and farmers' group discussions were used to collect data. Descriptive statistics were used to analyse the data. The results showed that a mixed farming system was the prevailing system in the area. The major crops grown in the area were potato, enset, wheat, barley and kale. There are two cropping seasons per calendar year and crop rotation is common in the area. The common intercropping practices were mixed intercropping of barley with lentil and wheat with linseed. Based on local classification the most common soil types were Modo (dark loam), Gobo (red clay) and Kalta (brown clay). Fertilizers used were farmyard manure, compost, urea and diammonium phosphate. Most of the households obtained a cash income from agricultural activities, mainly from crop production. The most important off-farm activity was weaving. The major constraints of the farming system include soil fertility depletion, low productive crop varieties, shortages of land, and lack of improved seed and of cash.

In Chapter 3, an attempt was made to establish a baseline for the current production system, to quantify the variation in input and output, and to identify constraints hindering expansion of potato production. A questionnaire was used to collect the data, employing individual interviews with household heads. Descriptive statistics were computed on biophysical and socioeconomic data to understand the diversity of crops and livestock and related management practices and income sources. In addition, Principal Component Analysis was computed using XLSTAT to understand the degree of association between input and output use and household characteristics in potato production. The results revealed that the farming system of the study area was a mixed farming system where crops and livestock husbandry occurred simultaneously. Input and product use and related constraints varied across household characteristics. Therefore, using improved varieties, inorganic fertilizers, and selling products were strongly and positively associated with the households' wealth, adoption, and education levels. On the other hand, problems of cash and inadequate produce negatively associated with wealth, adoption factors, and education levels whereas problems of access to improved varieties, training, and fertilizer were positively associated with age, family size and gender. Most of the non-adopting and uneducated households were poor and cash shortage was mainly associated with their inability to purchase inorganic fertilizer and labour. Land and labour shortages and pests were identified as cross-cutting constraints. Farmers specifically associated land and labour shortages to the large amount of land required to meet the recommended rotation and the high labour requirement of potato production, respectively. In general, there are three drivers of constraints which are related to: 1) access to inputs for willing producers most of whom are self-sufficient; 2) the poverty trap for the poorest and uneducated households whose farms are closed to most of the inputs and are characterized by a critical shortage of cash and produce for consumption; and 3) market access for proficient producers whose farms are open to most of the inputs and have surplus produce. Therefore, there is a need to have a pluriform advisory model, which recognizes and builds on alleviating the diversity of constraints identified in this analysis.

Chapter 4 describes and evaluates the frequency of potato cultivation in the rotation, animal feed balance and feed self-sufficiency, the existing soil nutrient balance and status, and the labour and economic performances at plot and farm level, and identifies constraints for sustainable intensification. Twelve farms were surveyed and crop and livestock and socioeconomic related data were collected for one year in two growing seasons. For each farm, soil analyses were carried out for texture, bulk density, pH, N, P, K, and organic carbon. Weather data were collected using an automatic weather station. Soil nutrient balance and flow, labour balance, gross margins, operating profit and feed balance were computed using the whole-farm bio-economic model FarmDESIGN. The labour balance was calculated as the difference between required and available labour per farm whereas labour use efficiency of crop production was manually calculated as monetary values of crop products divided by cost of labour at farm and plot levels. Operating profit was calculated by subtracting total costs of crop and animal production and fixed costs for assets. The economic efficiency of crop production was manually calculated as monetary values of crop products divided by the sum of the cost of seed, fertilizer and labour at farm and plot levels. The feed balance was calculated by subtracting the total available feed from crop products and other feeds from the total feed required for animal maintenance and production. Feed self-sufficiency (FSS) was manually calculated as $FSS = (1-D) \times 100$, where D is the estimated amount of imported grass divided by the total mass of dry matter fed to animals. The results revealed that the sustainability of the farming systems of Chencha district is constrained by low agricultural productivity, soil fertility, labour efficiency and economic return associated with improper crop rotation, inappropriate soil fertility management practices, shortage of animal feed, labour- and economically inefficient farm practices and labour shortage. Farmers practised improper crop rotation because they did not know the advantage of rotation from the point of disease management. They have some knowhow on the benefit of rotation for soil fertility maintenance but they did not sufficiently include pulse crops in the cropping systems. Moreover, low and variable soil fertility status might be caused by nutrient depletion through crop biomass harvesting, uneven farmyard manure application and insufficient use of fertilizers practised by farmers. Labour shortage could be attributed to mainly inefficiency of agricultural management practices and labour migration to towns for economic reason. The overall economic returns were partly affected by the low economic return from animal production mainly due to low productivity and high feed costs from external sources. Therefore, implementation is needed of appropriate crop rotation, proper management and use of farm yard manure, facilitating access to improved food and feed crop varieties, upgrading the productivity of local cattle breeds and introducing labour- and economically efficient farm practices.

