Sveriges lantbruksuniversitet
Swedish University of Agricultural Sciences

Department of Soil and Environment

Re-sourcing soil fertility

-Assessing the soil amendment potential of farm household resources and wastes in Bolo Silasie, Ethiopia

Jorunn Hellman

Master's Thesis in Soil Science
Agriculture Programme – Soil and Plant Sciences

Examensarbeten, Institutionen för mark och miljö, SLU   Uppsala 2020
2020:02

Re-sourcing soil fertility –
Assessing the soil amendment potential of farm household resources and wastes in Bolo Silasie, Ethiopia

Jorunn Hellman

Supervisor: Annika Nordin,Department of Energy and Technology, SLU
Assistant supervisor:Sigrun Dahlin, Department of Soil and Environment, SLU
Assistant supervisor: Linus Dagerskog, Stockholm Environment Institute & Stockholm Resilience Centre
Examiner: Johanna Wetterlind, Department of Soil and Environment, SLU

Credits: 30 ECTS
Level: Second cycle, A2E
Course title: Master thesis in Soil science, - Agrictulture Programme Soil/Plant
Course code: EX0881
Programme/Education: Agriculture programme – Soil and Plant Science (Agronomprogrammet – mark/växt 270 hp)
Course coordinating department: Soil and Environment

Place of publication: Uppsala
Year of publication: 2020
Cover picture: photo by author, 2019
Title of series: Examensarbeten Institutionen för mark och miljö, SLU
Number of part of series: 2020:02
Online publication: http://stud.epsilon.slu.se

Keywords: nutrient recovery, manure management, ecological sanitation, material flow analysis, East African agriculture

Sveriges lantbruksuniversitet
Swedish University of Agricultural Sciences

Faculty of Natural Resources and Agricultural Sciences
Department of Soil and Environment

Abstract

The global agriculture of today is to a high degree dependent on mineral fertilisers that through a constant accumulation of nitrogen (N) and phosphorus (P) in the biosphere contribute to greenhouse gas emissions and eutrophication of water bodies. At the same time, agricultural productivity around the world is largely constrained by low inputs of plant nutrients. Increased nutrient recovery from organic wastes and livestock and human excreta is needed to sustain soil fertility and ensure food security within the planetary boundaries. In this study, the resource management in Ethiopian farm households (hhs) has been studied to assess to what extent N, P and organic carbon (OC) could be recirculated to farmland from local farm household resources and wastes. The study included 15 farm hhs divided into three different socio-economic groups in the village of Bolo Silasie in central Ethiopia. The data collection was done through interviews, collection and weighing of waste fractions and lab analyses of total N, total P and OC for the most important farm resources and wastes. To understand the dynamics of nutrient accumulation and losses in the farm system, the data was analysed using material flow analysis (MFA). Additionally, 24 fields belonging to the study hhs were sampled and analysed to assess their current soil status in the village. It was found that although livestock are crucial components in the local farming system, only 19% of the manure is returned to the fields through compost application. Finding an alternative to the current use of manure as stove fuel was identified as the intervention with the highest potential for increased nutrient and organic matter recovery. Utilization of livestock urine and human excreta as well as improved management of compost could also make significant contributions to improved nutrient recovery. Depending on resource recovery ambition, local resources could supply up to 50 kg N and 12 kg P ha^{-1} y^{-1}. This should be compared to the current use of mineral fertilizers of 51 kg N and 26 kg P ha^{-1} y^{-1}. Today, however, many hh resources and wastes have an alternative use, and any intervention in the management system must be considered together with its social, practical and ecological implications. The three socio-economic groups were found to face different challenges and opportunities in nutrient recycling, mainly related to differences in access to livestock. This study hence suggests that research and advisory around local plant nutrient management should pay greater to socio-economic factors influencing hh resource and waste management.

Keywords: Nutrient recovery, manure management, ecological sanitation, ma-terial flow analysis, East African agriculture

Sammanfattning

Idag är det globala jordbruket i stor utsträckning beroende av mineralgödselmedel som genom en konstant ackumulation av kväve (N) och fosfor (P) i biosfären bidrar till växthusgasutsläpp och övergödning. Samtidigt är produktiviteten i jordbruket på många håll i världen begränsad av låg tillförsel av växtnäringsämnen. En ökad återförsel av växtnäringsämnen från organiskt avfall, gödsel och mänsklig avföring behövs för att upprätthålla bördiga jordar och säkerställa en tryggad livsmedelsförsörjning inom planetens ekologiska gränser. I den här studien har resurshantering i etiopiska jordbrukshushåll studerats for att undersöka i vilken utsträckning N, P och organiskt kol (OC) skulle kunna återföras till jordbruksmarken från lokala resurser och avfall. Studien har inkluderat 15 jordbrukshushåll från byn Bolo Silasie i centrala Etiopien som i delades in i tre socio-ekonomiska grupper. Datainsamlingen gjordes genom intervjuer, insamling och vägning av avfall och labbanalyser av total-N, total-P och OC i de viktigaste resurs- och avfallsfraktionerna. För att förstå dynamiken kring ackumulering och förluster av näring i hushållssystemet analyserades datan med materialflödesanalys (MFA). Tjugofyra fält tillhörande studiehushållen provtogs and analyserades för att undersöka den nuvarande marknäringsstatusen. I studien framkom att fastän djurhållning är en viktig komponent i det lokala jordbrukssystemet så återförs bara 19% av allt gödsel och inget alls av djururinen till fälten i form av medvetet spridd gödsel. Att hitta alternativ till den nuvarande användningen av gödsel som bränsle i matlagning identifierades som den förändring som har högst potential att öka återförseln av näring till åkermarken. Utnyttjande av djururin, humanurin och humanfekalier, liksom en förbättrad komposthantering skulle också innebära betydande bidrag till en ökad näringsåterförsel. Beroende på ambition kan lokala resurser bidra med upp till 50 kg N och 12 kg P ha^{-1} år^{-1} Det kan jämföras med de 51 kg N och 26 kg P ha^{-1} år^{-1} som idag tillförs via mineralgödselmedel. Idag har dock många av hushållens resurser och avfall en alternativ användning. Vid förändringar i resursanvändning bör man därför ta hänsyn till vilka sociala, praktiska och miljömässiga implikationer dessa skulle få. Det konstaterades att de tre socioekonomiska grupperna står inför olika utmaningar och möjligheter relaterade till näringsåterförsel, främst på grund av skillnader i tillgång till boskap. En slutsats av arbetet är därför att forskning och rådgivning kring lokal växtnäringsförsörjning bör ägna större uppmärksamhet åt socioekonomiska faktorer som påverkar jordbrukshushållens resurs- och avfallshantering.

Nyckelord: Näringsåterförsel, gödselhantering, ekologisk sanitet, material-flödesanalys, Östafrikanskt jordbruk

Populärvetenskaplig sammanfattning

Föreställ dig ett vetefält. För att det växa bra och ge god skörd behöver vetet näring, varpå bonden som äger fältet kommer gödsla det med djurgödsel eller mineralgödsel. När vetet är moget skördar bonden sitt fält, och mycket av den näring som lagts på åkern följer med vetet bort från fältet. Denna näring kommer dock sällan tillbaka, utan tar vägen förbi människor och djur och hamnar så småningom i avloppsystem och i naturen och bidrar så till både växthusgasutsläpp och övergödning. När bonden nästa år på nytt ska så sitt vete behöver hon eller han åter gödsla sitt fält med näring. För varje år hamnar alltså mer och mer näring där vi inte vill ha den, medan åkrarna varje år måste fyllas på med näring från annat håll.

Med en växande världsbefolkning ökar den globala efterfrågan på livsmedel. Idag produceras majoriteten av all mat delvis eller helt med hjälp av mineralgödsel som bryts i gruvor eller fixeras från luften i energikrävande processer som drivs med fossila bränslen. Regioner som använder mindre mineralgödsel, såsom subsahariska Afrika, har på många istället låga skördar vilket lokalt skapar brist på tillgängliga och näringsrika livsmedel. En viktig framtidsfråga är därför hur vi kan hitta bra sätt att återföra den näring som vi en gång hämtat från jorden genom maten, tillbaka till jordbruksmark där den åter kan göra nytta.

Etiopien är ett land med snabbt växande befolkning varav 85% lever av jordbruk. Många av Etiopiens jordar har i grunden låga nivåer av växtnäringsämnen och organiskt kol. Dessutom saknar många bönder tillgång till tillräckliga mängder djurgödsel och mineralgödsel vilket gör att skördarna på många håll är låga. Den här studien har undersökt vilka möjligheter småbönder i den etiopiska byn Bolo Silasie har att återcirkulera organiskt kol och växtnäringsämnena kväve och fosfor till sina jordbruksmarker från resurser och avfall de redan har tillgång till på sina egna gårdar. Näring och organiskt kol finns bland annat i djurgödsel, djururin, aska, matrester och mänsklig avföring.

En av de stora utmaningarna i att återföra näring i är att många av resurserna och avfallen redan har en funktion inom de etiopiska lantbrukshushållen. Djurgödsel, som på många håll i världen är en viktig växtnäringskälla, används i Bolo Silasie till exempel som bränsle vid matlagning. De resurser som blir kvar räcker inte för att ersätta den näring som idag tillförs via mineralgödsel, särskilt svårt skulle det vara att ersätta fosforn. Oavsett skulle *en del* av mineralgödseln kunna ersättas, vilket både skulle bidra till ökad oberoende av icke-lokala resurser och gå ett steg längre mot slutna näringskretslopp. Avfallen från hushållen skulle också kunna bidra med organiskt kol, något som jordarna kring Bolo Silasie är i stort behov av. I en framtid finns en chans att användandet av djurgödsel, djururin och mänsklig avföring som gödselmedel kommer att öka på grund av ökat tryck på världens näringsresurser.

Preface

This Master's thesis in Soil Science has been written as a part of the Agronomist program in Soil and Plant Sciences at the Swedish University of Agricultural Sciences. The report is based on research conducted in the Ethiopian village of Bolo Silasie, Minjar Shenkora woreda, from January to April 2019.

The study is a part of the Triple Green project in Ethiopia, which since 2012 has been working in Bolo Silasie with research and training in conservation tillage, rainwater harvesting and productive sanitation. The Triple Green project is a collaboration between Stockholm Resilience Centre (SRC), Stockholm Environment Institute (SEI) and Addis Ababa Institute of Technology (AAiT).

The field studies in Ethiopia were financed by the Triple Green project together with a scholarship from the Linneaus-Palme International Exchange Program through SLU and AAiT. A stipend for the study was also granted by Ellen and Tage Westins foundation for agricultural research.

Acknowledgements

It is with a deep and humble sense of gratitude I finish the last chapter of this work, surrounded by the verdure of early Swedish summer, a whole world apart from the dry and dusty winter days in Bolo Silasie where this journey once commenced. And I realize: this is the kind of moment when you could cite someone smart. So, I will.

Some people care too much, I think it's called love.

- Winnie the Pooh.

My greatest thanks,

To Zerihun Getaneh, Bikila Teklu, Laike Kebede, Melesse Temesgen, Erik Karltun, Tegbaru Bellete, Girma Gebresenbet, Fekede Terefe, Yeneneh Gesuneh, Demuz Bizan and Cecilia Lalander, for leading my way and so generously sharing your time and knowledge.

To Gedion Shone, Shiferaw Asnake, Alene Admas, Yenebeb Hailegiorgis, Alem Girma, Teshome Buta, Tsehay Yilma and Eskender Mulugeta for support and friendship that made a journey that could have been a quite lonely one, not really feel that way.

To Mitike Girma, Asnaku Abebe, Jonathan Sigvant and Malin Eriksson for taking care of me like the closest of family and dearest of friends.

To the fifteen families in Bolo Silasie that I have had the great pleasure to work with. Without your participation nothing of this work would have existed.

To my co-supervisor Sigrun Dahlin, for being the clear and grounded character and firm and knowledgeable expert I miss in myself.

To Linus Dagerskog, for inviting me into this world. For being always listening, attentive and encouraging. For being someone with who I can share not-so-common experiences like doing research in the haze of homebrewed *tella*.

To Annika Nordin, for being all the way through the most caring and intelligent supervisor I could ever think of.

And to David,
For being always so loving in your patience, and so patient in your love.

እግዚአብሔር ሁላችሁንም ይባርክ,
May God bless you all,
Jorunn
Uppsala, June 2019

Table of contents

Abbreviations

AAiT	Addis Ababa Institute of Technology
CEC	Cation Exchange Capacity
DA	Development Agent
DW	Dry weight
EC	Electrical Conductivity
EcoSan	Ecological Sanitation
ETB	Ethiopian Birr (national currency)
FS	Fixed Solids
GDP	Gross Domestic Product
GHG	Greenhouse Gas
hh(s)	household(s)
ICS	Improved Cooking Stoves
HI	Harvest Index
MFA	Material Flow Analysis
OC	Organic carbon
OM	Organic Matter
SDGs	Sustainable Development Goals
SEI	Stockholm Environment Institute
SOC	Soil Organic Carbon
SRC	Stockholm Resilience Centre
SOM	Soil Organic Matter
SSA	Sub-Saharan Africa
STAN	subSTance flow ANalysis
TOC	Total Organic Carbon
TLU	Tropical Livestock Unit
TS	Total Solids
UDDT	Urine-Diverting Dry Toilets
VS	Volatile Solids

Wordlist

When lacking established translations, Ethiopian words for units of measurement, foods and administrative units have been used in this work. A short wordlist is found below.

Areke	Distilled spirit consumed at all kinds of celebrations and events, typically made at the homestead out of corn, wheat or barley.
Atella	By-product from *areke* and *tella* production given to livestock as supplementary feed.
Berbere	Spice mix of chili pepper, garlic, ginger and numerous local spices and herbs.
Ebet	Fresh cattle manure used for construction and maintenance of buildings and for threshing pans in the fields.
Fino	Cereal bran purchased as animal feed
Fagullo	Oilseed cake, industrial by-product used as animal feed.
Gesho	*Rhamnus prinoides*. An herbal species used for *tella* production. Gives taste and has preservative properties, resembling the function of hops in beer.
Injera	Spongy sourdough flat-bread served to nearly all Ethiopian meals. Made primarily of teff, sometimes adding wheat or sorghum.
Fug	A mixture of straw and manure from donkey, sheep and goat used as stove fuel
Kebele	The smallest administrative unit in Ethiopia comprised by a few thousands of people
Kubaya	One “cup”. Measuring unit somewhat larger than the British cup (4,5 dl).
Kubet	Sundried cow dung “cakes” used as stove fuel
Teff	*Eragrostis tef*. Grain species native to the Horn of Africa and Ethiopia’s most important staple food.
Tella	Traditional homebrewed “beer”, in Bolo Silasie made of roasted corn paste, yeast and *gesho*.
Timad	The main unit for measuring agricultural land. Equals ¼ ha.
Woreda	Administrative unit comprising of several *kebeles*. Fairly comparable to a municipality.
Quintal	The main unit for measuring yields in Ethiopia, here pronounced *kuntal*. Equals 100 kg but is also often referred to as the volume of any product that can fit into a 100 kg cereal bag.

1 Introduction

A growing world population and global shifts in food preferences are putting pressure on agricultural productivity. Meanwhile, soils around the world are being depleted in organic matter (OM) and plant nutrients due to poor soil management and agricultural expansion of marginal land (Bridges & Oldeman 1999). Mineral fertilisers play an important role for the global food production. The constant fixation of atmospheric nitrogen (N) and outtake of phosphorus (P) from non-renewable mineral sources however lead to a continual accumulation of nutrients in the biosphere resulting broken geochemical cycles, eutrophication and greenhouse gas emissions (Steffen et al. 2015). The recirculation of plant nutrients exported from farmland through harvested biomass is small due to separation of production and consumption of food, poor manure management and almost none-existing nutrient recovery from human excreta (Bateman et al. 2011; Mihelcic et al. 2011). To sustain soil fertility and ensure food security within the planetary boundaries we need an increased understanding of how plant nutrients can be recirculated back to agricultural land.

Ethiopia is an ecologically diverse, landlocked country in Eastern Africa hosting 110 million people of which 85% base their livelihoods on mainly agricultural activities. Ethiopia face serious soil fertility challenges such as topsoil erosion, severe depletion of soil organic matter (SOM) and low nutrient stocks (IFPRI 2010). Due to low inputs of both mineral and organic fertilisers there are continuous yearly negative nutrient balances on agricultural land and a steady loss of soil fertility (Haileselassie et al. 2005).

There are several studies assessing soil fertility management opportunities in Sub-Saharan Africa, including improved manure management (Castellanos-Navarrete 2015; Lekasi et al. 2001; Rufino et al. 2006) and nutrient recovery from human excreta (Andersson 2015; Dickin et al. 2018; Meinzinger et al. 2009). Few studies however look into smallholder households' resource management system and systematically assess the potential of nutrient recovery from manure, human excreta and other resources and wastes available at the farm level. This study aims to do so, through empirical data collection and using the methodology of Material Flow Analysis (MFA) as a tool to visualise and assess how nutrients and OC flows, accumulate and are lost from the system.

2 Aim and research questions

2.1 Aim

This study assesses the flows of nitrogen (N), phosphorus (P) and organic carbon (OC) associated with resource use in rural Ethiopian households, with the aim to identify possible interventions for increased nutrient recycling to agricultural land.

2.2 Research questions

- Which are the main resource and waste flows containing plant nutrients and OC in Bolo Silasie households?
- What interventions in the current resource management system would be most impactful in their potential N, P and OC recovery?
- To what extent could N, P and OC recovered from resources and wastes contribute to local soil fertility?
- Is there a relationship between household's socio-economic status and their potential and constraints for resource recovery?

3 Background

3.1 Global challenges in soil fertility

The concept of *fertile land* has an almost poetic connotation: generating green, thriving, high-yielding crops and human prosperity. What builds up soil fertility is however a complex set of, arguably less poetic parameters including parent material, soil texture, nutrient stocks, soil depth, absence of toxic and adverse substances and organisms, a rich soil biofauna, soil organic matter (SOM), water and air permeability and a relatively neutral pH (Patzel et al. 2000).

This study focuses on *chemical soil fertility*. Thus, only chemical aspects of soil such as pH, SOM, cation exchange capacity (CEC) and plant nutrients (Hartemink 2007) are considered. Chemical soil fertility is said to be declining on a global scale due to intensified production, decreased inputs of organic soil amendments and enlarged use of marginal land (Ibid.). Nutrient depletion and loss of SOM undermine agricultural productivity which threatens both livelihoods and global food security. Thus, it is highly critical to increase the understanding of soil resources and their proper management.

3.1.1 Aspects of chemical soil fertility

Nitrogen (N) and phosphorus (P) are known as macronutrients, which refers to the fact that they are required in a substantially larger amount than micronutrients. N and P are the most common chemical elements in mineral fertilisers, but there are also four more macro nutrients (K, Ca, Mg and S) and at least nine micro nutrients (Fe, Mn, B, Mo, Cu, Mg, Zn, Cl and Ni), all essential for a plant's growth and reproduction (White & Brown 2010).

Plant roots take up N mainly in the form of ammonia (NH_4^+) and nitrate (NO_3^-). In the soil N is principally bound to organic compounds that to a certain degree is mineralised every season. The SOM content is thus an indicator of soil N stocks, which determine nitrogen availability over time (Bot & Benites 2005). Mineral forms of nitrogen are highly mobile in the soil and can easily be lost through volatilization, denitrification and leaching (Serrasolses et al. 1999). Phosphorus dynamics perform very differently. Although a soil may contain high levels of P, the larger share is normally present in forms unavailable for plant uptake. Moreover, P that is applied to a field can be immobilised due to processes of adsorption to clay minerals, precipitation or transformation to organic forms of phosphorus (Schachtman et al. 1998). The P fixating properties of soils largely depend on soil type and pH (Shen et al. 2011). Since P is largely bound to soil particles, the element is easily lost in erosion processes (Fraser 1999). Plants take up P in the form of $H_2PO_4^-$ and HPO_4^{2-} (Schachtman et al. 1998).

Soil organic matter (SOM) can be seen as a reflection of a general soil fertility. Up to a certain level, a high SOM indicates high microbiological activity, resistance to erosion and higher infiltration capacity (Horneck et al. 2011). SOM levels in soils can be increased by incorporation of crop residues, application of manure and perennial lays. Carbon stocks in the agricultural soil are decomposing by oxidization processes which are augmented by excessive soil tillage (Bot & Benites 2005).

Many chemical processes in the soil are determined by pH, why this is a key parameter for understanding soil fertility dynamics. Productive soils around the world range from pH 4.5 to 8.5, but optimal conditions for most plants are slightly acidic (pH 6-7) since the availability of plant nutrients is as highest at these conditions (Duncan 2012).

3.1.2 Broken nutrient cycles

Fertilizing a soil normally refers to adding plant nutrients to the soil, either from mineral or organic sources. Historically, the main source of plant nutrients in agriculture has been animal manure, crop residues or ashes from slash-and burn agriculture (McGrath et al. 2014; Pedroso Junior et al. 2009). The traditional agriculture has thus been based on the principle of recirculating nutrients taken out from the system back to the fields.

Since their appearance in the early 20th century, mineral fertilisers have become an increasingly common source of nutrients in the global agriculture. Mineral fertilizers have many benefits: They are easy to handle and spread with precision, they do not smell, and they contain nutrient forms that are directly available to the plants. Today, many farms are specialized in either livestock or crop production systems, resulting in a physical and structural separation of the production of manure and the consumption off fertilizers. Much of the rationale of recycling manure from the own farm has so been lost, and the transport of manure between farms might be both expensive and labour-intensive (Bateman et al. 2011). There is a large discrepancy in mineral fertiliser use over the world. Even though the annual growth in mineral fertiliser demand in SSA is the highest in the world, 4.7% yearly compared to the global average of 1.8% (FAO 2009), Africa accounted for no more than 3% of the global use of mineral fertilisers in 2013 (FAO 2015).

Mineral fertilisers have together with improved plant varieties, mechanisation and structural rationalisation of agricultural production been acknowledged as the groundwork for the huge increases in global agricultural productivity the last half century (Tilman et al. 2011). From a sustainability perspective, however, mineral fertilisers undoubtedly also have many potential drawbacks both at the local and the global scale. Atmospheric N fixation related to production of N-fertilisers is a highly energy-consuming process. Phosphorus in mineral fertilisers derive mainly from mining of phosphate rock. Except for being mined in geopolitically controversial areas it is just as fossil fuels a finite resource (Sutton el al. 2013). With the outtake rate of today, the estimated global phosphorus reserves will only last another 50 to100 years (Cohen et al. 2011). The accumulation of N and P in the biosphere driven by agricultural demand has exaggerated greenhouse gas emission and eutrophication processes. In comparison with manure, mineral fertilisers contain no organic carbon and the most common contain only N, P and perhaps K (Bindraban et al. 2015). Application strategies based only on NPK fertiliser leads in the long run to depletion of OC, other nutrient deficiencies and restrictions in crop productivity (Ibid.).

Today, it is estimated that half of the world's population are fed by agricultural based on mineral fertilisers. Increasing and volatile prices of mineral fertilisers might therefor threaten food security both locally and globally (Elser et al. 2014). On the other hand, increased prices might also become an eye-opener for the need for nutrient recirculation and closed biochemical cycles.

3.2 Options for nutrient recovery in SSA

Cereal yields in SSA have been increasing over the last decades but are still the lowest in the world, averaging 1.2 t ha^{-1} compared to the developing world mean yields of 3 t ha^{-1} (FAO 2009). SSA is also the region in the world with the lowest applications of mineral fertilisers, only 16 kg ha^{-1} (World Bank Data 2016). Among farmers in SSA that do not access fertilisers, the inputs of organic amendments are also reported to be low due to low access to livestock, lack of traditions of organic soil amendments and alternative uses of manure, among others (Hartemink 2007). Even though the consumption of mineral fertilisers increases, volatile prices threatens the accessibility. Many African soils are highly weathered and depleted in SOM and plant nutrients (Buresh et al. 1997; Giller et al. 1997) why nutrient recovery from already available sources could play an important role to improve and secure livelihoods both today and for the future. This section presents three possible pathways for increased nutrient recovery in SSA, related to livestock manure, human excreta and household wastes.

3.2.1 Improved management of livestock manure

In SSA, 70-80% of the farms are smallholder farms farming less than two hectares of land (Lowder et al. 2016). Smallholder farm in SSA are normally based on crop-livestock integrated production systems but do not necessarily take advantage of the nutrient recycling potentials of such systems (McIntire et al. 1992). Livestock can act as an important importer of nutrients to the farm, both from foraging at off-farm sites and through purchased feed (Lekasi et al. 2001). Yet, using manure as soil amendment is not a widespread practice in all localities, and manure management is often inadequate to maintain good quality (McIntire 1992). Nitrogen balances in Eastern Africa are estimated to range from –39 kg N and +29 kg N per Tropical Livestock Unit (TLU) (Snijders et al. 2009), implying that livestock may have a negative impact on farm nutrient balances if manure is handled poorly.

Increasing the quantities of nutrients from livestock manure to farmland can, somewhat simplified, be done in three ways: 1) By increasing the manure production (easiest done by increasing numbers of livestock), 2) by increasing the portion of available manure that is actually added to the fields, and 3) by improving the quality of manure by reducing nutrient losses in storage and application.

Increasing the numbers of livestock in SSA localities is often restricted by high population and livestock density. There is simply no room for growing more feed, and often also limited financial resources to purchase feed (McIntire et al. 1992).

Non-use of manure as a fertiliser can be related to alternative uses of the livestock excreta, such as biomass for combustion (Mekonnen & Köhlin 2008), lack of means for manure transport (McIntire et al.1992) or connected to cultural beliefs. For instance, when studying the manure management in the southern Ethiopian lowlands, Jagisso et al. (2019) concluded that 74 tons of manure containing 667 kg N had been accumulated over the years due to local believes that manure application in farmland would lead to misfortune. Livestock urine is an often-neglected resource which can be both because of low perceived value in animal urine or lack of knowledge on how to collect and manage the resource (Lekasi et al. 2003). Other constraints for using manure and urine as soil amendments mentioned in the literature include lack of financial resources to invest in appropriate equipment, poor institutional support, illiteracy and relatively low prices of mineral fertilisers which make them a more attractive alternative (Gbenou et al. 2017; Jagisso et al. 2019; McIntire et al. 1992).