Chapter 5 explores synergetic solutions for major constraints identified in Chapters 2, 3 and 4. These constraints were cash and labour shortages and low soil fertility status. Socioeconomic and biophysical data that were collected from twelve representative farms in Chapter 4 combined with additional secondary data gathered on improved technologies for possible intervention were used for the exploration. Multi-objective optimization was used for the twelve farms to explore possibilities to improve farm performance on the basis of only the currently existing farm components and practices or resources (Scenario 1) and by introducing new or improved technologies and practices to amend the current or existing farm management options (Scenario 2). The findings revealed that all of the farms were not optimized with the current farm configuration and there was ample scope to improve and simultaneously optimize the economic, social and environmental sustainability either through optimization of management within current farm resources, or through using improved technologies. However, the highest improvement was possible through the combined effects of improved technologies and subsequent optimized management or reconfiguring farm structure. Adjusting the crop

composition, by changing the plot areas of individual crops, played a major role in the optimization and this might be associated with the management practices applied for crops. However, adjusting areas of crops may not be practical for all crops and implementation of some other optimized options may be difficult for individual farmers unless they get advice from agricultural extension service. Increasing the area of eucalyptus, for instance, may not be practical due to land scarcity and the soil fertility exhausting nature of eucalyptus. The results also showed that use of improved storage could reduce the amount of N loss from farm yard manure. Therefore, there is a need to improve the awareness of farmers to wisely manage: crop area and associated crop and soil management practices, land use for eucalyptus, straw use and storage of farm yard manure. Moreover, it is important to diversify off-farm income sources, introduce alternative threshing machineries and improve market access for farm products.

Chapter 6 synthesizes the results of the study described in the previous chapters. The chapter gives better understanding of the prospects of potato production, the sustainability of the farming systems (from the perspectives of soil fertility, labour efficiency and economic performance), and the possibility of simultaneously improving the major constraints. The chapter summarizes the core messages of the study. These are: 1) the current potato production is characterized by low productivity and economic returns due to various socioeconomic, agronomic and biological factors; 2) the soil fertility is low and there is uneven distribution of nutrients over plots with high concentration in the homestead areas; 3) the current labour shortage can mainly be attributed to inefficiency of agricultural management practices and labour migration to towns for economic reason indicating that the farming system is not sustainable in terms of labour use; 4) considering the direct return from animal production, most of the farms had very low gross margin with the current management system and this has reduced the overall operating profit of farms. The low return from animal rearing was offset by the relatively high profit from crop production indicating the benefit of mixed farming system in sustaining agricultural production; and 5) each farm can have a wide range of optimized solutions mainly through introduction of improved technologies and subsequent redesigning of the farm managements.

In general, the findings of the current study indicate that it is worthwhile to assess the sustainability of agricultural production in different farming systems and agroecologies of the country. In addition, the combined effect of introduction of improved agricultural technologies and subsequent reconfiguration of the farm management is very crucial to increase and sustain agricultural production.