Nitrogen, P and OC concentrations in manure are largely variable and depend on factors such as animal feed, housing type and manure management before field application (Lekasi et al. 2003). Manure might be applied without any preceding decomposition or added after being composted for a longer or shorter period of time (McIntire 1992). Composting of animal manure improves its quality in various ways: it reduces seeds of weeds, pathogenic organism and odour, decreases the mass which facilitates field application and reduces the C:N ratio which make N more available to the plants (Hao & Benke 2008). Nevertheless, manure composting also produces N losses both through gaseous emissions and leaching, the former accounting for the larger part of N losses in semi-arid areas (Ibid.). Nutrient losses from manure composting largely depend on management, hence it puts demand on farmers knowledge, skills, time and interests to invest in manure quality.

3.2.2 Nutrient recovery from human excreta

Worldwide, 2.3 billion people are estimated to have unsatisfactory sanitation of which 890 million practice open defecation (WHO/UNICEF, 2017). Unsatisfactory sanitation and hygiene have huge societal costs, not least in the negative impacts on human health (Prüss-Ustün et al. 2014). Poor sanitation also contributes to environmental pollution, such as eutrophication of water bodies and emission of greenhouse gases (GHGs) to the atmosphere. Although sanitation is a globally prioritised target and part of the Sustainable Development Goal (SDG) 6, most sanitation initiatives fail to address the potential in resource recovery from human excreta. It is estimated globally that urine and faeces contain the equivalent of 22% of the phosphorous annually applied with chemical fertilizers (Mihelcic et al. 2011). However, today only an estimated 10% is recycled back to arable land (Cordell et al. 2009), as most is lost in pits or flushed into waterbodies. In contrast to the linear nutrient flows often resulting from conventional sanitation systems, *ecological sanitation*, commonly abbreviated simply EcoSan, sees human waste as a resource that, with proper management, can be safely recycled to serve a productive purpose (Winblad & Simpson-Hebert ed. 2004).

Much reuse-related research has been focusing on urine. Urine has high concentrations of N and P, low concentrations of pathogens and heavy metals and is thus to a high degree suitable as agricultural fertilizer. In fresh urine nitrogen is mainly found in the form of urea which is rapidly converted into ammonium/ammonia (NH_3/NH_4^+) when the urine is stored or transported (Winblad & Simpson-Hebert ed. 2004). NH_4^+

is available for plant uptake but is also easily lost through volatilization. Research has shown that ammonia losses can be low if urine is applied in furrows and covered with soil (Rodhe et al. 2004).

In human faeces around 50% of the nitrogen is directly available for plants, while the other 50% are bound to organic compounds (Jönsson et al. 2004), which means that faeces will support the plants with N both directly and long-term by building up the long-term nutrient stocks in the soil. Handling of faeces however requires precaution. To avoid pathogens, faeces should be stored at least for two years if not treating them chemically or thermally. In comparison, urine can be safely applied already after one month of storage (Ibid).

3.2.3 Utilization of farm household wastes

2.2.3.1 Greywater

Greywater is the common name for wastewater from laundry, shower and kitchen, thus all household wastewater except the toilet waste, the blackwater. The health risks with greywater are considered small, while its value as soil amendment is also rather modest due to low concentration of plant nutrients (Almqvist et al 2007). The chemical composition of greywater varies largely over the world and depends on water availability and what the water is used for. While water usage in poor countries can be as low as 20-40 l per person and day, industrialized countries normally use hundreds of litres per person (Our World in Data 2018). The sources of N and P and in greywater are food residues from kitchen water and “dirt” from laundry and shower water, and the concentrations are normally low (Ibid.).

2.2.3.2. Ashes

Ashes are the solid remains from combustion. They are of mainly mineral content but may include some organic, not fully combusted carbon compounds. Ashes are generated as a waste product both on a societal and hh level, deriving from wood industries and from households using biomass as source of energy for food preparation and heating. Wood ashes are alkaline, with a pH ranging from 9.0 to 13.5 (Demeyer et al. 2001). Since they are highly soluble, ashes can neutralize acid soils faster than the more traditionally used lime, but the effect is less persistent (Demeyer et al. 2001; Erich 1991). Ashes have been suggested to be suitable fertilizers mainly on forest soils and acidified tropical soils (Demeyer et al. 2001; Qin et al. 2017). There are however very few studies assessing the effect of ashes in already alkaline soils, and possible adverse effects such an application would implicate.

Ashes are nearly free from N and S and their agronomic potential is rather in their content of P and other nutrients that are not lost in combustion. Depending on the source, the phosphorus content in ashes is in the range of 1800 – 14 000 mg/kg (Demeyer et al. 2001). Ashes increase the electric conductivity (EC) of the soil and may contribute to soil salinization if applied in large quantities (Ibid.).

2.2.3.3. Organic household wastes

Organic household wastes may include slaughter remnants, cooking residues and food leftovers. Studies of nutrient recovery from household wastes normally focus on collection from urban areas, where larger waste masses are accumulated in a limited physical space. One such study on urban household waste being used as soil amendment in Cameroon show a high potential in replacing mineral fertilisers in agriculture around the capital Yaoundé (Jaza Folefack 2009). A well-establish system of peri-urban farmers collecting and trading urban wastes for soil amendment purposes has been documented in Kano, Nigeria, where the collection was motivated by the perceived long-term soil fertility benefits that the organic wastes brought to the fields (Lewcock 1995).

3.3 The context of Ethiopia

Ethiopia is a landlocked country in East Africa, neighbouring Somalia, Djibouti, Eritrea, Kenya, Sudan and South-Sudan. With its nearly 110 million inhabitants it is Africa’s second most populous country and keeps growing at a yearly rate of 2.4% (World population review 2019). Ethiopia is a highly diverse country hosting over 80 ethnic groups and languages. The natural geography is not less multifaceted, with a topography ranging from 150 m b s l to 4600 m a s l, accommodating at least three major climatic zones (Ethiopian Government Portal 2018). In 2000, Ethiopia was considered the second poorest country in the world. An astonishing yearly economic growth rate of 8% is however rapidly transforming the country, which has an outspoken ambition to become a middle-income country by 2025 (Moller 2015). Agriculture is by far the most important economic activity in Ethiopia, employing an estimated 85% of the population and accounting for over 40% of the gross domestic product (GDP) and more than 80% of the total exports (Infomineo 2016).

3.3.1 Agricultural landscape and current challenges

The Ethiopian agricultural sector is dominated by smallholders of which a majority farm less than one hectare of land. Despite being mainly oriented towards subsistence and small sales, smallholder farmers contribute to 95% of the agricultural GDP (FAO 2019). Integrated crop and livestock production is an increasingly common farm model, while pastoralism and farms having crop production without complementary animal husbandry are also widespread (Baye 2017; Haileselassie et al. 2005). Because of Ethiopia's many climate types, agricultural production systems range from lowland sesame, rice and cotton production to highland production of coffee, cereals, fruits, and the locally important crops chat and enset (Armede et al. 2017). The major soil types in Ethiopia are Andosols, Luvisols, Vertisols and Cambisols (Encyclopædia Britannica 2019).

Agricultural policies are strongly orientated towards agricultural productivity and growth, which is supposed to lead to complete national self-sufficiency, increased exports, poverty alleviation and general economic growth (Järnberg 2016). At the same time, land sizes per person are decreasing due to rapid population growth (World Bank Group) which puts pressure on the productivity of agricultural land. Mineral fertilises are vigorously being promoted by the government (Järnberg 2016), and their use have more than doubled since the beginning of the century (Moller 2015). The country has also enjoyed a considerable increase of total productivity the last years, related both to expansion of agricultural land and to an increase in average yields, not least in the five main cereal crops; wheat, teff, maize, barley and sorghum (Ibid.) Irrigation practices are not widespread in Ethiopia, which implies that crop production in many parts of the country is restricted to the relatively short rainy season (Ibid).

Ethiopia face several challenges in soil fertility. Acidification constraints yields in 40% of the soils, there are severe depletions of both macro- and micronutrients and it is also one of the most erosion-affected countries in world (IFPRI 2010). At a national level the nutrient depletion has been calculated to 122 kg N ha^{-1} y^{-1}, 83 kg K^{-1} ha^{-1} and 13 kg P ha y^{-1} per year (Haileslassie et al. 2005), erosion being estimated as the major cause of nutrient depletion. Diammonium phosphate (DAP) and urea have until recently been the only two mineral fertilisers used in Ethiopia (Haileselassie et al. 2005; Hailu et al. 2015). An ongoing work on mapping all Ethiopian soils (Ethiopian Agricultural Transformation Agency 2019) has led to new recommendations and to replacement of DAP in favour of microelement enriched nitrogen-phosphorus-sulphur (NPS) fertilizers, distributed according to specific deficiencies at every locality.

3.4 Material Flow Analysis (MFA)

3.4.1 Methodology and applications

Material flow analysis (MFA) is a tool originating from the field of industrial ecology, used to study and model how goods and substances flow within a given system (Brunner & Rechberger 2004).

In MFA, *substances* are defined as chemical compounds such as N, P, Cd or Pb. *Goods* are defined as elements containing one or several substances, like wastes, foods or water. While goods might transform in the processes, such as food converting to excreta through human metabolism, substances are normally seen as "conservative", or inalterable, through the whole system. *Materials* are used as a common name for both substances and goods. Studying a *system* requires a definition of its boundaries, which for MFA systems are both spatial and temporal. Flows are presented in masses per time unit. When entering the system, materials are called *imports*, while named *exports* when leaving the system. Within the system, there are system compartments called *processes*. Between the processes there can be *transports* of flows, called *inputs* and *ouputs* when entering or leaving a process. In the processes there is possible transformation of material and stock change due to depletion or accumulation of material. According to the principle of mass balance, the change of stock for the system will equal all imports minus all exports (Eq. 1) (Brunner & Rechberger 2004).

$$\Delta stock = \sum m(imports) - \sum m(exports) \qquad \textit{(Eq. 1)}$$

3.4.2 Previous MFA studies on SSA agricultural systems

There are various examples of MFA being used for describing, studying and modelling nutrient flows in SSA localities. MFA studies tend to focus on production, consumption and waste disposal in urban rather than rural areas, such as Belevi (2002) studying the city of Kumasi in Ghana and Hoekman & von Blottniz (2007) mapping material flows in Cape Town, South Africa. Some more recent studies include the assessment of rural areas, like a study by Lederer et al. (2014) of potential nutrient recovery from human excreta in Busia district in Uganda. The spatial scale of MFA studies is normally rather large, entailing cities, districts or countries (Fernandez-Mena et al. 2016). There are relatively few studies that map nutrient recovery potentials from resources and wastes at the farm or household level. One such exception is Krause & Rotter's (2017) MFA study on the effects of urine diverting dry-toilets and improved cooking stoves in Tanzanian smallholder households.

4 Materials and Methods

4.1 Determination of site and households for the study

This study has been conducted in the village of Bolo Silasie in Minjar Shenkora woreda in central Ethiopia from February to April 2019. Bolo Silasie has since 2012 been one of the research sites for the Triple Green project in Ethiopia, a project which this study forms a part of.

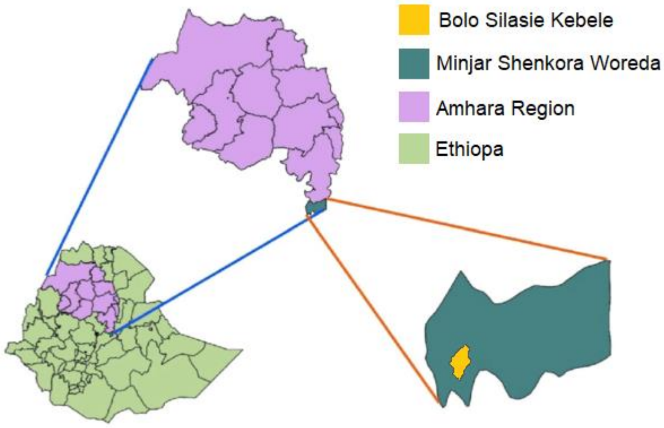


Figure 1. Map of the study area. Modified from Mebrahtu et al. 2018 (CC BY 4.0)

Minjar Shenkora woreda is situated in the southernmost corner of the Amharic region (8.874; 39.395) *(Fig.1)*. Located at around 1800 m a s l, the woreda belongs to the lower parts of *Woina Dega*, the Ethiopian subtropical zone (Amhara Livelihood Zone Reports 2007). The mean annual precipitation in the region is 850 mm, with most of the precipitation concentrated to the rainy season in June to September (climate-data.org n.d.). Minjar Shenkora is dominated by Vertisols (Abera & Kebede 2013). Soil surveys from Minjar Shenkora woreda show low levels of available phosphorus and low to medium levels of SOM (*Fig. 2*) (Ethiopian Agricultural Transformation Agency 2016).

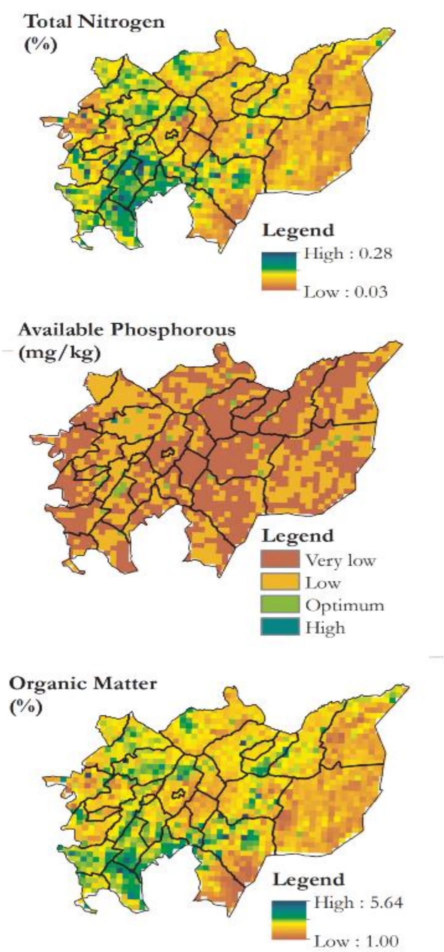


Figure 2. Soil status of TN, available P and SOM in Minjar Shenkora woreda *(Ethiopian Agricultural Transformation Agency 2016)*

Most people in Bolo Silasie base their livelihoods on rainfed agriculture. Farmers typically have both crop and animal production and depend on both for subsistence and income. Cattle are kept not least for ploughing, but also for meat and dairy products. Sheep, goat and poultry are kept for meat, skins and eggs, and donkeys, camels and horses are kept for transportation of people and goods (Amhara Livelihood Zone Reports 2007). Bolo Silasie has 5753 inhabitants, whereof 48% are women (Bolo Silasie Kebele Statistics).

Households from three different socio-economic groups were included in this study. Sizes of farmland and number of Tropical Livestock Units (TLU) owned by the hhs were chosen as indicators for hh socio-economic status, based on the Amharic Region Livelihood Report (2007) and Chaix-Bar (2014) *(Table 1).* Five hhs from every group (in total 15 hhs) were identified with the help of the *Kebele* administration and the local Triple Green interpreter and contact person.

Table 1. Socio-economic division of Bolo Silasie households based on sizes of farmland and number of TLU

	Amhara Livelihood Zone Reports (2007)			**Chaix-Bar (2014)**		**This study**		
	TLU	TLU in oxen	Farmland (ha)	TLU in oxen	Farmland (ha)	TLU	TLU in oxen	Farmland (ha)
Worse-off	0-1.75	0-1	0.5-0.75	0-2	0.5-2.0	0.7-2.6	0-1	0.25-0.63
Middle	1.25-6.75	1	0.75-1.0	1-3	1.9-8.8	2.9-4.1	2-3	0.5-1.9
Better-off	4.9-8.6	2-4	1.5-2.5	3-5	2.7-7.1	4.8-9.2	3-5	2.0-4.5

The Amhara Livelihood Zone Reports uses a division based on statistics of farmland sizes and TLU ownership for all hhs in Minjar Shenkora. Chaix-Bar (2014) and this study present average number of farmland and TLU/oxen among the farmers included in respective study of conditions in Bolo Silasie.

4.2 Household interviews

Interviews were carried out with the 15 study hhs as means to determine the important resource and waste fractions and estimating their sizes as well as understanding the local farming practices and the potentials and constraints for nutrient recovery. There were three main methodological interview approaches. The interviews included:

1) A systems-focus approach, where the households described their own farm system by creating *resource flow maps*. The maps were done on large white paper using painted images of crops, livestock etc. *(Fig 3)*. The methodology was inspired by Dagerskog (2018) and Defoer et al. (2000).

2) A structured interview approach where quantitative data was collected following pre-made questionnaires. Questions were asked on i) hh assets, such as livestock, farmland and yields ii) hh consumption of human foods, livestock feed iii) soil management practices.

3) A semi-structured interview approach, where discussions were held on hhs perceptions of i) soil fertility of their own fields and ii) risks and values with waste and excreta.

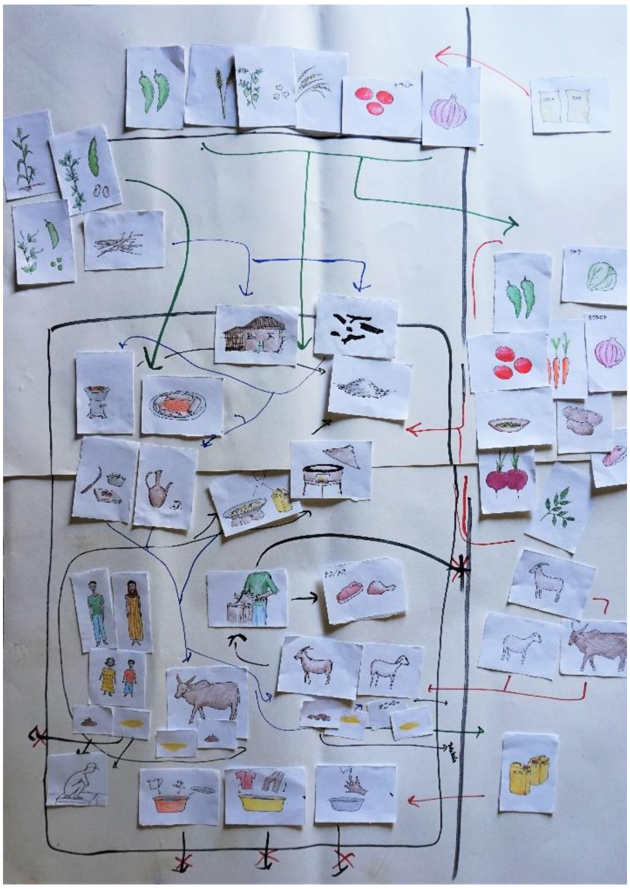


Figure 3. Example of a *resource flow map* created during the hh interviews, showing resources flowing from farmlands (top of the paper) to the household (central square) and to the market/commons (to the right)

A manual with questionnaires, checklists and tools for the interviews was prepared and tried out together with a pilot household. After the pilot survey the form was slightly adjusted. The final version of the manual is found in *Appendix 1*. In both the manual and in the interviews, the three methodological approaches were mixed during the sessions and interviews order rather followed themes, such as “household waste management” or “livestock system”. The 15 households were interviewed twice, 30-90 min per session, with the help of an interpreter. A consent form *(Appendix 2)* for participation in the study was handed out and signed.

The interview manual *(Appendix 1)* included, other than the abovementioned sections, a participatory exercise called the *Seasonal Calendar* (Defoer 2000; FAO (n.d.)) where the farming year was to described with the same material as for the *Resource flow maps*. This exercise was only made twice, once together with two farmer households, and once with the local development agents (DA).

4.3 MFA as used in this study

The methodology of MFA was used to study and illustrate how N, P an OC are imported, exported, lost and accumulated within smallholder farm households in Bolo Silasie. The *system boundaries* were set to include the farm household and its associated animal husbandry. The *substances* studied were N, P and OC and the *goods* are all materials containing any of these substances that were imported to the system, exported from the system, or transported between different *processes* within the system. Four processes were chosen, namely *Household consumption*, *Animal husbandry*, *Pit latrine* and *Compound ground*. The free software STAN 2.6 developed by Technical University of Vienna was used for the MFA.

4.4 Quantification of flows

In order to evaluate the flows of N, P and OM within the system, an estimation was required of 1) the masses of materials flowing between systems compartments within a certain time span, and 2) the substance concentration of the materials. While the interviews provided an overview of the resource and waste management system, complementary collection, weighing and conversion calculations were done to quantify the flow sizes in masses per time unit. Substance concentrations were determined by lab analyses of goods and taken from literature of earlier studies in Bolo Silasie. Statistical significance test (t-tests) were done in Microsoft Excel to assess differences between hh socio-economic groups.

4.4.1 Estimation of waste quantities by collection and weighing

The hh production of wastes was determined by collection. Different sized plastic buckets with lids *(Fig. 4)* were handed out to three hhs from every wealth group. The hh members were asked to collect ashes, food leftovers, kitchen greywater and laundry greywater in separate buckets. The produced quantities of greywaters and food leftovers were weighed daily during a three-days period, while ashes were weighed after one full week's collection. Ashes were collected in one single bucket regardless originating from cooking stove or injera stove.

Figure 4. Buckets used for collection of greywater, food leftovers and ashes

The scales used for the weighing was a SUPER-SS IP66 standing scale with the capacity of 6 kg and 1 g resolution, and a KERN CH50K50 hang-scale with 50 kg capacity and 50 g resolution.

4.4.2 Assumptions and conversion of interview data

The estimation of yearly household consumption of foods, livestock feed, water, firewood, charcoal, *fug* and *kubet* were based on interviews responses. During the interviews, consumption was often reported in volumes or in market prices and were therefore converted into masses according to *Table 2.*

Table 2. Methods of converting interview reports of household consumption into masses

Good	Reported unit	Method of converting into masses
Foods purchased at market	"5 ETB", "10 ETB" = the amount of food you would get for a 5 or 10 ETB at the market.	Repeated weighing of corresponding quantities of food purchased at the local market.
Fug, kubet, compost, straw & charcoal	"1 quintal", "1 madabara" = the volume of a 100 kg sack of grain or 50 kg sack of mineral fertilizer, respectively	Weighing of substrates in typical grain or fertilizer sacks.
Firewood	"Pile/time unit" = An amount of firewood used per day, week or 14 days.	Weighing of firewood piles

Total masses and nutrient contents in Bolo Silasie human excreta had earlier been studied by Dagerskog (2017). The numbers on total N and total P in daily excreta (faeces+urine) were triangulated with the following food intake-to-excreta conversion factor (Jönsson et al. 2004) (*Eq. 2; Eq. 3*).

$$N = 0.13 * \text{total protein intake} \quad \textit{(Eq. 2)}$$
$$P = 0.011 * (\text{total protein intake} + \text{protein intake from vegetable sources}) \quad \textit{(Eq. 3)}$$

USDA Food Composition Databases was used to determine protein content for the foods with unknown N and P contents. The protein intake from wheat and teff were determined by conversion from total N to protein content using the Jones factor (Breese Jones 1941) (*Eq. 4*).

$$\text{Protein content} = 6.25 * \text{total N content} \quad \textit{(Eq. 4)}$$

For the conversion of OC to OM and vice versa, the van Bemmelen factor (Kimble et al. 2000) was used (*Eq. 5*).

$$OC = 0.58 * OM$$
$$OM = 1.72 * OC \quad \textit{(Eq. 5)}$$

The lab analysis results on volatile solids (VS) in the different substrated studied *(chapter 4.4.3)* were used as a proxy for OM content (Dean 1974).

Livestock numbers from official statistics and reported in interviews were converted into Tropical Livestock Units (TLU), a theoretical animal of 250 kg body mass. Based on literature values (Haile et al. 2018; Haileselassie et al. 2005; Jahnke 1982) and discussions with the local DAs the TLU conversion factors for Bolo Silasie were determined as in *Table 3*.

Table 3. Conversion factors for livestock types into TLU

Livestock type	TLU
Oxen	1.0
Cow	0.7
Donkey	0.6
Camel	1.2
Sheep	0.15
Goat	0.15
Poultry	0.01

The manure production per TLU was determined to 1000 kg DW per year (Joint FAO/WHO 2005). The total N and P excreted by livestock in faeces and urine together were estimated to be 75% of P and N intake from feed (Šebek et al. 2014).

The volumes of feed intake were reported by hh in interviews, while the N and P concentrations were determined by lab analyses and complementary literature values for corn (USDA Food Databases). The OC concentration in fresh manure was estimated to 44% of DW (Kirchmann & Witter 1992).

Harvest indexes were used to calculate a theoretical straw production based on a known production of grain. The harvest indexes (HI) were set to 23% for teff and 35% for wheat, retrieved from Paff & Asseng (2019).

4.4.3 Determination of N, P and OM content in substrates

Samples of firewood, charcoal, farmyard manure (FYM), *fug*, *kubet*, *atella* and straw and grain of wheat and *teff* were donated from nine hh participating in the study in amounts of 100-550 g per sample and stored in separate plastic bags. Greywater and food leftover samples were collected once a day during a three-days period from the families collecting wastes in buckets for mass estimation. The greywater in the collection buckets was stirred with a stick before a sample was poured into an empty water bottle of 0.6 L. All the food leftovers found in the collection buckets were brought and stored in plastic bags. Ash samples were collected at the last day of the hh's weekly collection. The ashes were mixed in the buckets with a stick whereafter a representative sample was poured into a plastic bag. *Tella* was purchased from three village families, none of them being study households, and stored in separate 1 L water bottles. One kilogram each of *fino* and *fagullo* was purchased in the neighbouring town Arerti. The masses of all samples in their containers were noted, as well as the mass of the containers.

Food leftovers and greywater samples were stored cool in a fridge 1-3 days (depending on day of sample collection) before being analysed. Cooling was however not optimal because of intermittent electricity supply in the village during the days of sample collection.

Composite samples were prepared for all samples except for *fino*, *fagullo* and *atella*, which were one-source samples. For the other substrate types, equal masses of all collected samples (n=3-9) were mixed into composite samples with a mass of 400-1100 g. The subsamples of food leftovers were disintegrated and mixed with a spoon before preparing the composite sample. The solid samples were stored in plastic bags of 1.5 L (20 L bags for straw samples), and the liquid samples in 1 L water bottles of none-NH_4-impermeable plastic. Small amounts (10-100 g) of the subsamples for every substrate were kept in their original sample bags/bottles, except for water and food leftovers samples that were moved to 50 mL sampling jars with lids.

The samples were brought from Bolo Silasie to Addis Ababa in a closed cool bag with cool but not freeze cool packs the same day as finishing the last collection of water and food leftover samples.

One of each of the composite samples were handed in to Jije Laboglass Experimental Laboratory in Addis Ababa for analyses of TN *(ES ISO 11261:2015 - Kjeldahl)* and TP (*AOAC 986.24 – Colorimetric)*. For the two greywater samples, TN (*APHA 4500–Norg C.Semi-micro Kjeldahl)*, TP *(APHA 4500 P. C Vanadomolybdophosphoric Acid Colorimetric)* BOD *(APHA 5210 B. 5-day BOD Test)* and COD *(APHA 5220 B. Open Reflux Method)* were also analysed.

One of each of the composite samples were also analysed at biochemical engineering laboratory at Addis Ababa Institute of Technology (AAiT) for pH, EC, moisture, and volatile solids (VS). Heterogenous substrates, such as manure, straw and food leftovers, were homogenized in an electrical coffee grinder before being analysed (*Fig 5*).

Figure 5. Coffee grinder homogenisation of *kubet*

4.3.3.3. Total and volatile solids determination

The total solids (TS) and volatile solids (VS) content were determined for all non-liquid substrates. The analyses were done both for one-source samples, for composite samples (n=3-9) and for five of the corresponding subsamples. A small amount (3-20 g) of homogenised sample was placed in an aluminium crucible with a known mass and dried in an Electric Thermostatic Drier model 202-0A at 105°C for 24 hours. The water content was determined as equal to the mass loss after drying. The remaining mass corresponded to the total solids (TS), or dry weight (DW). The samples were further incinerated at 550 °C in a Vecstar Furnace for 6 hours, where after the volatile solids (VS) was determined as equal the mass loss on ignition.

4.3.3.4 pH and EC determination

The pH and EC were determined for the ashes and manures. One gram of sample was mixed with 9 mL distilled water. The pH was measured after one hour with a Jenway 3505 pH meter and EC with a Greisinger G1410 EC meter. The pH-meter was calibrated with pH 4.01, pH 7 and pH 10 standard solutions before any measurements. When checking the measurement accuracy of the EC meter with a 1413µS/cm standard solution, the EC indicated a value of 1240 µS/cm. The deviation in measured value (6%) was considered small enough to use the EC-meter.

4.5 Assessment of local soil status

4.5.1 Soil sampling

Fields farmed by the study hhs were sampled with the aim to understand the local soil status and to assess whether physio-chemical properties would correlate with soil and resource management practices reported by the hhs.

For each of the hhs, soil samples were taken from two fields, corresponding to the field with the highest and the field with the lowest reported addition of compost respectively. When no addition of compost was reported, or when the farmer did not report any difference in manure management, samples were taken from the closest and from the most distant field assuming the closest field generally would receive more attention and inputs. In cases when farmers only farmed one field, or when fields were situated at the same distance from the homestead and were believed not to exhibit any substantial differences, only one field was sampled. In total 24 fields were sampled *(Fig. 6)*. The fields varied in size from 0.16 to 0.46 ha.

Figure 6. The 24 sampled fields around Bolo Silasie village (*Maps.google.com 2019-05-29)*

The soil sampling was carried out at the end of the dry season. The soils were hard and showed deep cracks typical for Vertisols (Jones et al 2013). Stubble and harvest residues were still present in the fields *(Fig. 7).*

Figure 7. A dry and “cracking”Vertisol with stubble still present in the field

From each field, 20-25 subsamples were taken and pooled into one composite sample. The subsamples were taken from 0-20 cm depth and in a diagonal cross pattern over the field *(Fig. 8),* leaving out the field edges which might display divergent characteristics. The sampling was made with a soil auger *(Fig. 9)*

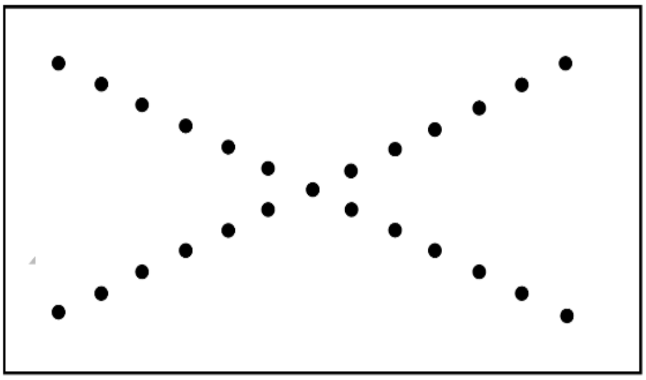


Figure 8. Composite sampling pattern across a field. Every dot symbolizing one subsample

The free cell phone software *Fields Area Measure PRO* was used to determine the coordinates for the fields and measuring their sizes and distances from the homesteads. For the soil data, Microsoft Excel was used for descriptive statistical analysis of and the software R was used for determining statistical correlations.

4.5.2 Sample preparation and laboratory analysis

The subsamples were collected in a large plastic bag and thoroughly mixed into one single homogenized composite sample in a plastic bucket *(Fig 9).* The samples were returned to large plastic bags to air-dry for one day. The samples were grinded in a mortar and passed through a 2 mm sieve. To reduce the sample volume, the composite sample was poured out on a pile covering two large papers, leaving half the sample on every paper. One such half, constituting 500-600 g of composite sample, was sent in to Horticoop Soil Laboratory in Debre Zeit for laboratory analysis of soil texture (Bouycous hydrometer method), OC (Walkely and Black), CEC (Ammonium Acetate Method), TN (ES ISO 11261:2015 Kjeldahl) and available K, P, Ca Mg and S (Mehlich-3).

A smaller amount (~80 g) of the composite samples was brought to AAiT in Addis Ababa in plastic 50 mL sample jars for analyses of EC and pH. For these analyses 10 mL of distilled water was added to 5,0 gram of soil sample (1:2 soil to water ratio) in plastic test tubes with lids. The solution was thoroughly mixed and shaken for one minute and then left to rest for one hour. The pH was measured with a Jenway 3505 pH meter and EC with a Greisinger G1410 EC meter.

Figure 9. Soil sample equipment: 1) Soil auger, 2) plastic bags for sample collection and air-drying, 3) plastic buckets for composite sample homogenisation, 4) traditional coffee mortar used for soil aggregate disintegration, 5) plastic bags for composite samples handed in to Horticoop Soil Laboratory, 6) 2 mm sieve and 7) sample jars for smaller amounts of composite samples brought for analyses at AAiT

5 Results

5.1 Farm and household system

The following section on the farm and hh system (5.1) is based mainly on interview responses. It also relies on official statistics from the local agencies, discussions with local developments agents (DA) and observations from six weeks' stay in Bolo Silasie.

The typical Bolo Silasie household is comprised by a two-generation, possibly three-generation family of 5.0 hh members (Bolo Silasie Kebele statistics). Close relatives, such as sister, brothers, and still-working elderly mothers and fathers commonly share the same compound and some of its facilities, while residential houses, fields and livestock are used separately by every household. Houses in the village are built close to one another while fields are scattered in large area around. The fields are roughly in the size of one *timad,* which equals 0.25 ha. Some hh have smaller (200-800 m^2) maizefields at the homestead where maize is grown mostly for animal feed.

Figure 10. Two examples of homestead kraals with stone or shrub fencing. Livestock are given feed and water within the enclosures and cattle do often not leave the kraal except for when needed for agricultural work. Some hh tether or look after their livestock in the fields a few hours a day

Livestock are kept at the homestead tethered to trees or other structures and/or kept in roofless kraals, surrounded by stone fencing, shrubs or thorn-bush branches *(Fig. 10).* Cattle are normally separated from sheep and goats due to their long and pointed horns, and only share the same kraal if they are tethered. Donkeys and camels are used daily all year round for transport of goods, while cattle are used more intensively during farming activities such as ploughing and threshing. Cattle, sheep and goats are by some hhs taken to the fields during daytime, where they are tethered or herded and fed with straw. During the growing season, field edges are cleared from grass and given to the animals as supplementary feed. Due to scarce land resources there is very little grazing land, neither as household tenure nor commonly own. The number and relative distribution of livestock types in Bolo Silasie have remained relatively constant over the last years, summing up to around 3400 TLU (*Fig. 11*).

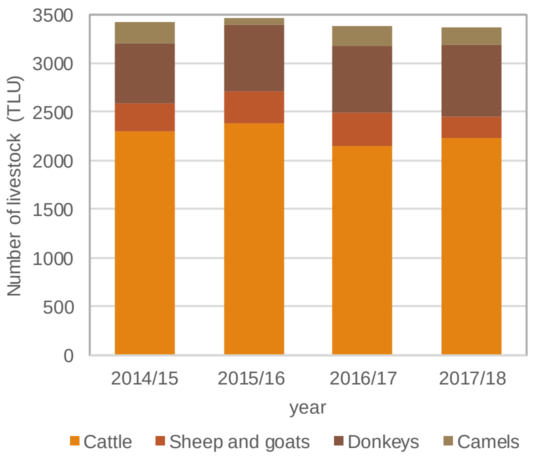


Figure 11. Total number of TLU in Bolo Silasie by livestock type over the last four years. Statistical years follow the Ethiopian calendar year sept – sept (*Bolo Silasie Kebele statistics)*

Water for household use is collected at the local community standpipe, typically in 25 litre jerrycans carried by donkeys from the well to the homestead *(Fig. 12).*

Figure 12. Jerrycans in line for water collection at the communal standpipe

There is in Bolo Silasie, like elsewhere in Ethiopia’s numerous kebeles, a well-established group of public officials called Development Agents (DA), giving advice on crop and animal production, administrating credit loans and distributing mineral fertilizers, among others. Other communal village assets include a farmer’s training centre and community mill running whenever there is electricity, charging a minor cost per kilogram of grain or seed. The access to markets is relatively good. Since 2013, an asphalt road leads to the main town Arerti 6 km to the North and to the larger city Mojo 55 km to the Southwest According to interview responses of farming practices, soil preparation is done with a pair of oxen and a single ploughshare. Fields are ploughed 4-5 times before seeding *(Fig. 13).* Sowing and mineral fertilizing is done mainly by hand-broadcasting or with simple appliances. At the labour-intensive weeding also women participate, while other field activities are mainly carried out by men. In wheat, herbicides are applied at least once during the season. Harvesting is done by hand and sickle. Harvested crops are gathered in large piles and stored for around a month before threshing. Threshing is normally done in the fields at threshing sites that remains constant over the years. Before threshing the field is levelled and compacted by oxen. Fresh cow dung is spread over the threshing area to dry, creating a hardpan that prevent grains from entering the soil. Cattle are made to walk on the hardpan, where harvested and dry crops are placed so that grains and straw are separated by the physical weight of the cattle tramples. The straw is piled up in large piles for long-term storage in the field, while grain is collected and brought from the field.

Figure 13. Ploughing in done just before the rainy season with a pair of oxen and a single ploughshare

Teff and wheat are the most important crops in Bolo Silasie, followed by onion and legumes (*Fig. 14*). The average yields in Bolo Silasie were in 2018 4.2 t ha^{-1} for wheat, 2.8 t ha^{-1} for teff, 20.4 t ha^{-1} for onion and around 2 t ha^{-1} for the different legumes (Bolo Silasie Kebele statistics).

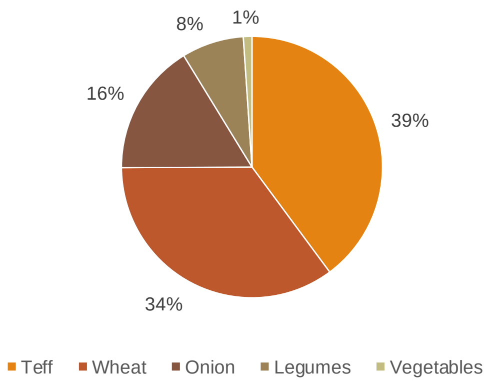


Figure 14. Main crops in Bolo Silasie by land cover 2018. Sorghum, which normally covers 5-10% of agricultural land was not grown 2018 due to low precipitation in the pre-season. Maize is an important crop for household consumption, but total land cover is less than 1% (Bolo Silasie Statistics)

The three socio-economic groups included in the study were identified by size of farmland and number of TLU. After performing the interviews, various characteristics were found to distinguish the three groups. There was a positive correlation in socio-economic status and number all kinds of livestock and number of productive trees, used for firewood collection, (*Fig 15*). While 80% of the worse-off

Figure 15. Firewood harvesting from acacia, done by cutting only the branches and leaving the tree for re-growth. Acacia is commonly planted in the fields for N-fixation and erosion control

hh had manual labour as a supplementary source of income, only 20% in the middle group and none of the better-off hh did manual labour beside the agriculture production (*Table 4*).

Table 4. Assets and features of Bolo Silasie farm households. Data for the three socio-economic groups are based on interviews responses while the data on average Bolo Silasie hhs comes from local Kebele statistics

	Worse-off (n=5)	**Middle (n=5)**	**Better-off (n=5)**	**Average study (n =15)**	**Average Bolo Silasie (n=1143)**
General					
Hh members	3.8	3.6	6.6	4.7	5.0
Years in farming (head of family)	21	29	39	30	N/K
Assets					
Farmland (ha)[1]	0.5	1.2	3.1	1.6	1.6
TLU	1.3	3.6	7.0	4.0	3.0
Oxen	0.2	2.4	3.6	2.1	1.5
Donkeys	0.4	1.0	2.0	1.1	1.0
Sheep & goats	2.2	4.0	5.8	4.0	2.0
Camels	0	0	0.6	0.2	0.15
Productive trees	10	43	80	44	N/K
Ponds	0	0.8	1.2	0.7	N/K
Production and income					
Total production, teff (tons)	0.51	1.7	2.5	1.6	1.7
Total production, wheat (tons)	0.80	1.1	1.9	1.3	2.7
Total production, onion (tons)	1.8	3.1	4.8	3.2	6.0
Total production, legumes (tons)	0.13	0.43	0.69	0.42	0.26
No of crops grown	6.6	12.0	14.0	10.9	N/K
No of crops grown for sell	3.4	7.7	9.2	6.8	N/K
Have maizefield at homestead	40%	60%	100%	67%	N/K
Do manual labour as supplementary source of income	80%	20%	0%	33%	N/K

1) Refers to size of cropland *actually farmed* by the household, figures on tenure looks slightly different. The better-off households typically hire land, while worse-off households commonly rent out.

According to interviews, Bolo Silasie hhs are to a high extent self-subsistent on staple food, livestock feed and stove fuel. Many resources and wastes are reused within the system, such as food leftovers given to animals and manure used as stove fuel, for construction and threshing pan preparation. Purchased goods include supplementary livestock feed, vegetables and legumes for human consumption, corn for production of *tella* and *areke* and some firewood. *Figure 16* gives an overview of the resource and waste management system within the average study hh, using an MFA diagram.

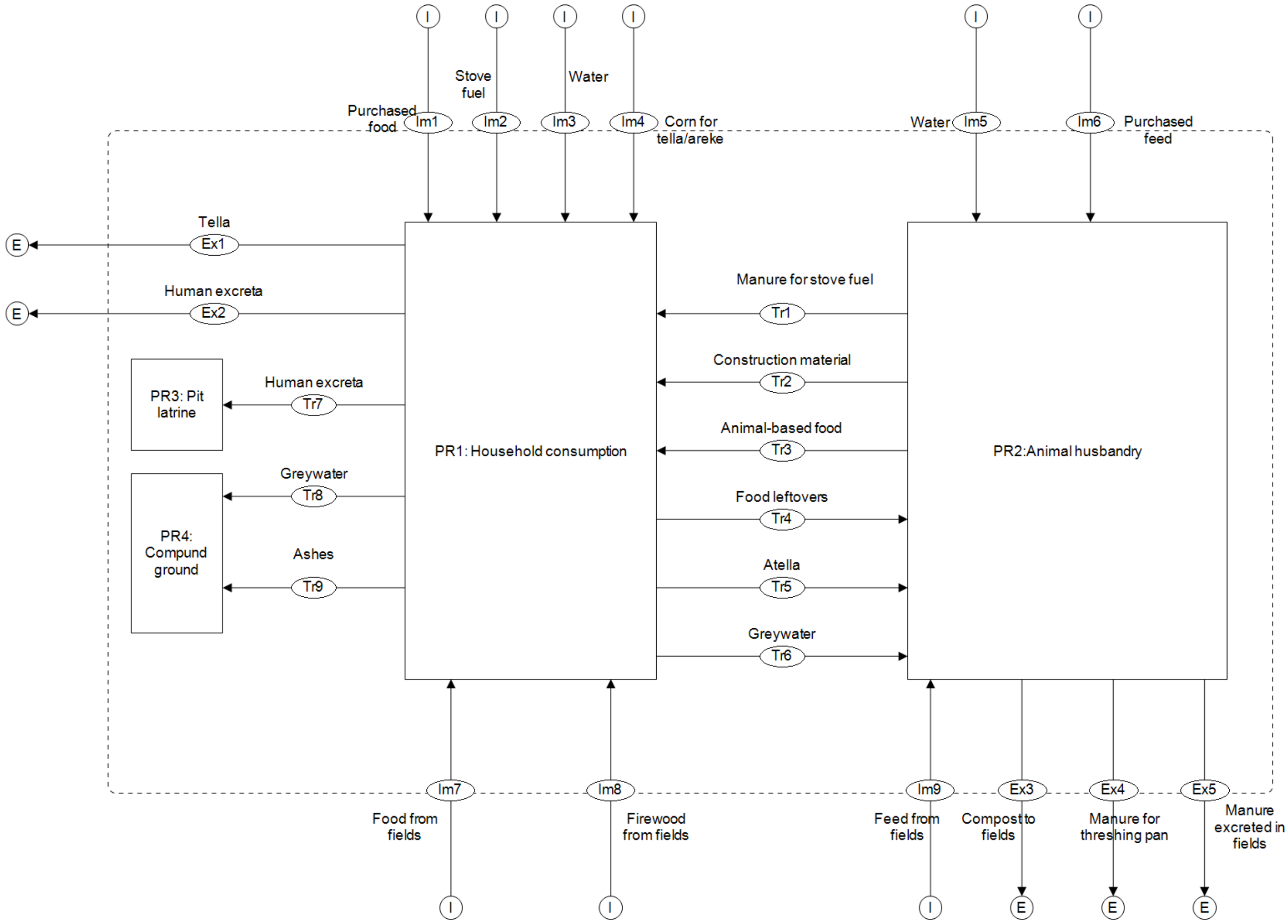


Figure 16. Material Flow Analysis (MFA) illustration of the farm household system and the flows of material into and off from the system. The arrows Im 1-9 are import flows, Ex 1-5 are export flows and Tr 1-9 are transport flows between processes within the system. The four processes considered are PR1: Household consumption, PR2: Animal husbandry, PR3: Pit latrine and PR4: Compound ground

5.2 Current management of household resources and wastes

5.2.1 Water

In Bolo Silasie, water used for washing, cooking, cleaning and drinking amounts to an average of 23 L water per person and day, or 111 litres daily for the average hh. Other than water for personal use, additional 110 litres water are used by the hhs for livestock and production of *tella* and *areke*. Water consumption for livestock show a clear positive correlation with household wealth *(Fig 17)*. Worse-off households also use less water for personal use (48 L d^{-1} compared to 99 L d^{-1} and 186 L d^{-1} for the worse-off, middle and better-off group, respectively).

From the households' collection of greywaters is was found that an average 8.5 L laundry water and 5.6 L dishwater was produced daily. The non-collected water equals on average 97 L, which suggests that the larger share of water for personal use is used for other activities, such as cleaning, body- and hand washing, drinking and cooking (*Fig. 18*).

Of the study hhs, 80 % give their kitchen water to livestock, which represent in average 1.1 L TLU^{-1} d^{-1}. Other than dishwater, livestock receive on average 25 L water TLU^{-1} d^{-1}.

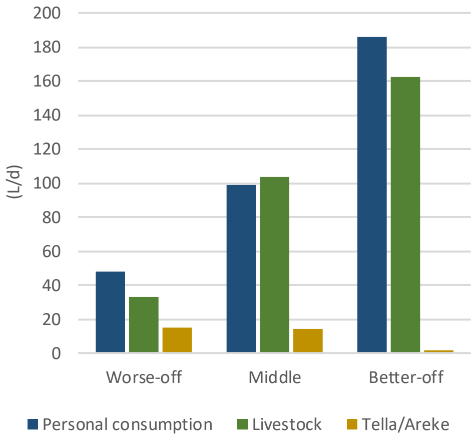


Figure 17. Water consumption for the three socio-economic groups, distinguishing between persona consumption, water for livestock and water for production of *tella* and *areke*

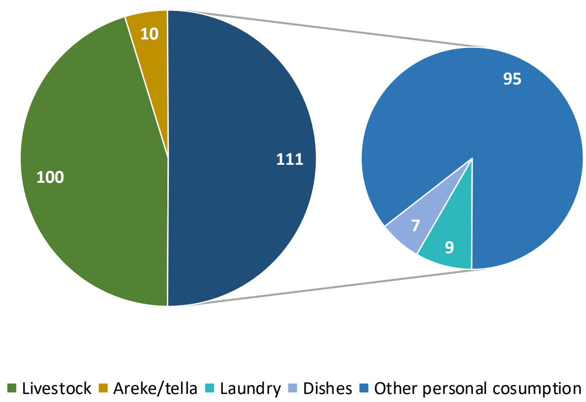


Figure 18. Distribution of water consumption (L d^{-1}) for different activities, showing the average study hh

5.2.2 Human food, food leftovers and excreta

Households in Bolo Silasie base their diet mainly on *injera* (flat sour-dough bread made of teff and wheat) and *wot* (stews of pulses and vegetables). According to interviews, the consumption of meat and dairy is low for all households. Grains and pulses are mainly sourced from own farm production, while vegetables most of the year are purchased from the nearby market town. Worse-off families purchase also pulses. Meat, milk, eggs and dairy are either from own production, bought from neighbours or purchased in Arerti. Worse-off hhs have a lower self-subsistence rate, both because of a less differentiated production and a lower total production.

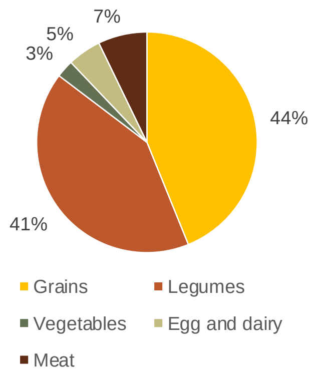


Figure 19. Protein sources in daily intake of food, consumed by the average Bolo Silasie hh

According to interview responses on food consumption and calculations on calorie and protein content in different foods, the average Bolo Silasie inhabitant consume 2600 kcal and 96 g protein daily, both calories and protein intake deriving mostly from grains and pulses *(Fig. 19).* These numbers can be compared with the average Ethiopian supply of 2130 kcal and 62 g protein daily (FAOstat).

Food leftovers and cooking residues were by collection and weighing estimated to 245g DW per hh and day. All hhs reported to give food leftovers to livestock as complementary feed.

From what was reported in the interviews, all hhs produce *tella* and *areke* for consumption at celebrations. Of the hhs in the study, 47% produce *tella* and/or *areke* every week with the purpose for selling to neighbours. The production of *tella* requires large quantities of water and corn. Hhs producing *tella* purchase on average 2000 kg corn yearly for its production, a number manifold larger than the hhs consumption of grain for food consumption. The *tella* and *areke* production generates the protein-rich by-product *atella*, which for the households constitutes an important supplementary feed type for all kinds of livestock. Due to the relatively large amounts of N, P and OC that are imported to the hh by the purchase of corn for *tella* and *areke* production and its interconnectedness to the rest if the hh resource management system, the production also needs to be considered in the MFA calculations for the hhs *(Fig. 20).*

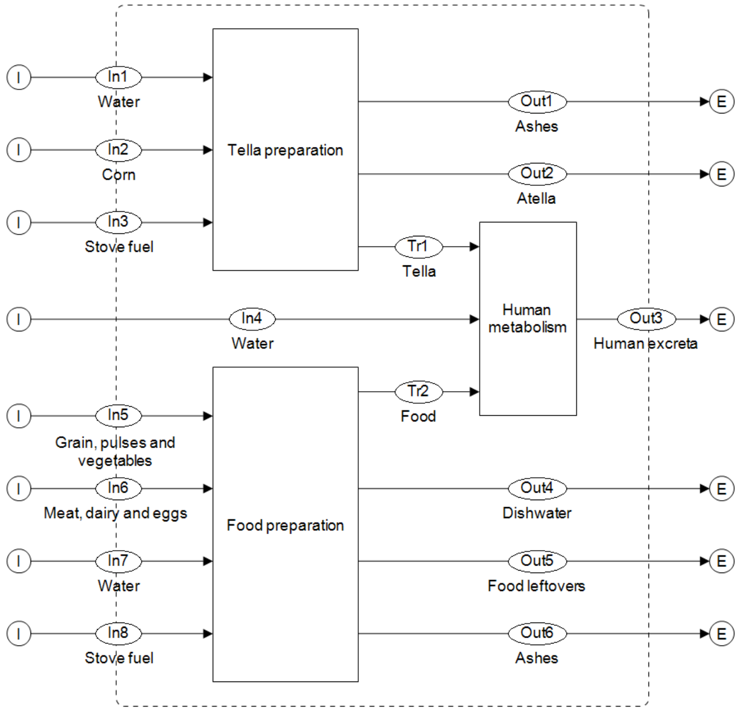


Figure 20. Material flows in the subsystem *preparation and consumption of foods and drinks*, within Process1: household consumption

5.2.3 Human excreta

The N, P and OC composition in human excreta in Bolo Silasie has not been assessed in study since this was already done by Dagerskog (2017). The section 5.2.3 is thus not entirely based primary on results from this study but include also earlier collected data in order to provide the full picture of Bolo Silasie hh resource and waste management system.