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Biography

The author was born at Motta, in East Gojjam Zone, in Ethiopia on July 4, 1966. He attended elementary, junior and secondary educations at Motta town from 1974 to 1983. He then enrolled at Alemaya University of Agriculture (now Haramaya University) where he studied for a BSc. degree in Agriculture, majoring in Plant Science from 1984 to 1988. He joined the Institute of Agricultural Research (now Ethiopian Institute of Agricultural Research) as Junior Research Officer in the field of Agronomy and Crop Physiology in September 1988. Due to administrative change, he was transferred to the Southern Agricultural Research Institute (SARI), based at Hawassa. Sponsored by SARI, he studied for an MSc. degree in Agronomy at Alemaya University (now Haramaya University) from November 1998 to July 2000. He served at SARI as Researcher mainly in two research centres (Hawassa and Areka) and his major area of research focused on improving crop and soil management practices. He, jointly with research colleagues, produced a number of publications mainly in journals, books and proceedings. He also served as Crop Research Coordinator, Centre Manager and site Project Coordinator for the African Highlands Initiative, which was an eco-regional programme active in East Africa. In March 2012, he was offered the PhD sandwich programme of the Wageningen University & Research by the joint sponsorship of Wageningen University, Teagasc (the Agriculture and Food Development Authority of Ireland) Walsh Fellowships Programme and Vita. During his PhD study, he worked on a thesis entitled “Agronomic and socioeconomic sustainability of farming systems: a case in Chencha, South Ethiopia” at the Centre for Crop Systems Analysis of Wageningen University & Research.

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Dersseh, W. Mazengia, Schulte, R., and Struik, P. 2015. Potato work on subsistence farms. Teagasc Research 10:4. www.teagasc.ie

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PE&RC Training and Education Statement

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

Review of literature (6 ECTS)

- Sustainable production and intensification in agriculture (2015)

Writing of project proposal (4.5 ECTS)

- Sustainability of farming systems: GHG emissions, climate change resilience, environmental and socio-economic sustainability

Post-graduate courses (3.2 ECTS)

- REDD+SCIENCE+GOVERNANCE: opportunities and challenges; REDD@WUR network (2012)
- Linear models; PE&RC (2012)
- Workshop on agriculture on the face of climate change; Bishoftu, Ethiopia (2012)

Laboratory training and working visits (4.5 ECTS)

- Practical training and exercise on FarmDesign model application: Teagasc, Johnstown Castle, Ireland (2012)

Deficiency, refresh, brush-up courses (6 ECTS)

- Quantitative analysis of cropping and grassland system; WUR PPS (2012)
- Analysis and design of organic farming system; WUR BFS (2012)

Competence strengthening / skills courses (1.5 ECTS)

- Advanced course guide to scientific artwork; WUR Library (2012)
- Adobe InDesign; WUR Library (2012)
- Information literacy PhD including EndNote; WUR Library (2015)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.5 ECTS)

- PE&RC Weekend first year (2012)
- PE&RC Weekend last year (2015)

Discussion groups / local seminars / other scientific meetings (6.3 ECTS)

- Chencha Potato Project workshop; WUR (2012)
- Annual research project review meeting of Southern Agricultural research Institute (SARI), Ethiopia (2013-2014)
- Monthly discussion among 3 PhD students and interdisciplinary team members of Chencha Potato Project (2013-2014)
- Three stakeholder workshops at Arbaminch & Chencha, Ethiopia (2013-2015)

International symposia, workshops and conferences (6 ECTS)

- 17th International Nitrogen Workshop; poster presentation; Wexford, Ireland (2012)
- African Potato Association 9th Triennial Conference; paper presentation; Great Rift Valley Lodge, Naivasha, Kenya (2013)
- Teagasc Food Security Seminar at the Royal Dublin Society; paper presentation (2015)

Propositions

1. The agricultural extension service in subsistence farming in Ethiopia is biased towards resource endowed households.
   (this thesis)

2. Land fragmentation in the highlands of Southern Ethiopia is an overlooked cause of reduced labour use efficiency and poor soil fertility management.
   (this thesis)

3. Weeds in crop fields are wanted plants in land scarce areas where mixed farming prevails.

4. Root pruning of eucalyptus reduces competition with adjacent field crops.

5. The ever increasing legal frame to protect the rights of individuals has changed human behaviour to that of a polar bear.

6. In developing countries, dictatorship and democracy are means to centralize and share corruption, respectively.

7. Supervision of PhD students is all about guiding them to pass through a jungle of confusion that leads to perfection.

Propositions belonging to the PhD thesis entitled: *“Agronomic and socioeconomic sustainability of farming systems: a case in Chencha, South Ethiopia”*

Waga Mazengia Dersseh

Wageningen, 17 October 2017