According Dagerskog (2017), Bolo Silasie inhabitants produce 1.6 L urine and 56 g faeces (DW) daily. The measured total N and total P in excreta per person and day was 10.6 g and 2.3 g, respectively *(Fig. 21)*. The majority of P was found in faeces while the majority of N was found in urine (*Fig. 22-23*). Based on protein intake from reported food consumption patterns, the theoretical amounts in human excreta are 11.9 g N and 1.9 g P per person and day. According to Dagerskog (2017) the typical Bolo Silasie inhabitant excrete 3.86 kg N and 0.84 kg P per person and year.

Some hhs mentioned in the interviews that they occasionally urinate on straw to increase the salt intake and palatability for the livestock. Other than that, human excreta lack current use.

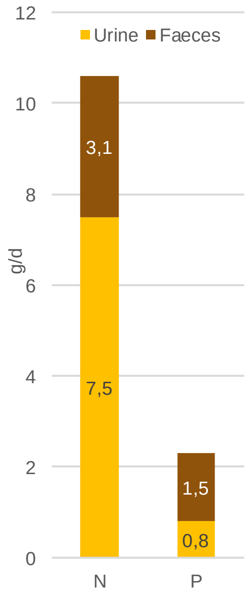


Figure 21. Grams of N and P excreted per person and day in urine and faeces (*Dagerskog 2017).*

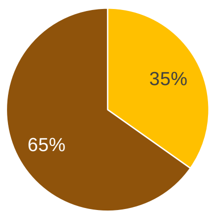


Figure 22. Distribution of P in urine and faeces (*Dagerskog 2017)*

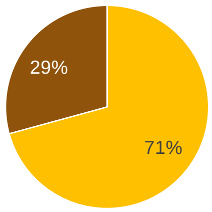


Figure 23. Distribution of N in urine and faeces (*Dagerskog 2017)*

Household members are according to the interviews daily engaged in activities such as farm work, church visits, market shopping and *tella* drinking with neighbours. Not least for men, the time spent outside the households varies during the year due to fluctuations in field-related workload. Taking such seasonal differences into consideration, women spend in average 1.6 h day^{-1} outside the household, while the same number for men is 7.4 h day^{-1}. In average, men and women together spend 4.6 h day^{-1} outside the homestead. Given that urine and faeces are excreted evenly distributed during the day, 19% of excreta will be deposited outside the farm compound.

5.2.4 Livestock feed

Straw of wheat and teff constitutes the very backbone of the Bolo Silasie livestock feed (88% of total consumed feed (DW)). As reported by hhs, livestock are also given supplementary high-protein feed such as *fagullo* (oil-seed cake), *fino* (cereal bran), *atella* (by-product from *tella* production), food leftovers and corn and wheat grain *(Table 5). Fino* and *fagullo* are both industrial by-products that households purchase, while the other feed types are typically sources from the own farm or household.

Table 5. Daily livestock intake of biomass (kg DW), N (g) and P (g) by feed type. Quantities based on interviews and collection, N and P concentrations based on lab analyses

Feed type	kg DW d^{-1} TLU^{-1}	N (%)	P (%)	N total g d^{-1}	P total g d^{-1}
Teff straw	3.4	0.42	0.070	14.3	2.4
Wheat straw	2.5	0.60	0.080	14.9	2.0
Fagullo	0.44	4.37	0.62	19.2	2.7
Fino	0.07	2.42	0.55	1.7	0.39
Atella	0.13	4.04	0.58	5.3	0.63
Food leftovers	0	2.17	0.086	0.65	0.03
Maize[1]	0.07	1.5	0.23	1.0	0.14
Wheat	0.07	1.93	0.26	1.0	0.17
TOTAL	**6.7 kg d^{-1}**			**58 g d^{-1}**	**8.5 g d^{-1}**

[1)] USDA Food Composition Databases

A TLU in Bolo Silasie consume on average 6.7 kg DW feed per day, corresponding to 2.7% of TLU bodyweight. In livestock feed, 54% of N and 55% of P derive from own farm production and 10% of N and 8.4% of P from food residues and *atella*. Purchased feed contributes with 36% of N and 37% of P.

In summertime, grass is harvested from the field edges and given to livestock. Sheep, goats and donkeys are during certain months allowed to graze communal spaces such as road edges. There is however no intentional forage production and no land assigned for grazing, neither communal nor privately owned. In the periods when supplementary grass is given to animals, straw still constitutes the larger share of livestock feed.

According Bolo Silasie statistics on land cover and average yields of teff and wheat, the theoretical production of straw in the village is 229% of the reported consumption. Households reported in interviews that they have a strategy of storing straw enough to feed livestock for at least for two years. All farmers thus store straw in large piles in the fields or at the homestead (*Fig. 24*). Generally, farmers do not give their livestock any intentional bedding material. Yet, kraal grounds typically have a cover of straw comprised by feed refusals which are trampled and incorporated into the farmyard manure (FYM).

Figure 24. Storage of teff and wheat straw is done in large piles in the fields

5.2.5 Livestock excreta

Livestock manure is a crucial component within the hh resource management system, filling several distinct functions. More than two thirds are used as fuel in the cooking stoves, while the uses for the last third include field application of compost, threshing pan construction, charcoal production cover and construction and maintenance material, listed in the order of importance (*Fig 25*).

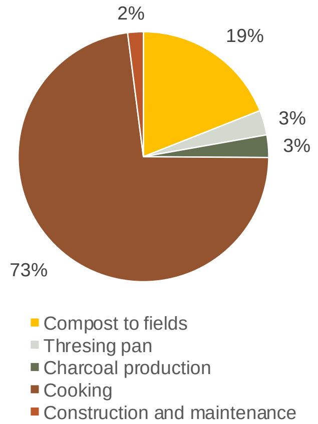


Figure 25. Distribution of current uses for manure by dry weight of goods

Livestock excreta can roughly be divided into five different categories: 1) *ebet*, fresh cattle excreta used for construction and threshing pan preparation, normally collected daily from the homestead kraal, 2) *kubet*, a high-quality stove fuel of dried cattle excreta, 3) *fug*, a lower-quality stove fuel of dung from cattle, donkey, goats and sheep mixed with straw, 4) *farm yard manure* (FYM), used as cover in charcoal production and as soil amendment after being decomposed in a manure compost, and 5) *decomposed manure compost*, normally aged one to four years before being applied to the fields *(Fig. 26)*.

Figure 26. Manure in four shapes. From above left to below right: *Kubet*, *fug*, FYM and decomposed compost

All households use manure as stove fuel, for threshing pan preparation and for other construction purposes. The use of FYM as cover for charcoal production *(Fig. 27)* is also relatively widespread. Of all hhs, 80% produce their own charcoal, 67% of them using FYM as cover in the process. Other households use soil and leaves.

Figure 27. Charcoal preparation under a cover of FYM

Animal urine is not collected or in any way diverted from the kraal but drains through FYM litter when livestock are at homestead. In the same way it is added to the fields by excreting livestock that are tethered or herded there in daytime. FYM is collected from kraals and compound grounds occasionally, ranging from every 14 days to once a year, and brought to a compost pit for decomposing. There is a widespread idea, supported also by the local development agents, that compost needs a substantial amount time of maturation before being used. Most commonly, households wait at least two or more years before bringing out the compost to the field. Compost heaps are normally not covered and only occasionally placed in the shade. 64% of the hh report to occasionally add ashes to compost heaps and/or homestead maizefields.

Livestock manure and urine are deposited both in the homestead kraals and in the fields. Of the hh, 53% report to keep their livestock at the compound when they are not used for work. The other 47% of hh keep their livestock tethered or herded in the fields for 4-10 hours daily. The average hh keep their livestock at the homestead 85% of the day. All hh keep their livestock home at night.

Although the management is not always optimized for avoidance of losses, such as those from non-covered compost heaps or non-collected animal urine, livestock excreta is an invaluable resource with multiple functions within the farm hh system. (*Fig. 28*).

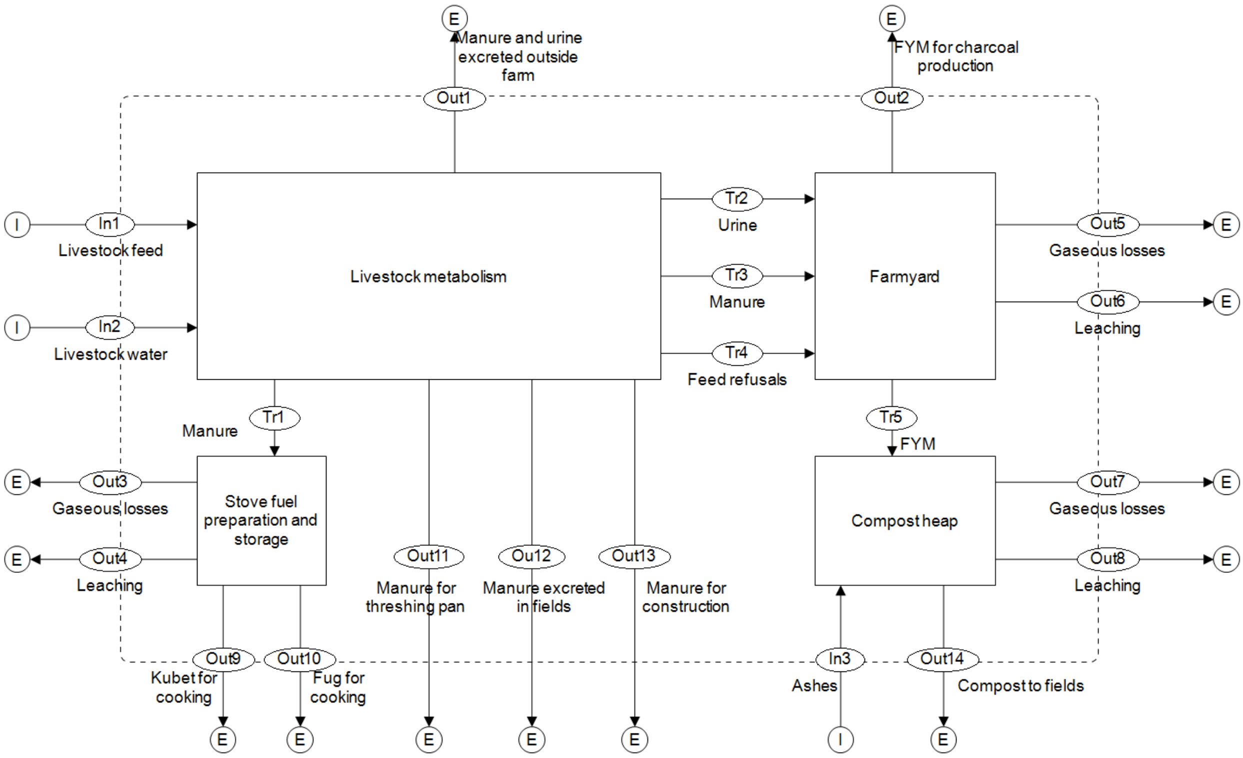


Figure 28. MFA diagram of the manure management system including expected sources of substance losses from the hh system

Due to large differences in numbers of TLU, the hhs' total production of manure differs largely between the three socio-economic groups *(Fig. 29)*. By dividing every hh's theoretical manure production with their respective sizes of farmland, a potential manure application rate for every group could be determined. Doing so, it appears that the middle group is the one with highest application potential (*Fig. 30*). Yet, the potential applications rates per hectare are relatively equal for all hhs, if *not* taking current cooking practices into account. When taking into consideration the current use of manure for other hh activities, the potentials for the different hhs groups look somewhat different. Since worse-off hhs use more manure than what is produced on their own farms, their application potential is zero, while the two other groups still have spare manure to use for compost (*Fig. 31*). The middle group is the one having the highest manure application potential per ha (*Fig. 32*).

The potential manure application per hectare scenario *(Fig. 32)* assume that all manure would be collected and that all collected manure would be used as soil amendment, thus a situation very different from the current. The quantities of manure are presented in DW and do not reveal anything about quality and nutrient content of the manure. Also, this scenario does not take into consideration weight loss in storage.

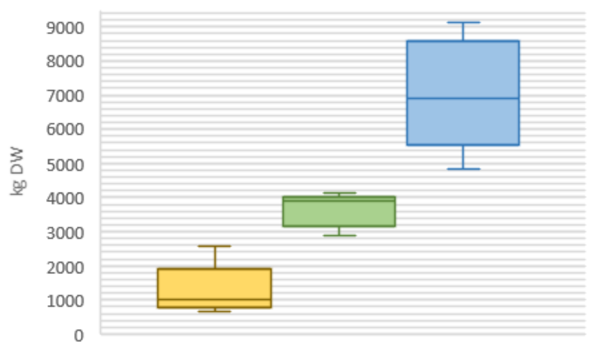


Figure 29. Theoretical manure production (kg DW) per hh group

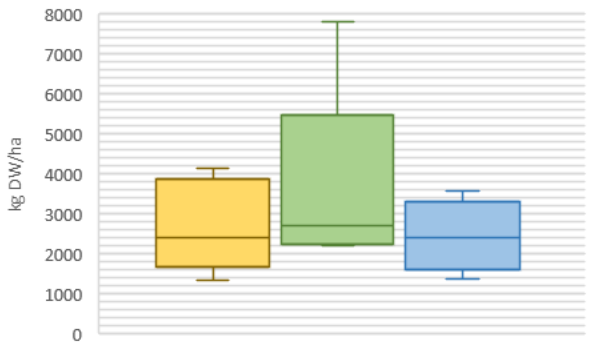


Figure 30. Potential manure application per hectare per hh group

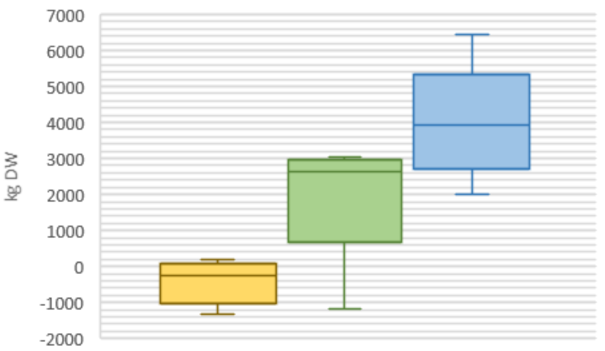


Figure 31. Manure available after considering current use as stove fuel

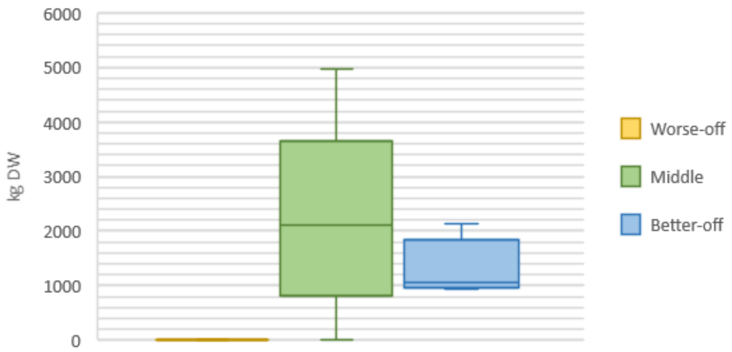


Figure 32. Current potential manure application per hectare, considering manure being used for stove fuel

5.2.6 Cooking fuel and ashes

Even though 77% of the hhs report to own a simple one-plate electrical stove, most cooking is done over open fire either indoors, using small charcoal cooking stoves, or in the separate cooking compartment where *injera* and *wot* is prepared using firewood, *kubet* and *fug*. Maize paste for *tella* and *areke* production is roasted outdoors using simple three-stone stoves *(Fig. 33).*

Figure 33. From left to right: 1) Stove for indoors cooking, used mainly for coffee and wot (stews), 2) Injera stove in the separate cooking compartment, 3) Roasting of corn paste for tella on an outdoors three-stone stove

Together, *fug* and *kubet* account for 77% of the biomass used for cooking, the rest being charcoal and firewood *(Fig 34).* The average hh uses 168 kg of charcoal yearly. Assuming a production efficiency of 14%, which has been reported for similar household charcoal production systems in Kenya (Okello et al. 2001), the charcoal consumption corresponds to 1200 kg firewood. If charcoal was to be counted in firewood equivalents, firewood would constitute around half the stove fuel biomass.

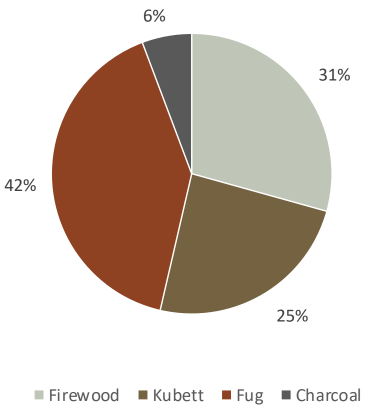


Figure 34. Distribution of stove fuel types for the average hh (based on dry weight). *Fug* and *kubet* are two types of manure

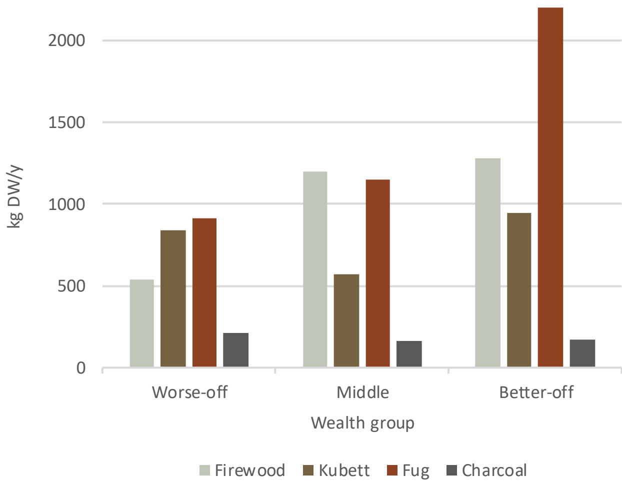


Figure 35. Sources and quantities (kg DW y^{-1}) of stove fuel biomass used by the three socio-economic groups

The share of *kubet* used as stove fuel is as high for the worse-off group as for the better-off and even higher than for the middle group, although worse-off hhs produce almost no *kubet* themselves but purchase from neighbours. *Fug* and firewood however show a positive correlation in consumption, the better the access to livestock and wood resources the hh *(Fig. 35)*.

Since the food preparation is one of the more demanding hh activities in terms of imported materials *(Fig. 36)*, it requires extra attention when studying the hh resource management system.

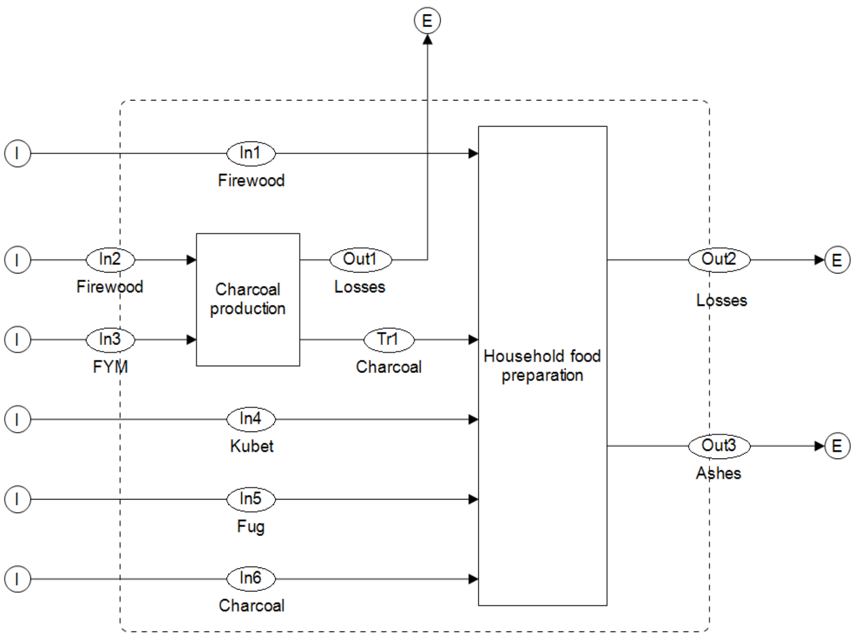


Figure 36. MFA diagram of biomass combustion within *Process 1: Household consumption*

5.3 N, P and OC within the household system

While resource management practices have been described in chapter 5.2, chapter 5.3 puts the different resources in relation to one another by *material flow analysis* of the whole farm system and by displaying their potential contribution of N, P and OC to farmland.

5.3.1 Nutrient and OC concentrations in goods

The *goods* that based on the interviews were found to be the most important nutrient and OC carriers within the hh systems showed a wide range of concentrations of TN, TP and OC *(Table 6). Materials* that are listed have been analysed either in this study or earlier within the Triple Green project in Bolo Silasie (Dagerskog 2014; Dagerskog 2017). Fresh livestock manure and urine are not included in *Table 6* since their nutrient and OC content have not been evaluated.

Table 6. N, P and OC concentrations (DW) and C:N ratios for household goods

Substrate	**TN (% DW)**	**TP (mg/kg DW)**	**OC (% DW) [5, 6]**	**C:N**
Teff grain (n=8)	1.93	2576	56	29
Wheat grain (n=8)	1.55	2464	57	37
Tella (n=3)	0.0138	39		
Firewood (n = undefined[1])	1.08	1039	54	50
Charcoal[2] (n=1)	0.34	260	54	159
Dishwater (n=9)	0.0138	48	0.29	21
Laundry water (n=8)	0.0113	49	0.18	16
Food leftovers (n=5)	2.17	860	39	18
Ashes (n=6)	0.11	8532	4,6	42
Teff straw (n=9)	0.42	703	54	129
Wheat straw (n=9)	0.60	801	52	87
Fagullo (n=1)	4.37	6218	53	12
Fino (n=1)	2.42	5477	55	23
Atella (n=1)	4.04	578	57	14
FYM (n=8)	1.27	2878	44	35
Kubet (n=7)	1.12	2588	47	42
Fug (n=7)	1.34	2668	44	33
Human urine[3] (n=20)	0.51	600		
Human faeces[3] (n=7)	5.5	26000	49	8.9
Pit latrine[4]	1.31	18928	16	12
Manure compost[4]	0.67	5210	13	19

[1)] Composite sample of sticks and branches from different tree species and various firewood piles [2)] Novak et al. 2009, [3)] Dagerskog 2017, [4)] Dagerskog 2014 [5)] OC = 0.58*OM (Kimble et al. 2000) , [6)] OC = (COD – 7.25)/2.99 (Dubber & Gray 2010),

5.3.2 MFA for the farm household system

MFA diagrams for all three substances were set up to study N, P and OC flows within the hh system. The data that underlies the diagrams is based on interviews, waste collection, lab analyses, databases and literature *(Table 7)*. Additional assumptions made in the MFA calculations are listed in *Appendix 3*.

Table 7. Data sources of substance flows in Material flow analysis (MFA) diagrams

Material flows	**Source of data used in MFA diagrams**		
	Masses, volumes	Dry weight (%)	N, P and OC concentrations
IMPORTS			
Plant-based food, purchased	Consumption reported in interviews. Converted to masses according to *Table 2*.		USDA Food databases. Substance concentrations given for wet weight products.
Plant-based food, own produce	Consumption of foods reported in interviews matched with farm production reported in interviews.	Lab analyses (grains)	Lab analyses (grains), USDA Food databases (pulses and vegetables), substance concentrations given for wet weight products.
Firewood	An aggragated mass of 1) firewood consumed directly as stove fuel, masses determined by weighing, and 2) firewood required to produce the reported consumption of domestic produced charcoal (assuming a 14% production efficeincy[1].)	Lab analyses	Lab analyses
Charcoal, purchased	Purchased consumption reported in interviews.	Lab analyses	Novak et al. 2009
Corn for tella and areke production, purchased	Purchased masses reported in interviews.		USDA Food Databases. Substance concentrations given for wet weight products.
Animal feed, purchased	Consumption reported in interviews. Masses determined by complementary weighing.	Lab analyses	Lab analyses
Animal feed, own produce	Consumption reported in interviews. Masses determined by complementary weighing.	Lab analyses	Lab analyses
TRANSFERS			
Manure for stove fuel	Consumption of fug and kubet reported in interviews. Masses determined by complementary weighing.	Lab analyses	Lab analyses
Manure for construction material	Reported in interviews as volumes of *ebet*. Masses determined by complementary weighing of known volumes.	Lab analyses	Treated as equal to substance concentrations in *kubet*.
Animal-based food, own produce	Consumption reported in interviews.		USDA Databases
Food leftovers and residues	Masses collected by families during three consecutive days.	Lab analyses	Lab analyses
Greywater	Volumes collected by families during three consecutive days. 80% of collected kitchen water was estimated to be given to livestock.		Lab analyses
Ashes	Masses collected by families during one week.	Lab analyses	Lab analyses
Human excreta	Urine and faeces production per person and day in Bolo Silasie, determined by Dagerskog (2017). Multiplied by average hh members and share of day spent at the homestead.	Dagerskog (2017)	Dagerskog (2017)
EXPORTS			
Human excreta	Urine and faeces production per person and day in Bolo Silasie, determined by Dagerskog (2017). Multiplied by number of hh members and share of day spent outside homestead.	Dagerskog (2017)	Dagerskog (2017)
Compost to fields	Reported as application in 50L bags. Complementary weighing of known volumes of compost material.	Dagerskog (2014)	Dagerskog (2014)
Manure excreted in fields	Total DW manure production per TLU and year[2], multiplied by number of TLU in the average study hh and the share of day livestock spend in the fields.		Dry weight concentrations of N and P calculated by a conversion factor from food intake[3] and OC from Kirchmann & Witter (1992)
Threshing pans	Reported as "bags" of *ebet* used for their construction. Complementary weighing of known volumes of *ebet*.	Lab analyses	Treated as equal to substance concentrations in kubet
Tella	Volumes quantities produced and sold as reported in interviews.		Lab analyses (this study). OC assumed to be negligible.

1)Okello et al. 2001, 2) Joint FAO/WHO (2005), 3) Šebek et al. 2014

The major imports of N to the farm household system resulted to be from feed, food, stove fuel and corn for production of *tella* and *areke (Fig. 37)*. The larger N transfers within the system include manure from the husbandry system being used as stove fuel in the household, human excreta deposited in pit latrines and *atella* given as livestock feed. The outflows from the system comprise of livestock manure and human excreta being deposited outside the hh, manure intentionally added as compost to the fields, manure used as threshing pans in the fields and *tella* sold to neighbours. According to the MFA calculations, there is an accumulation of N in all system compartments. The whole system accumulates 117 kg N y^{-1}.

The general pattern for the P flows vastly resembles the one for N *(Fig. 38)*. One major difference is the importance of ashes. While ashes are almost negligible in the N flow scheme, they are one of the larger transfers within the P system. The flow of compost to fields is twice as large as the flow of manure excreted in fields, due to high P concentration in the compost and low initial P concentration in fresh manure. Accumulation of P mostly occurs within the two compartments of latrines and compound ground. The whole hh system accumulates 12.6 kg P y^{-1}

For OC there are mainly two large import flows, namely feed and firewood from the own farm system *(Fig. 39)*. There are basically no important export flows. Due to large imports and almost no exports of OC, the system accumulates 7040 kg OC y^{-1}, primarily within the compartments of household consumption and animal husbandry.

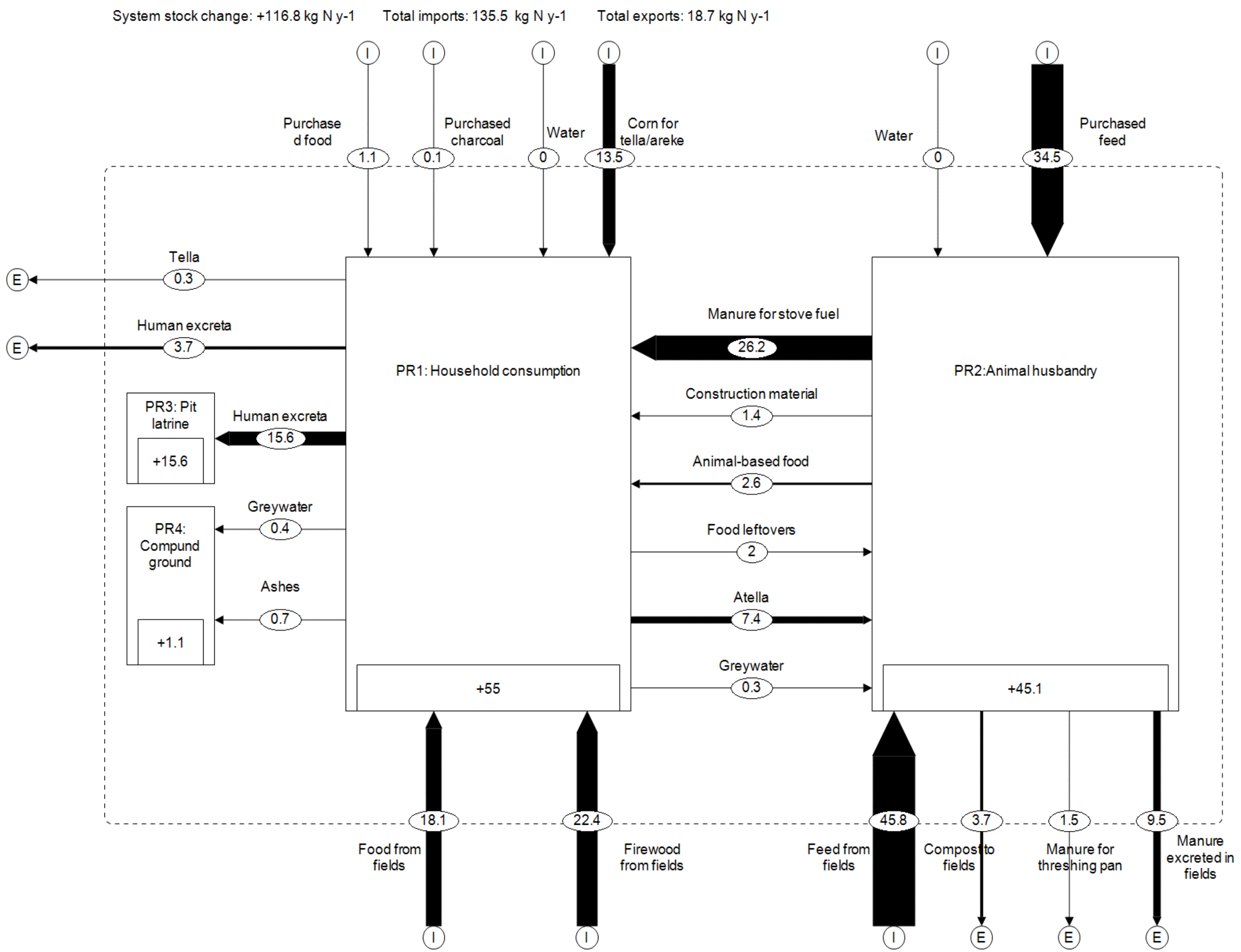


Figure 37. MFA diagram of the hh system showing flows of N in kg per year

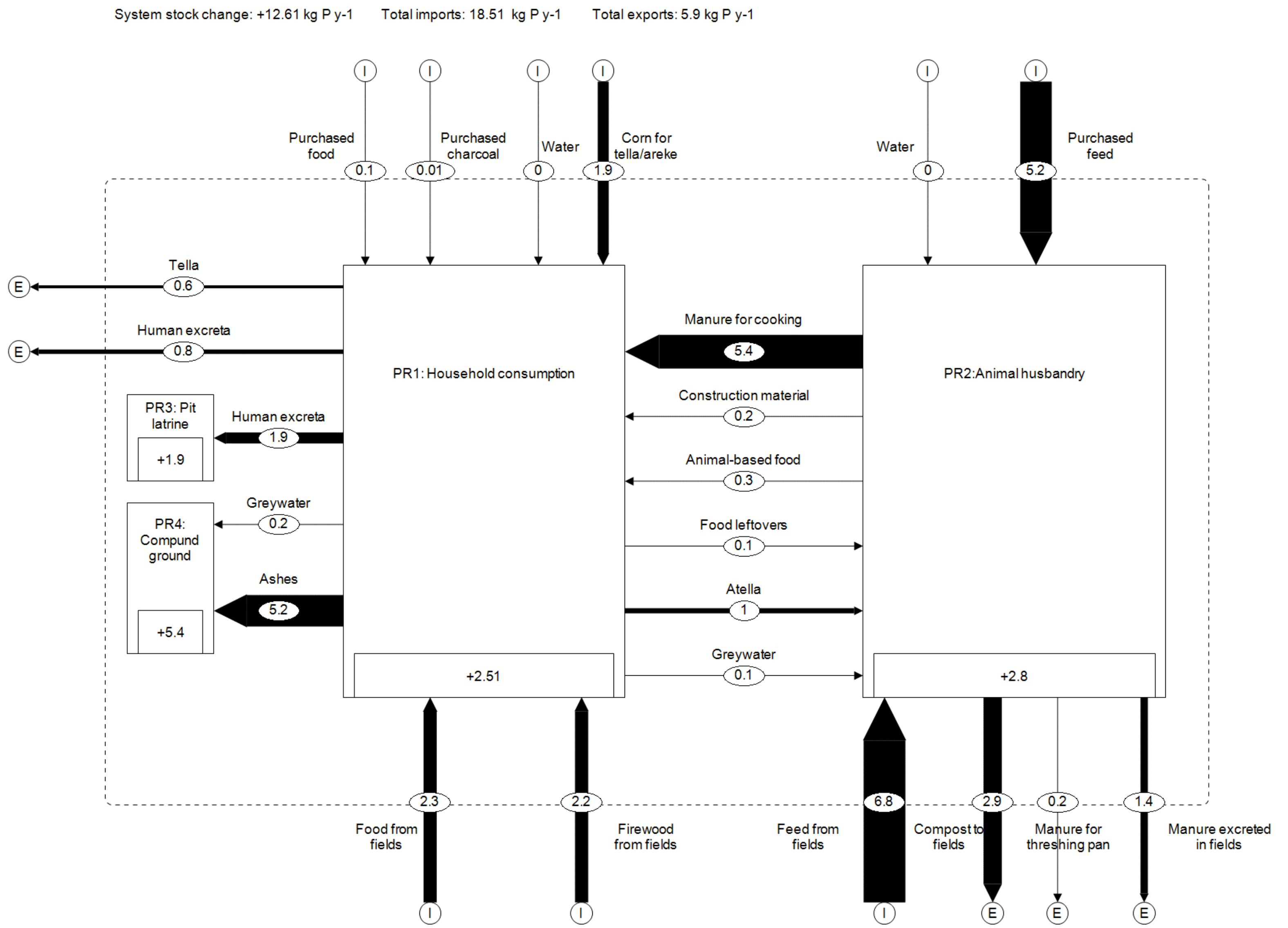


Figure 38. MFA diagram of the hh system showing flows of P in kg per year

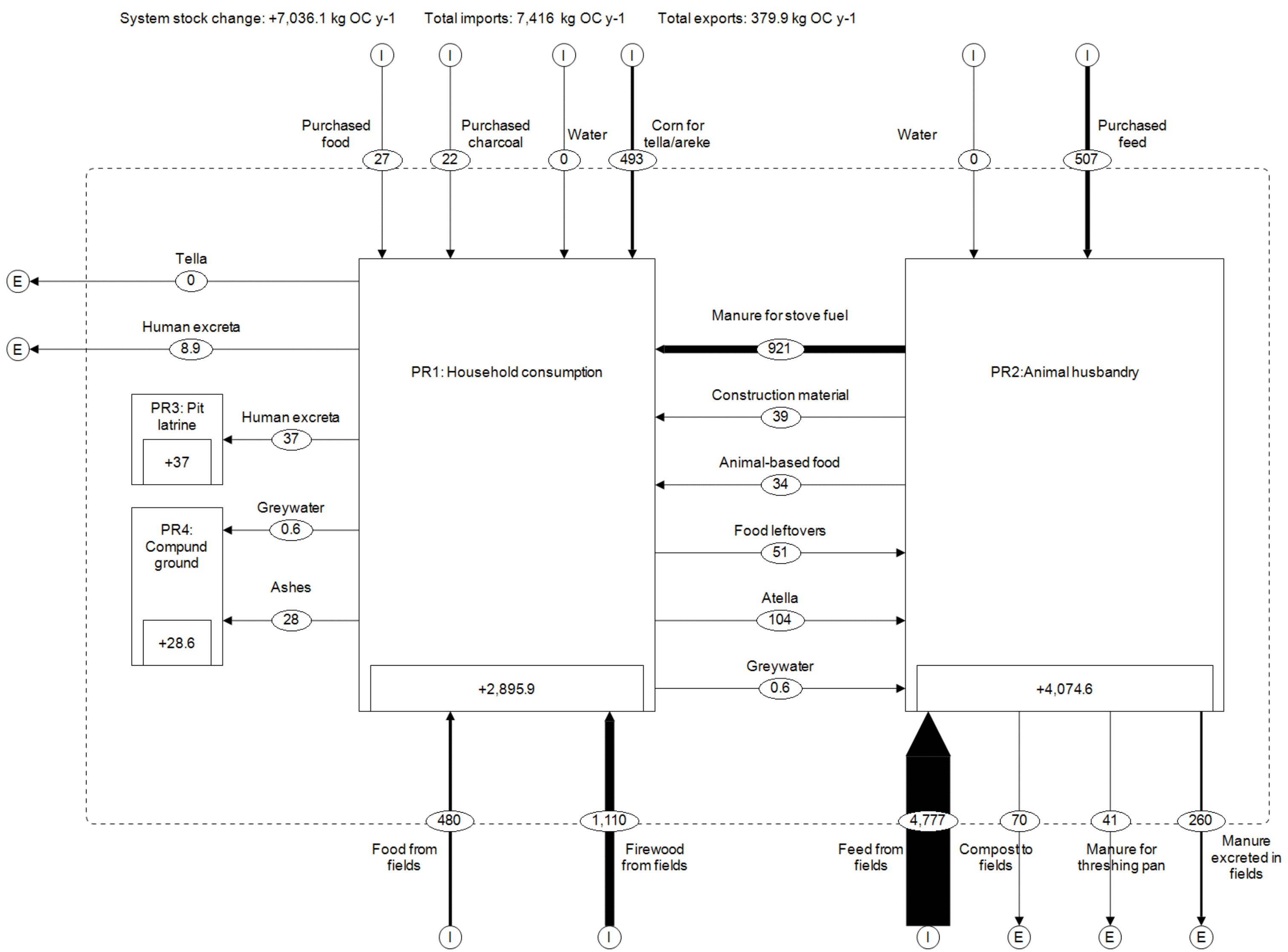


Figure 39. MFA diagram of the hh system showing flows of OC in kg per year

Once a substance is imported to the system it can take different pathways, either accumulating within the system or being exported through goods and by losses. For instance, ashes ending up in the compartment of *compound ground* results in an accumulation of P, and manure excreted in the fields will imply the export of all three substances from the system.

For all three substances, the accumulation outranges the sum of export flows *(Table 8*). The accumulation within the system is highest for OC (95%), followed by N (86%) and P (68%). For P, the accumulation within the compartment of household consumption relatively low (14%), while it accumulates 41% of N and 39% of OC. The largest accumulation of P is instead found at the compound ground where the ashes terminate.

Table 8. Distribution of imported substance (N, P and OC) into export flows and into processes

	Distribution of imported substance		
Exports	N	P	OC
Ex1: Tella	0.25%	3.2%	0.01%
Ex2: Human excreta	2.7%	4.3%	0.12%
Ex3: Compost to fields	2.8%	15%	0.94%
Ex4: Threshing pan manure	1.1%	1.2%	0.55%
Ex5: Livestock excreta excreted in fields	7.0%	7.5%	3.5%
Total exports	14%	32%	5.1%
Accumulation			
PR1: Household consumption	41%	14%	39%
PR2: Animal husbandry	33%	15%	55%
PR3: Pit latrine	12%	10%	0.5%
PR4: Compound ground	0.81%	30%	0.4%
Total accumulation	86%	68%	95%
TOTAL	**100%**	**100%**	**100%**

The MFA diagrams for the hh system *(Fig. 37-39)* show the flow sizes of N, P and OC related to the average study hh. The sizes of imports, exports and accumulations however differs substantially between the three socio-economic groups. The accumulation of N, P and OC for the worse-off group is 54-56% of the average hh while the better-off have an accumulation 139-151% of the average hh, depending on substance *(Table 9)*. A detailed table including all the flows for the three different substances and the three different socio-economic groups and is found in *Appendix 3*.

Table 9. Sizes of import, export and transport flows along with stock change for the three different socio-economic groups and three different substances studied (N, P and OC)

	N				P				OC			
	W-o	Mid	B-o	Av hh	W-o	Mid	B-o	Av hh	W-o	Mid	B-o	Av hh
Tot. imports (kg y^{-1})	73.8	141	192	136	9.4	18.7	27.1	18.5	3810	7460	10990	7420
Tot. exports (kg y^{-1})	8.0	18.9	29.1	18.7	2.4	7.1	8.1	5.9	128	390	623	380
Stock change (kg y^{-1})	**+65.8**	**+123**	**+163**	**+117**	**+7.1**	**+11.6**	**+19.0**	**+12.6**	**+3680**	**+7070**	**+10360**	**+7040**

W-o= worse off hh, Mid = middle hh, B-o = Better-off hh, Av hh = Average study hh.

5.3.3 Potential N, P and OC contributions to farmland by resources and wastes

Knowing the quantities produced of different goods and their respective concentrations of N, P and OC, their potential contributions to farmland could be estimated *(Table 10; Fig 39-40)*. Together, they were found to nearly reach up to the current application of N, but not of P. For OC, the potential contributions clearly surmount the current application levels.

Livestock urine is not collected today, and the prospects of starting to do so have not been investigated in this study. Further, the N and P concentrations in livestock urine have not been empirically measured in Bolo Silasie. The figures of potential contribution by livestock urine do consequently have a higher uncertainty than the data on the other goods. Due to the apparent excess of straw within Bolo Silasie, 10% of the total production was included in the list as a possible soil amendment.

Table 10. N, P and OC leverage per ha, by current or potential soil amendments and fertility management practices

Management practice or strategy	Contribution (kg/ha)		
	N	P	OC
Current amendments			
NPS, current application	24	26	
Urea, current application	27		
Manure compost, current application	2.3	1.4	44
Livestock tethered in fields	5.9	0.9	163
Application through threshing pans	0.9	0.15	25
Potential amendments			
Manure, currently used as stove fuel	16.4	3.4	576
Livestock urine, excreted at homestead[2]	5.9	<0.1	
Human urine collected in latrines	7.1	0.84	
Human faeces collected in latrines	2.7	1.3	24
Household ashes	0.4	3.2	18
Household food leftovers and food residues	1.3	0.1	32
Household *atella* production	4.6	0.60	65
Household kitchen greywater	0.3	<0.1	0.4
Straw, 10% of total production	2.1	0.32	230
Other practices			
N-fixation by legumes[3]	18		
Sum current amendments	60.1	28.5	232
Sum potential amendments + current organic inputs	49.9	12.4	1080

Calculations based following figures from Bolo Silasie Kebele Statistics (2019); Total area of Bolo Silasie farmland: 1837 ha; number of hh: 1143; number of inhabitants: 5753; number of TLU: 3361. [1)] Conversion from protein intake in feed, Šebek et al. (2014) and WHO/FAO (2005), given that 24% of N is found in urine (chapter 6.2.2) and 85% of the day is spent home (chapter 5.2.5), [2)] Rufino et al. (2006); Gustafson & Olsson (2004), [3)] Haileselassie et al. (2005)

The potentials of nutrient and OC recovery depend on amendment ambition and interchangeability of the different goods. *Atella*, food leftovers and manure used for firewood are goods that already have a function, why they might have a low relevance as soil amendments. Ashes might on the other hand not be suitable for application due to alkaline properties. *Fig. 42* show the potential applications if these goods are not considered.

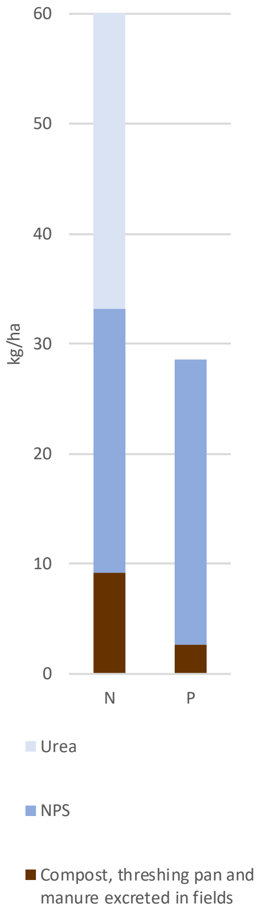


Figure 40. Current application of N and P (kg ha^{-1}) by mineral and organic fertilisers, average applications for 2017-2018 (*Bolo Silasie statistics)*

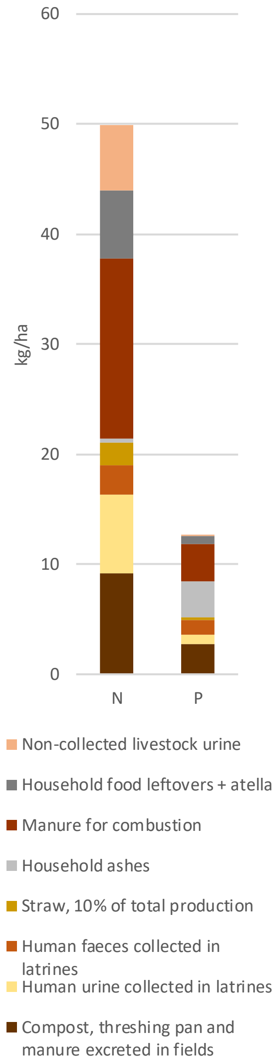


Figure 41. Potential contribution of N and P (kg ha^{-1}) by farm household resources and wastes, including livestock urine

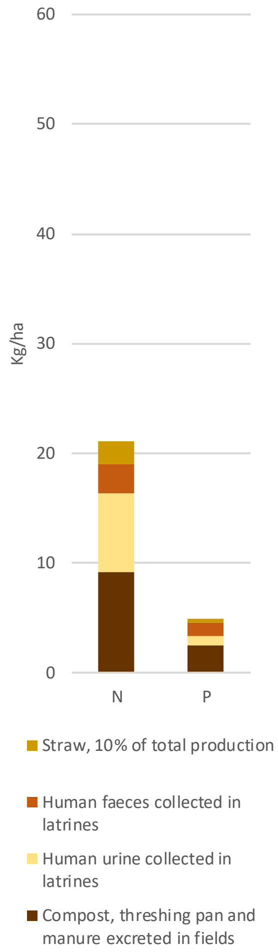


Figure 42 Potential contribution of N and P (kg ha^{-1}) by farm household wastes that today lack current alternative use. Livestock urine and ashes not included

5.4 Soil characteristics and management strategies

5.4.1 Current soil management and perceptions on fertility

The interviews showed that less than half the study hhs had applied manure compost to their fields the preceding year. None of the worse-off households applied compost. When examining the average application rates for the study hhs *(Table 11)* two features can be highlighted. Firstly, the variation in application is large, which only in part is explained by the fact that 53% of hh applied 0 kg/ha. The average application rates among the households that *did* apply compost was 772 ± 864 kg/ha. Secondly, the application rates are considerably lower than the local DA recommended doses of 10 000 kg ha^{-1} (Buta 2019). The compost application recommendations are however designed for a fertilising strategy based solely on organic inputs and can be compared with the mineral fertilizing strategy recommendations of 100 kg NPS and 100 kg urea ha *(Table 12).* These two strategies supply about the same amount of N (~65 kg ha^{-1}) but the mineral strategy adds less P and no organic carbon.

Table 11. Application of compost to farmland and correspondent input of N and P, average ± standard deviation

	Worse-off (n=5)	**Middle** (n=5)	**Better-off** (n=5)	**All** (n=15)
Hh applying compost	0%	80%	60%	47%
Total compost application by hh (kg)	0 ± 0	846 ± 515	823 ± 860	556 ± 711
Compost application per ha (kg ha^{-1})	0 ± 0	691 ± 1080	265 ± 243	348 ± 730
N-input by compost (kg ha^{-})	0 ± 0	4.6 ± 7.2	1.8 ± 1.6	2.3 ± 4.9
P-input by compost (kg ha^{-})	0 ± 0	3.6 ± 5.6	1.4 ± 1.3	1.8 ± 3.8

According to local statistics, the average Bolo Silasie household applies more NPS and less urea than recommended by the local agricultural extension workers *(Table 12).* The application of manure compost corresponds to no more than 3.5% of the recommended application dose.

Table 12. Recommended and current average application of mineral and organic fertilisers in Bolo Silasie

	Recommended Mineral strategy (kg/ha)				**Recommended Organic strategy (kg/ha)**				**Current practice (kg/ha) Mixed strategy**			
	Product	N	P	OM	Product	N	P	OC	Product	N	P	OC
NPS	100	18	20	0					142	24	26	0
Urea	100	46	0	0					56	27	0	0
Compost					10 000	67	52	1260	348	2.3	1.8	44
TOTAL		64	20			67	52	1260		53	28	44

On average, worse-off farmers do not apply less mineral N or P than the other wealth groups. The mean hectare receives 53 kg N ha^{-1} and 27 kg P ha^{-1}, which is 83% of recommended N and 135% of recommended P. Given that fertilisers are applied in equal amounts on all land, the partial nutrient balance for the two most common crops, teff and wheat, are -22 kg N ha^{-1} and +9 kg P ha^{-1} for teff and -92 kg N ha^{-1} and +5 kg P ha^{-1} for wheat. The partial nutrient balance is based on N and P in current amendment practices, local statistics on grain yields, HI for teff and wheat (source) and N and P concentration determined by lab analyses. In the calculation, all crop residues are assumed to be removed from the fields while in reality 10-15 cm of straw base is left in the fields and incorporated to the soil when ploughing.

In the interviews, 62% of hh responded that the soil fertility of their land has decreased since they started farming. Erosion and low inputs of organic fertilisers were mentioned as reasons for the decline. 23% of hh responded that they cannot see any change in soil fertility, and 15% responded that soil fertility has improved since they started farming. All the interviewed hh practiced crop rotation, and none of them practiced fallow nor burned cereal stubble or other crop residues in the field. Since a couple of years back, B and Zn deficiencies identified in the local soils (Ethiopian Agricultural Transformation Agency 2016) are mitigated by B and Zn supplements in the locally distributed NPS fertilisers (Bolo Silasie Local Statistics).

5.4.2 Soil status for the study households

Of the sampled fields, 22 of 24 are classified as clay soils, while the other two are classified as clay loam and loam. SOM is low to moderate and both total N and available P are low. The soil pH for the 24 fields ranges from 7.0 to 8.3, most fields having pH around 7.5 (mildly alkaline). In general, the soils have a high CEC *(Table 13*). According to interviews and local statistics on fertiliser use (Bolo Silasie Kebele statistics) there is no application of K to Bolo Silasie soils other than from organic sources. Available K is however classified as very high.

Table 13. Mean, median and range for analysed soil parameters, including interpretation of values

Parameter	Mean	Median	Range	Interpretation of mean
Sand (%)	23	22	18 – 48	
Clay (%)	47	48	26 – 58	} Clayey soils
Silt (%)	30	29	24 – 38	
pH	7.5	7.4	7.0 – 8.3	Mildly alkaline (Bruce & Rayment 1982)
EC (dS/m)	0.12	0.11	0.06 – 0.22	Non-saline (Richard 1954)
CEC (cmol/kg)	39	43	18 – 47	High (Metson 1961)
SOM (%)	2.29	2.22	1.57 – 3.29	Low (Kemper & Koch 1966)
SOC (%)	1.17	1.29	8.42 – 14.7	Low (Kemper & Koch 1966)
Total N (g/kg)	0.12	0.11	0.09 – 0.18	Low (Bruce and Rayment 1982)
Available P (mg/kg)	33	22	9.0 – 150	Low (Holford 1990)
Available K (mg/kg)	711	648	479 – 1220	Very high (Heckman 2006)
Available Ca (mg/kg)	6120	5920	3810 – 8850	Very high (Heckman 2006)
Available Mg (mg/kg)	831	823	217 – 1320	Potentially low due to high Ca:Mg ratios (Eckert 1987)
Available S (mg/kg)	8.3	7.4	6.0 – 17.1	Very low (Zbíral et al 2018)
Available Na (mg/kg)	17	14	11.0 – 79.6	Low (Metson 1961)
C:N	11.7	11.9	8.42 – 14.7	No restriction for N mineralisation (Brady & Weil 2002)
K:Mg	1.0	0.85	0.47 – 2.80	Risk for K deficiency at K:Mg < 0.70 (Hailu et al 2015

Texture: *Bouycous hydrometer*. pH & EC: *(1:9 soil to water)*. CEC: *Ammonium Acetate* SOC & SOM: *Walkley Black.* Total N: Kjeldahl, Available P, K, Ca, Mg, S, Na: *Mehlich-3 extraction*

According to interviews and local statistics on fertiliser use (Bolo Silasie Kebele statistics) there is no application of K to Bolo Silasie soils other than from organic sources. K values in the soil are high, why deficiencies would normally not be expected. However, the high Mg concentrations in the soil might induce K adsorption to clay mineral exchange sites, which in turn might induce deficiency of K (Hailu 2015). The K:Mg rations should not be lower than 0.7:1, which nonetheless is the case for eight of the studied fields *(Table 13).*

5.4.3 Soil management and fertility

The fields' soil parameters were evaluated according to four sets of field dichotomies; a) closest field/farthest field, b) reported "best field"/reported "worst field", c) threshing sites/non-threshing sites and d) fields belonging to hh applying compost/fields belonging no hh not applying compost *(Fig. 43)*. No statistically significant differences could be revealed in any of the comparisons. The largest tendencies to differences could be seen for the set of "best fields" versus "worst fields", were the perceived "best fields" perform better for all parameters. Threshing sites seem to perform well and exceeds the average values with 8-20%. The application of compost only seems to have some importance for P, while distances between fields and homestead do not seem to have a clear importance for any of the parameters.

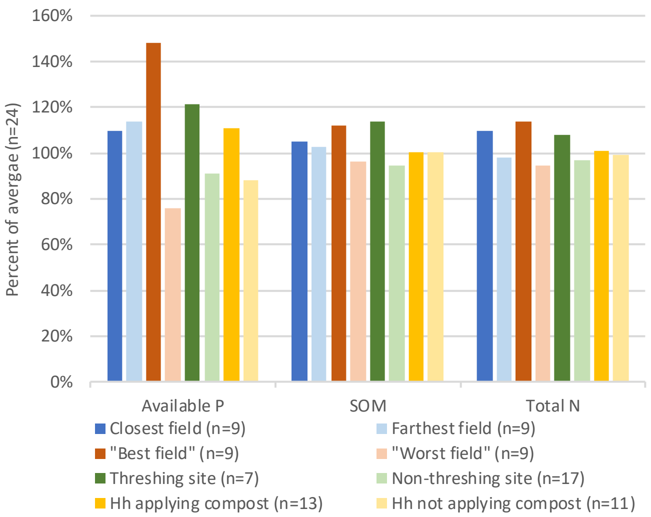


Figure 43. Available P (Mehlich), SOM and Total N for fields grouped according to the dichotomies a) closest/farthest, b) "best field"/"worst field", c) threshing sites-non/threshing sites and d) fields belonging to households applying compost/fields belonging no those not applying compost. Available P, SOM and Total N levels are shown as percent of the levels for the average field (n=24)

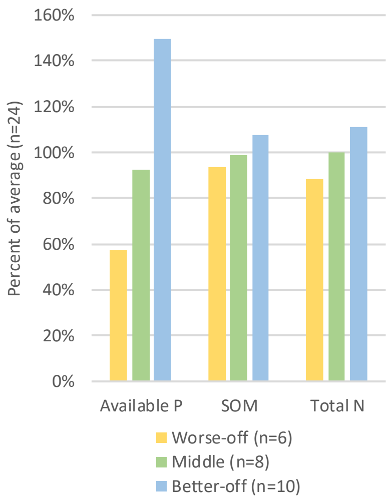


Figure 44. Available P, SOM and total N for fields grouped according to hh socio-economic group. Available P, SOM and Total N levels shown as percent of the levels for the average field (n=24)

The fields were also grouped according to hh socio-economic groups, and analysed for the values on TN, available P and SOM *(Fig. 44)*. Although all parameters show a uniform positive trend of higher values in the fields belonging to wealthier households, no statistical significance could be found. Significant positive correlations were however found between number of TLU and both P (p=0.0296) and TN (p=0.0456) *(Fig. 45 & 47)*, but not for SOM *(Fig. 49)*. No correlations could be determined in distance from homestead and SOM, total N or available P *(Fig 46, 48 & 50)*.

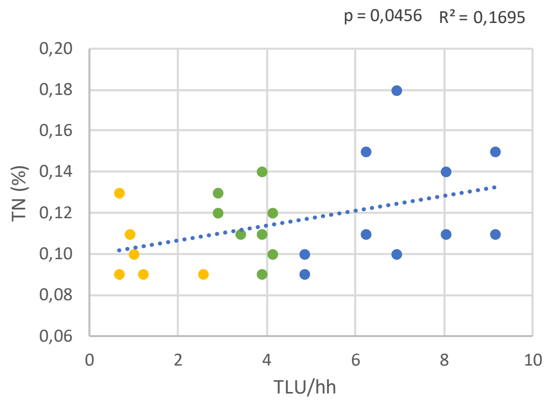


Figure 45. Linear regression of soil total N concentrations and TLU per hh

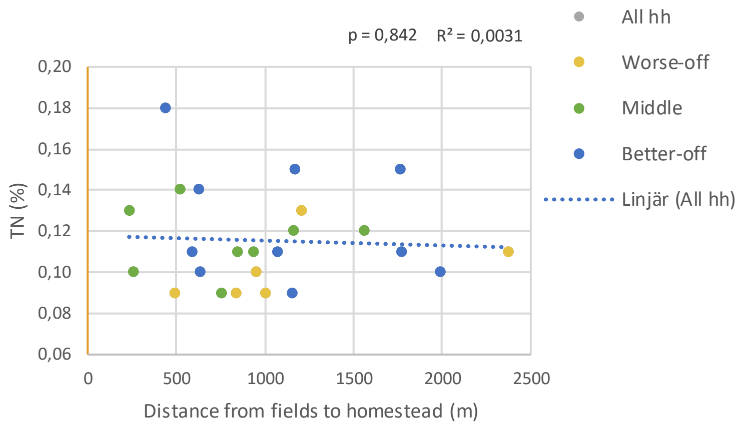


Figure 46. Linear regression of soil total N concentrations and distance from fields to homestead

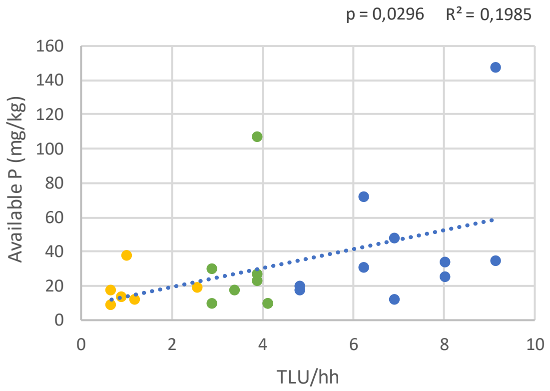


Figure 47. Linear regression of soil available P concentrations and TLU per hh

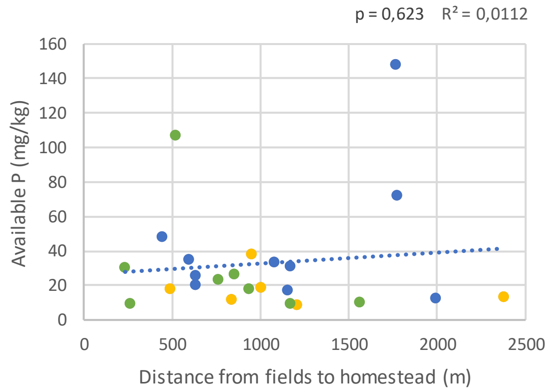


Figure 48. Linear regression of soil available P concentrations and distance from fields to homestead

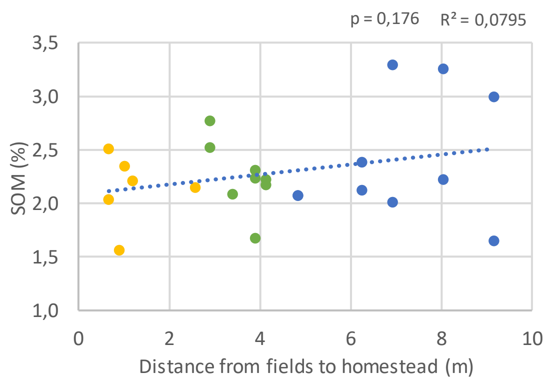


Figure 49. Linear regression of SOM concentrations and TLU per hh

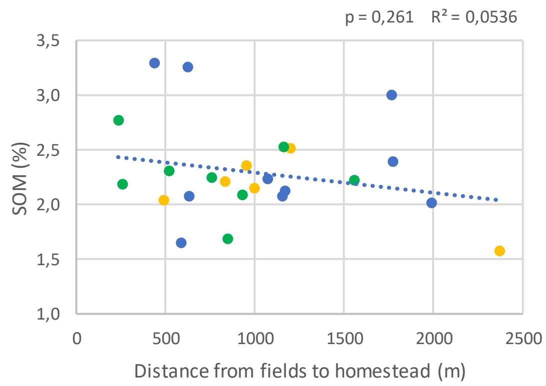


Figure 50. Linear regression of SOM concentrations and distance from fields to homestead

6 Discussion

6.1 Recovery potential from household resources and wastes

6.1.1 Water

In Bolo Silasie water is scarce and must be carried by animals from the community well to the hh. Still, the reuse of water is relatively small and restricted to dishwater being given to livestock. If the kitchen greywater collected in the study equals the true total production, this corresponds to no more than 2.5% of the total water consumption and 4% of the water given to livestock in the average hh.

Total N and TP concentrations for kitchen and laundry greywater substantially exceed the levels measured in Western localities (Almqvist et al. 2007; Oteng-Peprah et al. 2018). This may suggest that the total quantities of collected greywater, which at the first glace seem low, still might reflect a realistic scenario. Thus, that the concentrations of food leftovers and dirt (the sources of nutrient in greywater) are higher simply because Bolo Silasie hh use less water when making laundry and washing up the dishes. Despite high concentrations, the total amounts of N, P and OC in the two types of greywater studied are however very small compared to other nutrient flows on the farm (*Fig. 37-39, p. 53-55)*. Greywater will thus not play any important role neither as soil amendment nor as nutrient provider in livestock feed. Nonetheless, water transferred from the household to the livestock system means less water to fetch at the community standpipe, which saves both water and time.

The positive correlation between total water consumption and number of TLU was naturally expected in contrast to what other pattern could be found: that water consumption for personal needs is also significantly higher the higher economic status of the hh *(Fig. 17, p.39)*. For the better-off group, this pattern is explained by the fact that better-off families are generally larger than the two other groups. The reasons for the substantially lower water consumption for personal use among the worse-off group have not been examined in this study but might be related to the lower access to livestock for water transport among this group, which indirectly also affect the access to water from the community standpipe. Water consumption patterns for the three wealth groups hence exemplifies how economic status will affect hh resource management practices in ways that might not be understood or recognized at a first glace.

6.1.2 Human food and excreta

According to interview data, Bolo Silasie inhabitants have a slightly higher calorie intake and a higher protein consumption than the average Ethiopian (FAO stat). If interview responses reflect reality, it implies that human excreta will also contain higher total quantities of P and N than the excreta from the average Ethiopian person. The N and P content in human excreta in Bolo Silasie is known since before (Dagerskog 2017) and can be converted into corresponding protein intake (Jönsson et al. 2004). Such a conversion however suggest that the villagers have a protein intake rather similar to the average Ethiopian and that food consumption reported in the interviews might be somewhat exaggerated.

Human excreta are together with livestock urine and ashes the least exploited hh wastes and their use are restricted to human urine sporadically being applied to straw to increase fodder palatability for livestock. An estimated 19% of the human excreta is deposited outside the homestead, while the majority stays within the household and *could* have a nutrient recovery potential. Until recent years most Bolo Silasie hh practiced open defecation, often at the homestead maizefield (Dagerskog 2019, p. com). During the last decade there has been a rapid installation of pit latrines in Bolo Silasie, resulting in that nearly all households own one by today (Chaix-Bar 2014). While pit latrines have a potential in improving sanitation by decreasing open defecation and its associated risks, they also have relatively high nutrient losses through leaching, volatilization and denitrification (Jacks et al. 1999; Montangero and Belevi 2007). The remaining N in abandoned pit latrines were estimated to no more than 15-20% of the original content, when studied in Botswana (Jacks et al. 1999). In addition, pit latrines are not designed to be emptied. Urine-diverting toilets offer a simple solution for nutrient recovery from human excreta by enabling collection of urine alone, which can be used as soil amendment after a short storage period (Jönsson et al. 2004; Morgan 2007). Additionally, the dryer states the faeces will have when not mixed with urine makes the handling easier. Urine-diverting toilets that last for decades can be constructed by simple means and relatively low financial inputs (Morgan 2007).

In an earlier study of the potential for urine recycling in Bolo Silasie encompassing 112 farmers (Chaix-Bar 2014), 80% answered that they were interested in trying urine as fertiliser after being presented to the concept, and 96% said they would eat crops grown with the application of urine. One major obstacle is however the relatively small economic benefit that the utilization of urine brings. Farmers in Bolo Silasie in have in earlier studies mentioned the moneysaving aspect of using urine as a fertiliser (Chaix-Bar 2014). The economic value when replacing mineral fertiliser with one person's yearly production of urine and faeces is around 7 USD (Dagerskog 2017). For the typical Bolo Silasie family, this value corresponds to 35 USD for the average family which represent 32 kg NPS or 40 kg urea (conversion from local prices; Dagerskog 2019 p. com), a substantial share of what is being purchased today. It can be costly and cumbersome to store, transport and apply the large volume of urine produced. Alternative ways to enhance urine reuse could be to encourage the tradition of urinating on straw to enhance fodder palatability or to add urine to the FYM compost (Dagerskog 2019, p. com) or introduce methods for urine-drying. Other challenges in nutrient recovery from urine include local perceptions that the smell of urine brings the common cold and worries for low acceptance from neighbours (Chaix-Bar 2014).

6.1.3 Livestock feed

Today, livestock in Bolo Silasie largely depend on external resources (purchased *fino* and *fagullo*) *(Table 5, p.43),* while farm resources, such as straw, are not fully utilized. Theoretically, there is a considerably higher production of straw than what is consumed within the village. There might therefore be a potential of having larger numbers of TLU in Bolo Silasie, and thus higher manure production, without larger imports of animal feed. Straw has a lower protein content than other feed types and increasing the share of straw might however affect the livestock growth and overall health (Qi et al. 2003). Another option for a straw management that would be beneficial for soil fertility is using it as bedding material, something that is not done today. Excessive straw as kraal bedding in Mali has shown to potentially double the produced FYM with the same to the amount of dung excreted (Defoer et al. 2000). Nzuma & Murwira (2000) also show that bedding reduced ammonia volatilization with more than 80% in kraals in Zimbabwe. Straw could also be directly incorporated into the soil, preferably together with a concentrated N fertiliser, such as purchased urea or hh urine. Increasing the use of straw would however oppose the local idea of saving up straw for repeated low-yielding years, a practice that is an important aspect of the villages both real and perceived degree of self-subsistence and resilience.

The custom of giving all cooking residues and food leftovers to the animals expose a resource-efficiency characterising the whole resource management system in Bolo Silasie. In absolute quantities, the contributions to livestock feed from these fractions are nonetheless small, and almost negligible from a nutrient and OM perspective (*Figure 37-39, p. 53-55*). For the families that produce large quantities of *tella* and *areke*, however, the by-product *atella* plays a rather important role in the animal feed composition (*Table 5, p.43*).

6.1.4 Livestock excreta

Livestock excreta have a central role for the Bolo Silasie farm hh resource management, both in its current use and in its potential value as soil amendment. Today, the field application rates of manure are low in relation both to what is recommended *(Table 12, p.60)* and to what is actually produced on the farms *(Fig 29, p.47)*. Assuming a constant number of TLU, an increased nutrient recycling from the livestock husbandry system to the fields could be done either by increasing the share of manure used as soil amendment or by reducing nutrient losses in the storage of manure. Considering the current rates of application (19% of the total manure available (*Fig. 25, p.44*)) the effects from reducing losses will have fairly little importance as long as the application rates used does not increase.

While the inputs to the animal husbandry system are 90 kg N, 13 kg P and 5440 kg OC, only 15 kg N, 4.5 kg P and 370 kg OC is returned to the soil through compost application, threshing pan preparation and manure excreted from animals tethered in the fields (*Fig 37-39, p.53-55*). Out of these three, only compost application can be understood *primarily* as a soil amendment strategy. Earlier studies from the Kenyan highlands have shown that the manure application potentials are higher for smaller farms than for larger, mainly because of higher livestock densities on small farms (Lekasi et al. 2001). In Bolo Silasie, TLU and land tenure follow a positive linear relationship, which imply that the potential manure application rates per hectare are relatively similar for the different farm sizes with a small dominance for the middle group *(Fig. 30, p.47)*. However, since most manure is used as stove fuel, the real application rates for the hh were remarkably different. Worse-off hh use more manure for fuel than they produce themselves, resulting in zero application potential *(Fig. 31, p.47)*. At current management practices, the middle hh group result to be the group with largest application potential in kg manure per hectare, which is however still low compared to the recommended application rates *(Table 12, p.60*). The low field application rates of manure, not least among poor families, are also described in Mekonnen & Köhlins (2008) study on manure used as stove fuel in the Amhara region in Ethiopia.

While the manure application to farmland is low due to alternative uses for manure, livestock urine is not collected at all. Some urine is deposited in the fields by tethered animals, but most of it is deposited at the homestead kraal. Although urine temporarily add some nutrients to the FYM, studies show that it does not have any lasting effect on N and P levels (Lekasi et al. 2003).

The hh practicing composting put the manure in heaps or pits without roofs, cover or impermeable floors and normally store the manure for over two years, according to interviews. Such management have shown to lose 75% of N and 60% of P already after six months when studied in Kenya (Tittonell et al. 2009). The practice of adding ashes to the compost increase the pH which may further increase N losses volatilization (Hao & Benke 2008). Analyses show that compost pits in Bolo Silasie have a pH of 9.0 (Dagerskog 2014) that might be related to the addition of ashes that various hh reports. High losses of N are for various reasons expected from the compost pits.

6.1.5 Cooking fuel and ashes

Food preparation is one of the more resource consuming activities in Bolo Silasie hh today, having high N, P and OC inputs and almost no outputs with a productive use. Today, 77% of the stove fuel biomass used by hh is comprised by manure although other biomass resources do exist *(Fig. 34, p.48).* It was however not assessed in this study to what extent firewood could replace manure without negative ecosystem impacts, or what other fuel sources could serve as a substitution. The stove types used in Ethiopia today are highly energy inefficient (Dresen et al. 2014). There have been various studies on improved cooking stoves (ICS) both for injera and other food preparation in Ethiopia that have shown a good potential to decrease the biomass demand. High perceived price and a sense of non-scarcity of local fuel biomass resources are two constraints mentioned for their adoption (Dresen et al. 2014; Mamuye et al. 2018).

Charcoal enables indoor cooking and not least indoor coffee preparation which is an important part of the everyday life and culture in Ethiopia. Still, charcoal is a very resource inefficient type of stove fuel, especially when being prepared with the low turnout rates typical for low-technological homestead charcoal preparation (Okello et al 2001). Moreover, FYM is often used as cover material used for charcoal production, which further amplify the losses of N and OC from the farm system.

Other than some sporadic application to compost, ashes lack a current function within the hh system. Since biomass contain micronutrients that are not lost in combustion (Cox et al. 2001), ashes from manure do most likely contain valuable elements that are overlooked today.

6.2 The pathway of nutrients and OC

6.2.1 Where did it all go? - Interpretation of the MFA

The MFA diagrams of the hh system (Fig. 37-39) display all known imports and exports of substances. There are however various expected losses that are not included as export arrows, such as N ad OC lost in combustion or leaching of N and P from compost heaps. Due to lack of data of the sizes of such losses, these export flows remain unaccounted for in the MFA diagrams and calculations.

Table (p.56) displays how the imported substances are distributed on export flows and accumulations within hh processes. The differences in accumulation in *PR1: Household consumption* between OC (39%), N (41%) on the one hand and P (14%) on the other, suggest that there are exports flows of N and OC that are not currently included in the model, and that these flows are not exporting P in the same extent. In combustion of biomass will nearly all N and OC be lost, while P stays in the ash fraction. At the compound ground we thus find less than 1% of N and OC, but 30% of P. It is thus likely that a large share of what looks like an accumulation of N and OC within the process in actually are losses from the system.

Similar losses occur within the other processes, although many unknown variables make the size estimation of these losses difficult. From *Process 3: pit latrine* and *Process 2: animal husbandry* there are constant losses of N, P and OC from excreta through ammonia volatilisation, OC decomposition, denitrification and leaching. The accumulation within *PR2: Animal husbandry* might be related to growth of livestock, accumulation within PR1 might to a small extent reflect human growth. Some accumulation might also be related to inaccuracies in the collected data. To some extent there *is* however an accumulation of nutrients, in compost pits that are not fully used, in pit latrines and in piles of ashes, although the size of this accumulation is not possible to estimate with the data available. Regardless if the accumulation within the different processes reflect losses or for real accumulation, it is evident that the ratio of imported nutrients that are recycled back to the agricultural fields is very low and according to the hh system MFA *(Fig. 37-39, p. 53-55)* no more than 11% of N, 25 % of P and 5.0% of OC *(Table 8, p.56).*

The imports, exports and stock changes of N, P and OC for the three different socio-economic groups show that while the numbers for the average hh and the middle group conform well, there is a considerable deviation between the average of the two other groups *(Table 9, p.57).* Due to large differences in hh resources, the stock change (i. e. accumulation) is more than 2.5 times higher in the better-off hh than in the worse-off. Consequently, the average hh presented in the MFA diagrams *(Fig-37-39, p. 53-55)* fails to describe a large part of Bolo Silasie hhs accurately and might both overestimate and underestimate the flow sizes and their implications if treated as a map for any given Bolo Silasie hh.

6.2.2 What if it came back? – comments on potential recovery

Could the current soil amendment strategy based mainly on mineral fertilisers be replaced with a strategy based merely on farm hh resources? Today, the average Bolo Silasie hectare of farmland receives 51 kg N y^{-1} and 26 kg P y^{-1} from mineral fertilisers and additionally 9.21 kg N y^{-1} and 2.5 kg P y^{-1} from compost, threshing pans and livestock tethered in the fields *(Table 10, p.58).* If aggregating the current manure inputs with all household resources and wastes they would contribute with 49.9 kg N ha^{-1} and 12.4 kg P ha^{-1}. This calculation takes into account nutrients from the manure that currently is used as stove fuel, food leftovers and *atella* that are given to livestock and the ashes, even though they are unsuitable for soil application due to their alkaline properties. Around the half of the ashes (0.2 kg N and 1.6 kg P) are also counted twice, since they currently derive from manure. If manure, food leftovers, atella and ashes (goods that currently have alternative uses or considered unsuitable as soil amendment) are subtracted from the calculations, the potential application is reduced to 18 kg N ha^{-1} y^{-1} and 2.5 kg P ha^{-1} y^{-1} *(Table 10, p. 58).* These two calculations take into 10% of total straw production and livestock urine, goods that is not used as fertilisers today today. Livestock urine has possibly a high potential as N fertiliser, while the P contribution is probably low. This study did not measure the repartition of N and P between urine and dung from livestock, why its potential value is more uncertain than for the other, empirically studied goods.

The variation in repartition of N and P in urine and faeces is high and depends on feed composition and total protein intake (Luo & Kelliher 2014; Snijders et al. 2009). In a literature review of mainly SSA livestock systems by Rufino et al. (2006), the faecal N production for steers is between 30-50 g N TLU^{-1} (based on 18 cases). Given that this range is valid also for Bolo Silasie and considering the measured feed N intake of 44 g N TLU^{-1} day^{-1} (conversion from 63 g N in feed intake (Šebek et al. 2014), one would expect the remaining 0-14 g N in the urine, or 0-47% of excreted N. The average of this range of urinary-N (24%) in somewhat lower than the percentage of urinary-N estimated by Rufino et al. (2006) for the case of milk cows in Ethiopia fed with hay. The repartitioning of P in urine and faeces seem to be even less studied, especially in the SSA context. Knowlton & Herbein (2002) estimate the P in urine for dairy cows in the United States to in be 1-3%, while Gustafson & Olsson (2004) measured 0.3-1.2% for growing dairy-breed steers. Urinary-P will thus most probably have a negligible role as soil amendment (Fig. 41, p.59). For N however, it would make a considerable contribution. Without livestock urine, the potential of currently available resources is reduced to 19.8 kg N ha^{-1} y^{-1}.

6.3 Soils of Bolo Silasie

6.3.1 Interpretation of general soil properties around Bolo Silasie

Vertisols, the predominant soil type in Bolo Silasie, are soils with moderate to high agricultural potential. Major constraints for agricultural production in Vertisols include waterlogging and water erosion due to low infiltration through the clayey soil profiles (FAO 1984). Erosion and standing water were also constraints described and managed by several of the study hhs *(Fig. 51)*. With improved drainage and tillage practices, vertisols have been stated to be among the SSA soils with highest productivty potential (Mamo et al. 1993).

Figure 51. Field edge bunds and open ditches for drainage and erosion control can be seen at some fields around Bolo Silasie

Except for the two fields with loamy soils, most fields exhibited high CEC levels, which are more likely to derive from 2:1-layer clay minerals characteristic for Vertisols (Virmani et al. 1982) than from the relative low levels of SOM. A high CEC indicates high nutrient holding capacity and resistance against acidification. The risk for acidification in Bolo Silasie soils is nonetheless small, with current pH levels of 7.0 - 8.3. Instead, nutrient deficiencies might be induced by the high pH. B and Fe are becoming less available at pH >7.5, Cu at pH > 8.0, and P at pH > 8.5 (Hazelton & Murphy 2007). Risk for phosphorus fixation due to high pH should only be a risk for a few of the fields above pH 8. Regardless, phosphorus fixation processes are likely to occur in the local soils due to the mineral composition of Vertisols (Hailu et al. 2015).

Farmers in Bolo Silasie are applying on average 35% more P than the recommended. Due to the P fixing properties of Vertisols along with P losses through erosion and runoff common for Vertisols, the turnout in plant available P concentrations might however be low, which is also indicated by the low levels of available P found in the analyses *(Table 13, p.63)*. Hailu et al. (2015) remark that low responses to P application in Vertisols in the central Ethiopian highlands might also be due to the low availability of other nutrients, such as S, Zn and Fe that can potentially limit plant growth regardless of levels of available-P. Locally, B and Zn have been identified as deficient, which is since a few years back treated with Zn and B enriched NPS fertilisers (Bolo Silasie statistics, personal communication, DA).

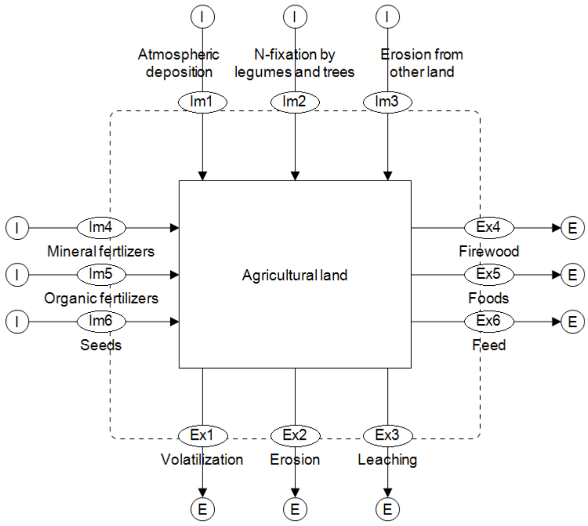


Figure 52. Conceptual model for full soil nutrient balance calculations. The horizontal flows represent those included in a partial balance calculation, while vertical flows should also be considered in a full nutrient balance calculation

Total N and SOM are closely interrelated soil parameters, since the largest stocks of nitrogen are normally found in organic forms (Bot & Benites 2005biri). In Bolo Silasie, TN and SOM levels are low for most fields. Tropical soils are generally low in SOM (FAO 1984) because of rapid decomposition rates at high temperatures. Low TN and SOM levels in Ethiopian highland Vertisols have as well been documented in various studies (Hailu et al 2015). Still, SOM rates in Bolo Silasie soils could arguably be expected to be higher than elsewhere in Ethiopia and higher than what the analyses show. While burning or removal of plant residues and straw stubble is a common practice in the central Ethiopian highlands (Ibid.), stubble is in Bolo Silasie left in the fields until incorporated to the soil at ploughing. The relatively high yields, 1.5 t ha^{-1} higher than the Ethiopian average, implies high biomass production also belowground which contribute to larger SOM stocks than in low-yielding areas (Berhongaray et al. 2019).

6.3.2 Nutrient balances

A partial nutrient balance can be established by comparing solely the nutrients exported by harvested biomass with the nutrient applied, such as done in chapter 5.4.1, *(p. 61)*. A full soil nutrient balance calculation including all inputs and output would however be required to assess whether Bolo Silasie soils are being depleted or enriched in N and P. Other than the partial balance calculation, such calculation takes into account atmospheric deposition, N-fixation by legumes, erosion, gaseous emissions and leaching *(Fig. 52, p. 74)*. The importance of those processes should not be underestimated. When performing full soil nutrient balances of the whole country of Ethiopia, Haileselassie et al. (2005) concluded that the major nutrient losses of from agricultural soils in the country were related to erosion, and that these losses were manifold higher than the outtake by harvested biomass.

Apart from what nutrients flow into and out of the system, the availability and offtake of N and P also depends on in-situ soil dynamics. There will for instance be considerable yearly mineralisation of organic N, while P dynamics will be determined by various processes of adsorption and mineralisation (Shen et al. 2011).

Although no full balance calculations have been made within this study, a few conclusions of nutrient balances can still be drawn from the information on current soil amendment practices. Firstly, the application rates compensate for the offtake P, but not for N. Neither would the recommended doses of mineral fertilisers compensate for the N offtake in harvested biomass. Secondly, from what is known about the local soils and their P-fixating properties, the seemingly too generous application rates of P *(Table 12, p. 60)* might still have a rationale since not all applied P can be expected to be available. From the soil analysis, available P was very variable, but low in in average. Thirdly, the applied nutrients are limited to N, P, S, and to a smaller degree also to Zn and B, while the offtake in harvested biomass will be of all essential plant nutrients. Basing a fertilisation strategy merely on mineral fertilisers are hence likely to cause nutrient deficiencies in the long run, although the risk for severe depletion of base cations is unlikely considering the current high levels.

6.3.3 Soil management practices and fertility

Total N, available P and SOM concentrations in soils are parameters that are largely determined by soil management and inputs of mineral and organic fertilisers (Buresh et al. 1997; Tittonell et al 2013; Yimer et al. 2007). Since it is more labour intensive and time consuming to apply fertilisers, not at least voluminous compost, on distant fields than on fields close to the homestead, the TN, available P and SOM was expected to decrease with distance from homestead. Such relation has been documented in literature covering SSA smallholder farms (Defoer 2000; Tittonell et al. 2013; Zingore et al. 2007) but could however not be determined by the data collected in this study (*Fig. 46, 48 & 50, p. 64*). One possible explanation is that manure today is applied in such low amounts that it does not play any substantial role for OC, N and P levels in the fields. Such a supposition would be supported by the minimal and non-significant comparison of fields belonging to farms applying compost with fields belonging to those who do not apply compost *(Fig. 43, p.63)*.

Figure 53. Fields from above at threshing times. Threshing sites are the larger round-shaped brown areas surrounded by a brighter circle of straw. Piles of straw look like bright bumps beside the threshing areas. *(Maps.google.com 2019-05-29)*

Although the application of manure compost is done to serve fertilising purposes, the practice of having livestock tethered or herded in fields was in the MFA calculations found to be more important for the recirculation of N and OC to the fields *(Fig. 37-39, p.53-55).* Livestock are normally tethered in the fields where threshing sites are built up at threshing times, and where piles of straw are stored. This should be one of the reasons for why the average field with a threshing site seem to perform higher in N, P and OC than the average field where compost is added *(Fig. 43, p. 63).* This relation could however be expected to be even more distinctive and does not show any statistical siginificance.

There are tendencies of higher N, P and SOM values in fields farmed by better-off households. The reason may seem obvious: better-off household should reasonably have better access to plant nutrients than the two other groups, both in access to expensive mineral fertilisers and in large quantities of manure excreted by their many TLU. Such correlations would further be supported by the positive relationships in number of TLU TN, P and SOM concentrations in the soil that were significant for TN and available P. The reported application of mineral fertilisers per hectare are however not higher for the better-off group. Even though they produce more manure, the larger land sizes imply that their theoretical application rates per hectare were not higher than for the middle groups. Earlier discussion furthermore concluded that current manure application plays only a little, if any, role for N, P and SOM concentrations in the fields. The positive relationship in higher nutrient and SOM the higher economic status can hence not be explained by current practices revealed by this study.

6.3.4 Soil application suitability of hh wastes and excreta

Earlier sections in the discussion have been focusing on the current or potential availability of different resources and wastes. Yet, their importance as soil amendments will be determined just as much by their suitability for application, a feature determined by the properties of both potential fertiliser substrates and soils.

Fresh manure normally contains high carbon levels, resulting in high C:N ratios that might induce short term deficiencies of N in the soil (Hazelton & Murphy 2007). *Kubet*, *fug* and FYM all have C:N ratios above 25, which implies slow decomposition not applied together with additional N. The same logic applies to straw. Although continuous incorporation of straw and other crop residues will have positive effects on SOM, the C:N ratio above 100 foretell that N will temporarily be locked up while the OM is decomposing. Mineral N fertilisers or urine, containing relatively high concentration of N but no or very little C would be a suitable complementing amendment. The composted manure has a C:N ratio of 19 which makes it appropriate for application and indicates a moderate decomposition rate, while human faeces and pit latrines however have C:N ratio of below 10 and a rapid decomposition can be expected (Hazelton & Murphy 2007).

The soils around Bolo Silasie are slightly alkaline which may affect the availability of micronutrients like B and Zn (Hazelton & Murphy 2007). Ashes are rich in micronutrients, not least B (Cox et al. 2001), and could be anticipated as highly suitable as soil amendment. Applying alkaline ashes might however exaggerate the soil alkalinity, at least short-term, which somewhat paradoxically could further decrease the availability of micronutrients. Likewise, because of increasing P fixation to Ca minerals at higher pH there is a risk that ash application would not increase the quantities of available P for root uptake even though ashes contain high concentrations of P (Shen et al. 2011).

Since nearly all N and P in human and livestock urine prevail in plant available forms, urine highly resembles mineral fertilisers and can be suitable for application to farmland. Due to high pH in the local soils there is a high risk for volatilization of ammonia at urine application, just as for mineral fertilisers based on ammonia (Virmani et al. 1982). Human urine has substantial concentrations of Na, which in soils can have a damaging effect on soil structure and plant growth. The current Na levels in the soils around Bolo Silasie are however considered low (Richard 1954). In low-Na soils, application of urine in the scale of plant requirements of N should not constitute a risk of Na-induced growth inhibition (Sene et al. 2013). However, since Na tend to stay in the soil and not leach out, a fertilising strategy based on urine might be problematic in a longer perspective (Ibid.)

6.4 Interventions for incresed soil fertility

From a soil fertility perspective, the single most impacting change in resource management for the farm households would be to abandon the current practice of preparing food with livestock manure and instead allocate these resources to the agricultural land. The total amounts of nitrogen in the manure that is used as stove fuel is 1.8 times higher than what is recirculated to the fields by manure compost, threshing pans and manure excreted by field-tethered animals, together.

Abandoning the practice of cooking with manure would not be done overnight, and such a change of habits cannot be proposed without presenting a reasonable fuel source alternative. In Bolo Silasie, trees are relatively scarce and managed with care. A higher rate of firewood collection from local tree resources would put high pressure on an already vulnerable resource. Firewood collection has been identified as one of the main drivers for deforestation in SSA (Dresen et al. 2014) and further studies would be needed to investigate the local environmental impacts of a higher firewood outtake. While food preparation with electrical stove is started to be practiced, unstable provision of electricity still makes the biomass stove fuels the default option. Improved cooking stoves (ICS) might be a part of the solution as having shown to reduce biomass inputs considerably (Mamuye et al. 2018). The perception of non-scarcity of stove fuel biomass mentioned by Mamuye et al. (2018) as a constraint for ICS adoption might be valid also for Bolo Silasie. According to interviews, manure is also the preferred fuel due to the specific taste it is perceived to bring to the foods, which is one of the reasons why worse-off families consume just as much *kubet* as the better-off groups, although they produce very little themselves. The use of manure is hence not only connected to scarcity of alternative resources but also to local preferences and traditions. The worse-off families access far less firewood resources than the other groups, owning less trees *(Table 4, p.37)*. However, when purchasing biomass for stove fuel, the worse-off goup prefer manure before firewood.

If all livestock excreta produced in Bolo Silasie ended up on agricultural land it would contribute with 29 kg N ha^{-1}, an albeit highly hypothetical number since N losses in management will always occur and since there are no currently practiced methods to collect livestock urine among farmers in Bolo Silasie. Today, farmers apply 54 kg N ha^{-1} in compost and mineral fertilisers. In the case of P, the total excreta production would only supply the soils with 4.2 kg P ha^{-1} which is far lower than both the recommended and the current applications rates of 20 kg P ha^{-1} and 28 kg P ha^{-1} respectively.

In contrast to other studies pointing out low availability of local feed resources as a constraint for livestock production and thus positive OC dynamics (Abegaz et al. 2007), there seem to be a potential in Bolo Silasie of improved OC and nutrient dynamics through a relatively high straw production. From calculations of theoretical straw yields, the availability of straw within Bolo Silasie appear to be substantially higher than the consumption of the same, which indicates that there is a potential of increasing the numbers of TLU and hence the manure production. Straw could also be incorporated directly in the soil to increase SOM, P and N levels in the soil. Incorporation of straw would not contribute considerably to N and P, but if 10% of the total straw production would be incorporated, its OC contribution would be more than five times higher than what currently is applied in compost per year *(Table 10, p. 58).*

Other than producing larger quantities of manure, it would also be an important nutrient recovery measure to improve the management of already available excreta. Today, there is no collection of livestock urine at all, although a large share of N excreted by livestock is found in urine (Luo & Kelliher 2014; Snijders et al. 2009). Cattle urine is probably for most families one of the more important bearers of N among the non-utilized resources (i.e. livestock urine, human excreta and ashes) *(Fig 41-42, p. 59).* Collection of urine would require some kind of sloping floor or slab. Potentially, the value in the urine could help to cover for such an investment (Mrema 2011). Today, there are very little measurements taken to avoid nutrient losses when composting, even though losses can be mitigated by simple measurements, such as floor, covers or simple roof constructions. Further studies would be required to better understand what would be required in terms of financial investments, knowledge and incentives for farmers to improve their management of livestock excreta.

Today, the human urine and faeces that is not deposited outside the compound ends up mixed in pit latrines from where nutrient recovery is both difficult and unlikely. Separation of urine and faeces using UDDT, would improve the potentials in using both urine and faeces as soil amendments. Considering the inconvenience in faeces management in combination with its relatively small nutrient recovery potential *(Fig 40, p. 59),* utilization of faeces as soil amendment will probably not be considered attractive enough at current availability of mineral fertilizers and manure in Bolo Silasie.

Nutrient management is not all about amendments. Even though all farmers practice crop rotation, no more than 8% of the land is cultivated with legumes *(Fig. 15, p. 36)* Growing larger areas of N-fixating crops could help to improve N levels in soils. Although N-fixation by leguminous crops can exceed 100 kg ha^{-1}, Haileselassie et al. (2005) estimated an average N-fixation in Ethiopian soils cultivated with legumes to no more than 18 kg ha^{-1} y^{-1}. Yet, this number corresponds to a third of the current application of N per hectare (*Table 10, p. 58.*). Legume grain and hay could possibly be used as livestock feed and so higher the potential TLU numbers in Bolo Silasie and consequently increasing also the manure production. The practical feasibility and economic viability of such a strategy would need to be assessed further. Considering that erosion at national and regional scale are estimated to be the most important processes in loss of plant nutrients from the soil (Haileselassie et al. 2005), measures to improve infiltration and avoid soil erosion could potentially be just as important as increased application rates to sustain and improve soil fertility in Bolo Silasie, not least considering the waterlogging properties of Vertisols.

6.5 Nutrient recovery in Bolo Silasie - a benefit for whom?

From a waste management and nutrient recovery perspective, an urban household in an industrialised country performs far worse than a rural household in Ethiopia. In Bolo Silasie food, fodder and fuel are mainly sourced locally. Food leftovers are given to animals and turned into egg, meat and skin. The overflowing number of packages that is an almost inevitable part of urban food consumption today and that put large pressure on societies' capacity of solid waste management, does not really exist in this context. Manure that is not used as soil amendment is to a high extent used for other productive purposes, such as construction or food preparation. This is to compare with the situation in many Western localities in which agriculture is specialized into such a degree that crop and animal production are separated, and manure is not economically viable to return to the fields due to high costs of transport. This raises the question whether improved nutrient recovery for the Ethiopian rural context is at all a relevant question for research and implementation initiatives, or if the focus rather should be on improvement somewhere else. A couple of arguments could be raised for why there is a rationale of nutrient recovery in Bolo Silasie and elsewhere in rural smallholder communities.

Firstly, there is a potential of direct benefits for the farmers in terms of potential for improved economy and increased resilience that follows with less dependency on mineral fertilisers. Today, many farmers in Bolo Silasie purchase fertilizers on credit. Prices on mineral fertilisers are volatile and expected to increase in the future.

Secondly, because of the short distances between households and farmland, recycling is relatively easy compared to the longer and more complex route of urban-rural recycling. In industrialized countries and urban localities waste management is normally costly and from a strict economic perspective not always justifiable. In Bolo Silasie, nutrient recovery does not require high technological solutions or large investments.

Thirdly, sooner or later societies relying on ending resources will have no option but to change. Apart from the potential of improving soil fertility locally, the total effects of increased nutrient recovery might not be huge for every Bolo Silasie farm hh. Considering, however, that smallholder farms together represent 2 billion people around the world (Cook 2009), the importance of such resource management shifts cannot be neglected.

There is among the hhs however a variance in potential benefits from increased nutrient recycling. The role of hh wastes and human excreta will play the largest role for the worse-off hhs, who access fewer TLU and who farm smaller sizes of land compared to the total production of hh waste and human excreta. Not least when taking into account that their current soil amendment potential per ha is zero *(Fig. 31, p.47)*.

The current soil amendment potential of zero for the worse-off group is an interesting characteristic revealing the importance of both traditions and economic status in hh resource management. Although the worse-off group have as high theoretical manure application potential per hectare as the other groups due to farming small areas of land (), that potential is all erased with current cooking practices. Worse-off farmers own fewer trees and lower access to firewood, but the choice of stove fuel type is not only determined by availability. The preference for *kubet* before firewood is clearly exposed in what the worse-off choose to purchase. The good taste that *kubet* brings to the injera was also mentioned various times in the interviews. Earlier studies on manure management in SSA have done estimations on potential manure application rate based on farm TLU numbers (Onduru et al. 2008).Few studies however take into account the current management of manure or differences in hh economic status. Ignoring the local resource practices is a simplification of the management system which may lead to conclusions with only little value.

6.6 Relevance of findings for other localities

This study has been assessing hh resource management in the Bolo Silasie context. Although there is literature supporting that much of what was found in Bolo Silasie is found also elsewhere in Ethiopia, such as manure used as stove fuel (Mekonnen & Köhlin 2008), poor management of available manure (Jagisso et al. 2019), non-utilization of human excreta for productive purposes (Meinzinger et al. 2009) and P-fixation in highland Vertisols (Hailu et al. 2015) it is without further research difficult to estimate the applicability of the findings from this study for other Ethiopian localities or smallholder communities in general.

Farmers in Bolo Silasie base their soil nutrient management strategy almost merely on mineral fertilisers and apply close to what is recommended by the extension service. The average mineral fertilising rates in Ethiopia are however substantially lower. While the local yields in Bolo Silasie are of 4 t ha^{-1}, the reported average yields for Ethiopia 2015-2017 are 2.5 t ha^{-1} (FAO stat n.d.). Resources that would have a minor contribution to the total current fertilising strategy in Bolo Silasie, such as human excreta, could play a much larger role in a context were very low amounts of plant nutrients are added to the soil. Manure being used as stove fuel is not a practice unique to Bolo Silasie but a widespread custom in all the Ethiopian highlands (Mekonnen & Köhlin 2008). It has been estimated the combustion of manure instead of using it as a soil amendment reduces Ethiopia's GDP with 7% (Zelleke et al. 2010). In a country were most soils are depleted of SOM and TN, a shift towards other sources of energy for food preparation in favour of increased manure application on soils would be highly beneficial at most localities.

Although ashes have a low potential as source for nutrient recovery in Bolo Silasie due to alkaline conditions in the local soils, 40% of Ethiopian soils are acidified (IFPRI 2010) and could benefit from ash application. Both the liming properties in the ashes and the high phosphorus and micronutrient content could be highly valuable in such areas.

6.7 Comments on the choice of methods

6.7.1 Socio-economic division of households

As a means for understanding the dynamics of resource management and hh socio-economic status, the study hhs were grouped into three socio-economic groups. The division is artificial in the sense that it is not based on any official wealth classification. Neither are there any obvious indicators nor ways to draw the borders between groups. There are for many of the hhs particularities and conditions possibly making them atypical member of their groups. Nonetheless, the division turned out be a helpful tool in describing general differences in potential of nutrient recovery and expected benefits of the same.

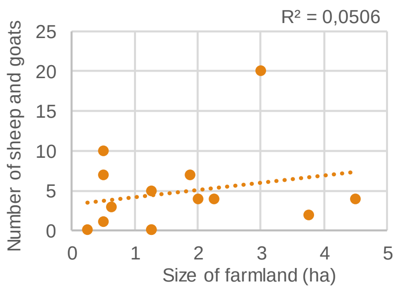


Figure 54. Number of sheep and goats and sizes of farmland for the 15 study hhs

Appropriate classification indicators should be linearly intercorrelated and serve as good proxy for *general* socio-economic status. In this study two indicators were used for the identification of hhs, namely number of TLU and sizes of farmland. When comparing some possible indicators and their correlations with farmland sizes, *number of sheep and goats* showed to have a low correlation (R^2=0.051) *(Fig. 54)*. The relations between *number of oxen* and farmland were on the other hand best explained by a flattening non-linear regression which means that the larger the farmland sizes are, the lower are the correlations with oxen ownership *(Fig. 55)*. *Number of TLU* and land tenure however show a linear relationship with a decent R square value (R^2=0.67) *(Fig. 56)*. The p-value has not been assessed.

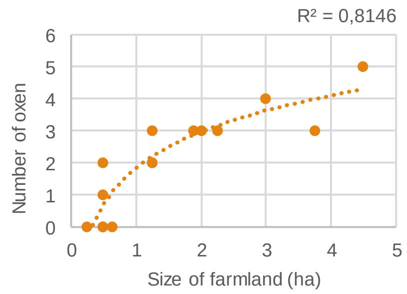


Figure 55. Number of oxen and sizes of farmland for the 15 study hhs

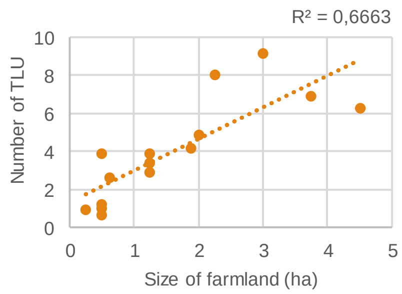


Figure 56. Number of TLU and sizes of farmland for the 15 study hhs

The combination of TLU and farmland also seemed to fulfil the criteria of reflecting general socio-economic status. Significant differences between the different classes could be observed for many aspects relevant for nutrient flow mapping, such use of fertilisers, total yields in grain and total production of manure. It can hence be concluded that 1) The chosen combination of indicators served their distinguishing purpose and 2) the differentiation between hh types was relevant for the understanding of nutrient flow dynamics within Bolo Silasie hhs.

The better-off households showed to be significantly larger in hh member size than the two other groups. The causality of large hh and high socio-economic status is not investigated, but the correlation is documented also in the Amhara Livelihood Zone Reports (2007). In order to account for this social structure in the study, the consumption of foods, stove fuel and water was not corrected for number of hh members. This means that the larger sizes of flows for the better-off hh described in the report do not necessarily reflect a larger consumption per person. However, the studied entities of this study have been *households* rather than *individuals*, since households rather than individuals are the agents owning farmland, keeping animals, consuming goods and producing and managing wastes.

The average study hh has 4.7 hh members, 4.0 TLU and 1.6 ha of land, while the average Bolo Silasie hh has 5.0 hh member, 3.0 TLU and 1.6 ha of land *(Table 4, p. 37)*. The fairly conforming figures indicate that the average study hh is a relatively good proxy for the average Bolo Silasie hh, in spite the small size of the study group (15 hh).

6.7.2 Interviews

Interviews are a good way, presumably the *only* way, to get first-hand information of how resource management, consumption and waste production is done locally. A large focus was for this reason put on extensive interviewing with the 15 hhs. The variety of interview methodologies and approaches that were used helped to understand the system from different angles and perspectives. Not least the participatory sections initiated interesting and informative discussions that raised new relevant questions that deepened the understanding. The choice of doing the interviews in two rounds showed be a rewarding strategy, since the first round gave birth to new insights and learnings that made the second rounds questions and discussions more applied to the context of Bolo Silasie.

At times, the completion the interviews however left a lot be desired. The interpreter was well familiar with both the 15 study hhs and the local farming system which hugely facilitated the establishment of contact with the hh members and basically enabled the whole study. Language barriers and non-satisfactory translation in both directions was however considered a problem during the interview sessions and a probable source of misinformation in the data collection. In the interviews the respondents were often basing their answers on how things were at the very moment, even though questions were formulated to account for the whole year, and/or variations between seasons. Because of lack of time or patience from the interpreter, the additional questions required to get information of exceptions and variations were not always asked. At times, there were obvious contradictions in the answers. These might reflect inexact translation, respondents answering questions without being completely sure about the answer, or respondents replying what they thought was expected from them rather than what they knew was correct. The interpreter's role as a neighbour and friend to many of the respondents might have been an affecting factor. For instance, nearly all respondents reported to have bought mineral fertilizers in cash, while the local Kebele statistics report that not even half the distributed fertilizers were purchased in cash. Being able to buy fertilisers in cash might speculatively be considered a respectable trait which was more favourable to be associated with.

The rather strict gender division of farm and household activities was also a challenge in the interview process since both genders were not always present at the interview session. In general, men had very little idea of household issues and women were normally not very involved in the field work. The lack of full gender representation was sought to be corrected in the complementary interview round but was for two of the hhs not possible to achieve.

6.7.3 Sample collection and lab analyses of soils and hh wastes

The quantities of ashes, foods and greywater used for the MFA diagrams and calculations were based on the collection of these substrates from nine families. The accuracy of these figures however can be questioned on several grounds.

Firstly, just as for the interviews, language barriers made the information exchange unsatisfactory. While the translation was rather poor in general, there might also be cultural and linguistic differences in how concepts such as "food leftovers", "cooking residues" or "dishwater" are understood.

Secondly, the collection of waters and food leftovers was done over three days only, and for the ashes over one week. For a better accuracy the collection could have been done during a longer period of time or repeated at several occasions.

Thirdly, the values were not at all cases consistent with information from observations and triangulation. For instance, when the production of ashes estimated by hh collection were compared to the theoretical production from reported stove fuel consumption and ash content of every fuel type, the collected ashes only added up to 75% of the theoretical values. The reported volumes of stove fuel might therefore be overestimated, not least for the better-off group that in average only collected 51% of their theoretical production of ashes. Larger discrepancies were found for the *tella* producing hhs than for non-*tella* producing families which also suggests that ashes from *tella* production was not collected by the families. Likewise, there is from observations a high probability that not all water was collected. Especially dishwater, where dishes often are made quickly for single plates or cups without collecting the residual water in any container. Consequently, it is likely that measured greywater does not equal the true greywater production. However, the collection probably reveals the share of water that easily is collected, which from a resource recovery perspective might be just as relevant.

6.7.4 Use of data sources

The results presented in this thesis rely on interviews, statistics from local *woreda* and *kebele* agencies, earlier findings from previous studies in Bolo Silasie, database, literature sources and triangulations and calculations, which at times have presented conflicting data. One example such example was the production of ashes, which according to the collection was substantially lower than the theoretical production based on reported use of stove fuel and analysed ash content in the goods used. In this case, the theoretical ash contents were used in the MFA calculations since they better paired with the imports of stove fuel. Another example was the use of mineral fertilisers, which in the interviews seemed to be considerably higher than what could be found about average purchases in the local statistics. The average application rates for the two years of 2016-2017 were chosen to be used in this study. It can however not be excluded that the consumption has increased since 2016-2017 and was actually higher during the cropping year of 2018.

Choosing different methodology and data sources in different cases might seem somewhat arbitrary. Although the choices were made to strive for the highest possible accuracy in every particular case, it comes with the cost of less methodological consistency. For all goods included in the MFA diagrams, all sources of data are listed in *Table 7 (p.52).*

6.7.5 The MFA methodology

A weakness in many MFA studies is that they too a high degree base their findings on secondary data. Such data is normally sourced from official statistics or earlier studies that describe conditions at other localities and are potentially not applicable to the context in which the MFA study is performed. This study aimed to present primary data on the household resource management system, something that is rarely done. The study however exhibits weaknesses in its lack of first-hand data on the livestock system. Births, growth, slaughters and constant selling and purchasing of live animals as well as very variable and context-dependent manure quality are just a few of the dynamics that make nutrient flows in livestock systems challenging to assess, something described in various articles of farm nutrient management in SSA (Casu 2018, Onduro et al. 2008).

In this study the MFA methodology has been used as a tool for calculating and visualising nutrient flows within the farm household system. As Fernandez-Mena et al. (2016) points out, MFA models are however restricted in their possibility of describing nutrient dynamics in space and over time. The spatial and temporal boundaries constraint the understanding of how applicable the findings are at other localities, or within a shorter or longer time frame. Also, they fail to provide any information on social and cultural dimensions of the processes they are describing, why agents and stakeholders in the resource management are excluded from the analyses. Even though MFA offers a good overview of the biophysical aspects of nutrient management (Fernandez-Mena et al. 2016), in itself it provides a somewhat unsatisfactory knowledge base for resource management decision-making and needs to be complemented with social, economic and cultural frames of interpretation.

7 Conclusions

The most important inflows of N, P and OC to the Bolo Silasie hh system include food, animal feed and stove fuel. The major exports are found in human excreta excreted outside the compound and livestock manure being added to fields via compost and threshing pan preparation as well as directly being deposited as manure and urine by livestock tethered and herded in the fields. Within the system, there are also major nutrient flows between hh compartments, including manure being used as stove fuel, hh wastes given to livestock as feed and human excreta stored in latrines and ashes stored on compound ground. In this study, the nutrient balance of the typical Bolo Silasie hh was estimated to +117 kg N y^{-1}, +12.6 kg P y^{-1} and +7040 kg OC y^{-1}. This accumulation is however largely expected to represent unaccounted losses related to biomass combustion, leaching, volatilization, denitrification and organic matter decomposition.

Today, the larger share of livestock manure, representing 26 kg N y^{-1}, 5.4 kg P y^{-1} and 920 kg OC y^{-1} for the average hh, is used as stove fuel. In this process, nearly all N and OC is lost in combustion while P terminate in ashes that today lack a productive use. The most impacting change in resource management within the farm hh would be to decrease the share of manure in cooking in favour for the application of larger quantities of manure to farmland. Further studies are needed to better understand the ecological consequences of an increased local firewood outtake, or the potentials in changing to more resource efficient stoves which would make more manure available for field application. Other interventions with nutrient recycling potential include collection of livestock urine, improvement of compost management and utilization of human urine and faeces as soil amendment. Application of ashes to soil would increase already high soil pH and is not recommended due to the risk of decreasing P and micronutrient availability.

If all manure that today is used for other activities would be applied to fields together with hh wastes of food, water and ashes, it could nearly replace N but not P inputs by mineral fertilisers. In contrast to mineral fertilisers, organic fertilisers from hh waste and excreta could however supply the soil with OC and micronutrients, which are indispensable for sustaining soil fertility in a longer perspective. Bolo Silasie soils are like many Ethiopian soils low in SOM, which further underlines the importance of OC recirculation.

The three different socio-economic groups showed to face different challenges and possibilities in resource and nutrient management. The worse-off group has a current potential manure application rate of zero, while the middle group has the largest manure application potentials. Because of lower access to livestock, hh wastes and human excreta are relatively more important for the worse-off group than for the two other groups in their potential as soil amendments. It was shown in this study that socio-economic status is a factor to take into consideration when assessing or advising on resource management optimisation, since both potentials to behavioural change and consequences of such changes might look different depending on the household's assets.

From this study it can be concluded that there are local resources within Bolo Silasie households that, if managed differently, in a higher extent than today could contribute to enhancing soil fertility on the households' fields. However, the study also exposes that these resources are embedded in a complex resource management system developed in a context of resource scarcity. All interventions in the system must therefore be assessed and understood in the light of what social and ecological consequences they would have for the local community and ecosystem.

References

Abegaz, A., van Keulen, H. and Oosting, S.J., 2007. Feed resources, livestock production and soil carbon dynamics in Teghane, Northern Highlands of Ethiopia. *Agricultural systems*, *94*(2), pp.391-404.

Abera, Y. & Kebede, M., 2013. Assessment on the Status of Some Micronutrients in Vertisols of the Central Highlands of Ethiopia. *International Research Journal of Agricultural Science and Soil Science* Vol. 3(5) pp. 169-173

Almqvist, H., Andersson, Å., Jensen, A. and Jönsson, H., 2007. Sammansättning och flöden på BDT-vatten, urin, fekalier och fast organiskt avfall i Gebers. *Svenskt Vatten Utveckling rapport*, *5*.

Amhara Livelihood Zone Reports. 2007. *Minjar Shenkora Woreda.* North Shewa Administrative Zone.

Andersson, E., 2015. Turning waste into value: using human urine to enrich soils for sustainable food production in Uganda. *Journal of Cleaner Production*, *96*, pp.290-298.

Armede, T., Auricht, C., Boffa, J.M., Dixon, J., Mallawaarachchi, T., Rukuni, M. and Teklewold-Deneke, T., 2017. *A farming system framework for investment planning and priority setting in Ethiopia*.

Bateman, A., van der Horst, D., Boardman, D., Kansal, A. and Carliell-Marquet, C., 2011. Closing the phosphorus loop in England: the spatio-temporal balance of phosphorus capture from manure versus crop demand for fertiliser. *Resources, Conservation and Recycling*, *55*(12), pp.1146-1153.

Baye, T.G., 2017. Poverty, peasantry and agriculture in Ethiopia. *Annals of Agrarian Science*, *15*(3), pp.420-430.

Belevi, H., 2002, May. Material flow analysis as a strategic planning tool for regional waste water and solid waste management. In *Proceedings of the workshop" Globale Zukunft: Kreislaufwirtschaftskonzepte im kommunalen Abwasser-und Fäkalienmanagement."GTZ/BMZ & ATV-DVWK Workshop during the IFAT* (pp. 13-15).

Berhongaray, G., Cotrufo, F.M., Janssens, I.A. and Ceulemans, R., 2019. Below-ground carbon inputs contribute more than above-ground inputs to soil carbon accrual in a bioenergy poplar plantation. *Plant and Soil*, *434*(1-2), pp.363-378.

Bindraban, P.S., Dimkpa, C., Nagarajan, L., Roy, A. and Rabbinge, R., 2015. Revisiting fertilisers and fertilisation strategies for improved nutrient uptake by plants. *Biology and Fertility of Soils*, *51*(8), pp.897-911.

Bot, A. and Benites, J., 2005. *The importance of soil organic matter: Key to drought-resistant soil and sustained food production* (No. 80). Food & Agriculture Org..

Brady, N.C. and Weil, R.R., 2002. The nature and properties of soils, Upper Saddle River. *New Jersey*.

Breese Jones, D. (1941) Factors for Converting Percentages of Nitrogen in Foods and Feeds into Percentages of Proteins, United States Department of Agriculture, Circular 183, 1931 (slightly revised August, 1941).

Bridges, E.M. and Oldeman, L.R., 1999. Global assessment of human-induced soil degradation. *Arid soil research and rehabilitation*, *13*(4), pp.319-325.

Bruce, R.C. and Rayment, G.E., 1982. *Analytical methods and interpretations used by the Agricultural Chemistry Branch for soil and land use surveys*. Queensland Department of Primary Industries

Brunner, P. H., Rechberger, H., (2004) Practical Handbook of Material Flow Analysis. Lewis Publishers.

Buresh, R.J., Smithson, P.C. and Hellums, D.T., 1997. Building soil phosphorus capital in Africa. *Replenishing soil fertility in Africa*, pp.111-149.

Castellanos-Navarrete, A., Tittonell, P., Rufino, M.C. and Giller, K.E., 2015. Feeding, crop residue and manure management for integrated soil fertility management–A case study from Kenya. *Agricultural Systems*, *134*, pp.24-35.

Casu, F.A., 2018. *Manure Management and nutrient cycling in smallholder crop-livestock systems in Nyando, Kenya.* MSc study. Animal production systems group. Wagenigen University.

Chaix-Bar, M. 2014. *Opportunities and constraints of using urine as a fertiliser in Silassie, Ethiopia.* BSc study. Environmental Department, University of York.

Climate-data.org. n.d. *Climate Arerti.* https://en.climate-data.org/africa/ethiopia/amhara/arerti-718548/ [2019-06-07]

Cohen, Y., Kirchmann, H. and Enfält, P., 2011. Management of phosphorus resources–historical perspective, principal problems and sustainable solutions. In *Integrated Waste Management-Volume II*. IntechOpen.

Cook, J.A., 2009. Smallholder agriculture and the environment in a changing global context. *WWF MPO. May*.

Cordell, D., Drangert, J. O., & White, S. (2009). The story of phosphorus: global food security and food for thought. *Global environmental change*, *19*(2), 292-305.

Cox, D., Bezdicek, D. and Fauci, M., 2001. Effects of compost, coal ash, and straw amendments on restoring the quality of eroded Palouse soil. *Biology and fertility of soils*, *33*(5), pp.365-372.

Dean, W.E., 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition; comparison with other methods. *Journal of Sedimentary Research*, *44*(1), pp.242-248.

Defoer, T., Budelman, A., Toulmin, C. and Carter, S.E., 2000. Building common knowledge: Participatory learning and action research. *Royal Tropical Institute, Amsterdam, The Netherlands*, *207*.

Demeyer, A., Nkana, J.V. and Verloo, M.G., 2001. Characteristics of wood ash and influence on soil properties and nutrient uptake: an overview. *Bioresource technology*, *77*(3), pp.287-295.

Dickin, S., Dagerskog, L., Jiménez, A., Andersson, K. and Savadogo, K., 2018. Understanding sustained use of ecological sanitation in rural Burkina Faso. *Science of the Total Environment*, *613*, pp.140-148.

Dresen, E., DeVries, B., Herold, M., Verchot, L. and Müller, R., 2014. Fuelwood savings and carbon emission reductions by the use of improved cooking stoves in an Afromontane Forest, Ethiopia. *Land*, *3*(3), pp.1137-1157.

Dubber, D. and Gray, N.F., 2010. Replacement of chemical oxygen demand (COD) with total organic carbon (TOC) for monitoring wastewater treatment performance to minimize disposal of toxic analytical waste. *Journal of Environmental Science and Health Part A*, *45*(12), pp.1595-1600.

Duncan, R., 2012. *Crops as enhancers of nutrient use.* Academic Press. 588p.

Eckert, D.J., 1987. Soil Test Interpretations: Basic Cation Saturation Ratios and Sufficiency Levels 1. *Soil testing: Sampling, correlation, calibration, and interpretation*, (soiltestingsamp), pp.53-64.

Elser, J.J., Elser, T.J., Carpenter, S.R. and Brock, W.A., 2014. Regime shift in fertilizer commodities indicates more turbulence ahead for food security. *PLoS One*, *9*(5), p.e93998.

Encyclopædia Britannica (2019) *Ethioipia - Soils*. https://www.britannica.com/place/Ethiopia/Soils [2019-05-27]

Ethiopian Agricultural Transformation Agency (2019). EthioSIS. https://www.ata.gov.et/programs/highlighted-deliverables/ethiosis/ [2019-05-22]

Ethiopian Government Portal (2018) http://www.ethiopia.gov.et/ [2019-03-04]

Erich, M.S., 1991. Agronomic effectiveness of wood ash as a source of phosphorus and potassium. *Journal of Environmental Quality*, *20*(3), pp.576-581.

FAO (no date). *Participatory survey methods for gathering information*. Annex II SPFS/DOC/18 handbook series volume II Special programme for food security

FAO. 1984. *Fertilizing and plant nutrition guide.* Fertilizing and plant nutrition Service. Land and water development division. Bulletin 9.

FAO. 2009. High Level Expert Forum - How to Feed the World in 2050 Office of the Director, Agricultural Development Economics Division Economic and Social Development Department

FAO. 2015. World fertilizer trends and outlook to 2018. *Food and Agriculture Organization of the United Nations. Report.*

FAO. 2019. *Ethiopia at a glance* http://www.fao.org/ethiopia/fao-in-ethiopia/ethiopia-at-a-glance/en/ [2019-06-05.]

FAO-stat. *Average total cereal yield 2015-2017,* http://www.fao.org/faostat [20190525

Fernandez-Mena, H., Nesme, T. and Pellerin, S., 2016. Towards an Agro-Industrial Ecology: A review of nutrient flow modelling and assessment tools in agro-food systems at the local scale. *Science of the Total Environment*, *543*, pp.467-479.

Fraser, A.I., Harrod, T.R. and Haygarth, P.M., 1999. The effect of rainfall intensity on soil erosion and particulate phosphorus transfer from arable soils. *Water science and technology*, *39*(12), pp.41-45.

Gbenou, B., Adjolohoun, S., Ahoton, L., Houndjo, D.B.M., Saïdou, A., Houinato, M. and Sinsin, A.A., 2017. Animal dung availability and their fertilizer values in a context of low soil fertility conditions for forage seed and crops production in Benin (West Africa). *Am. J. Agric. Res., 2(12),* pp.1-16.

Giller, K.E., Cadisch, G., Ehaliotis, C., Adams, E., Sakala, W.D. and Mafongoya, P.L., 1997. Building soil nitrogen capital in Africa. *Replenishing soil fertility in Africa*, (replenishingsoi), pp.151-192.

Gustafson, G.M. and Olsson, I., 2004. Partitioning of nutrient and trace elements in feed between body retention, faeces and urine by growing dairy-breed steers. *Acta Agriculturae Scandinavica, Section A-Animal Science*, *54*(1), pp.10-19.

Haile, K., Haji, J. and Tegegne, B., 2018. Technical Efficiency of Sorghum Production: The Case of Smallholder Farmers in Konso District, Southern Ethiopia. *Agricultural Development*, *3*(2071-2019-040), p.1.

Haileselassie, A., Priess, J., Veldkamp, E., Teketay, D. and Lesschen, J.P., 2005. Assessment of soil nutrient depletion and its spatial variability on smallholders' mixed farming systems in Ethiopia using partial versus full nutrient balances. *Agriculture, ecosystems & environment*, *108*(1), pp.1-16.

Hailu, H., Mamo, T., Keskinen, R., Karltun, E., Gebrekidan, H. and Bekele, T., 2015. Soil fertility status and wheat nutrient content in Vertisol cropping systems of central highlands of Ethiopia. *Agriculture & Food Security*, *4*(1), p.19.

Hao, X. and Benke, M.B., 2008. Nitrogen transformation and losses during composting and mitigation strategies. *Dynamic Soil, Dynamic Plant; Hao, X., Ed.; Global Science Books: London, UK*, *2*, pp.10-18.

Hartemink, A. E. 2007. Soil Fertility Decline: Definitions and Assessment. ISRIC–World Soil Information, Wageningen, The Netherlands

Hazelton, P. and Murphy, B., 2016. *Interpreting soil test results: What do all the numbers mean?*. CSIRO publishing.

Heckman, J.R., 2006. Soil fertility test interpretation: phosphorus, potassium, magnesium and calcium. *Fact Sheet FS719 Rutgers Cooperative Extension, New Jersey Agricultural Experimental Extension*, *4*.

Hoekman, P. and von Blottnitz, H., 2017. Cape Town's metabolism: insights from a material flow analysis. *Journal of Industrial Ecology*, *21*(5), pp.1237-1249.

Holford, I.C.R., 1997. Soil phosphorus: its measurement, and its uptake by plants. *Soil Research*, *35*(2), pp.227-240.

Horneck, D.A., Sullivan, D.M., Owen, J.S. and Hart, J.M., 2011. Soil test interpretation guide. Oregon State University Extension Service.

IFDC 2015, *Assessment of Fertilizer Consumption and Use by Crop in Ethiopia.*

IFPRI 2010. Fertilizer and Soil Fertility Potential in Ethiopia Constraints and opportunities for enhancing the system

Infomineo (2016) Agriculture in Ethiopia. https://infomineo.com/agriculture-in-ethiopia-3/ [2019-02-18]

Jacks, G., Sefe, F., Carling, M., Hammar, M. and Letsamao, P., 1999. Tentative nitrogen budget for pit latrines–eastern Botswana. *Environmental Geology*, *38*(3), pp.199-203.

Jagisso, Y., Aune, J. and Angassa, A., 2019. Unlocking the Agricultural Potential of Manure in Agropastoral Systems: Traditional Beliefs Hindering Its Use in Southern Ethiopia. *Agriculture*, *9*(3), p.45.

Jahnke, H.E. (1982) Livestock production systems and livestock development in tropical Africa.

Jaza Folefack, A.J., 2009. The substitution of mineral fertilizers by compost from household waste in Cameroon: economic analysis with a partial equilibrium model. *Waste Management & Research*, *27*(3), pp.207-223.

Joint FAO/WHO Expert Committee on Food Additives. 2005. *Toxicological Evaluation of Certain Veterinary Drug Residues in Food.* Meeting, World Health Organization

Jones, A., Breuning-Madsen, H., Brossard, M., Dampha, A., Deckers, J., Dewitte, O., Gallali, T., Hallett, S., Jones, R., Kilasara, M. and Le Roux, P., 2013. *Soil atlas of Africa.*

Jönsson, H., Stintzing, A.R., Vinnerås, B. and Salomon, E., 2004. *Guidelines on the use of urine and faeces in crop production*. EcoSanRes Programme.

Järnberg, L., 2016. Prospects for a sustainable agricultural transformation in Ethiopia: green niche actors navigating a challenging institutional context.

Kemper, W.D. and Koch, E.J., 1966. *Aggregate stability of soils from western United States and Canada* (No. 1488-2016-124039).

Kimble, J.M., Stewart, B.A. and Follett, R.F., 2000. *Assessment methods for soil carbon.* CRC press.

Kirchmann, H. and Witter, E., 1992. Composition of fresh, aerobic and anaerobic farm animal dungs. *Bioresource technology*, *40*(2), pp.137-142.

Knowlton, K.F. and Herbein, J.H., 2002. Phosphorus partitioning during early lactation in dairy cows fed diets varying in phosphorus content. *Journal of Dairy Science*, *85*(5), pp.1227-1236.

Krause, A. and Rotter, V.S., 2017. Linking energy-sanitation-agriculture: Intersectional resource management in smallholder households in Tanzania. *Science of the Total Environment*, *590*, pp.514-530.

Lederer, J., Karungi, J. and Ogwang, F., 2015. The potential of wastes to improve nutrient levels in agricultural soils: A material flow analysis case study from Busia District, Uganda. *Agriculture, Ecosystems & Environment*, *207*, pp.26-39.

Lekasi, J.K., Tanner, J.C., Kimani, S.K. and Harris, P.J.C., 2001. Manure management in the Kenya highlands: Practices and potential.

Lekasi, J.K., Tanner, J.C., Kimani, S.K. and Harris, P.J.C., 2003. Cattle manure quality in Maragua District, Central Kenya: effect of management practices and development of simple methods of assessment. *Agriculture, ecosystems & environment*, *94*(3), pp.289-298.

Lewcock, C., 1995. Farmer use of urban waste in Kano. *Habitat international*, *19*(2), pp.225-234.

Lowder, S.K., Skoet, J. and Raney, T., 2016. The number, size, and distribution of farms, smallholder farms, and family farms worldwide. *World Development*, *87*, pp.16-29.

Luo, J. and Kelliher, F., 2014. *Partitioning of animal excreta N into urine and dung and developing the N2O inventory*. Ministry for Primary Industries.

Lynch, K.M., Steffen, E.J. and Arendt, E.K., 2016. Brewers' spent grain: a review with an emphasis on food and health. *Journal of the Institute of Brewing, 122*(4), pp.553-568..

Mamo, T., Astatke, A., Srivastava, K.L. and Dibabe, A., 1993. Improved management of Vertisols for sustainable crop-livestock production in the Ethiopian highlands: Synthesis report 1986-92.

Mamuye, F., Lemma, B. and Woldeamanuel, T., 2018. Emissions and fuel use performance of two improved stoves and determinants of their adoption in Dodola, southeastern Ethiopia. *Sustainable Environment Research*, *28*(1), pp.32-38

McIntire, J., Bourzat, D. and Prabhu, P., 1992. *Crop-livestock interaction in sub-Saharan Africa*. Washington, DC: World Bank.

McGrath, JM. Spargo, J., Penn C.J. (2004) Soil Fertility and Plant Nutrition.

Mebrahtu, K., Teshale, S., Esatu, W., Habte, T. and Gelaye, E., 2018. Evaluation of spray and oral delivery of Newcastle disease I2 vaccine in chicken reared by smallholder farmers in central Ethiopia. *BMC veterinary research*, *14*(1), p.48.

Meinzinger, F., Oldenburg, M. and Otterpohl, R., 2009. No waste, but a resource: Alternative approaches to urban sanitation in Ethiopia. *Desalination*, *248*(1-3), pp.322-329.

Mekonnen, A. and Köhlin, G., 2008. Biomass fuel consumption and dung use as manure: evidence from rural households in the Amhara region of Ethiopia. *Environment for Development Discussion Paper-Resources for the Future (RFF)*, (08-17)

Metson, A.J., 1961. Methods of chemical analysis for soil survey samples, soil bureau bulletin 12. *Department of Scientific and Industrial Research, New Zealand.*

Mihelcic, J.R., Fry, L.M. and Shaw, R., 2011. Global potential of phosphorus recovery from human urine and feces. *Chemosphere*, *84*(6), pp.832-839.

Montangero, A. and Belevi, H., 2007. Assessing nutrient flows in septic tanks by eliciting expert judgement: A promising method in the context of developing countries. *Water research*, *41*(5), pp.1052-1064.

Morgan, P., 2007. *Toilets That Make Compost: Low-cost, sanitary toilets that produce valuable compost for crops in an African context.* EcoSanRes Programme.

Mrema, Geoffrey C. 2011. *Rural structures in the tropics: Design and development.* Rome: FAO.

Novak, J.M., Busscher, W.J., Laird, D.L., Ahmedna, M., Watts, D.W. and Niandou, M.A., 2009. Impact of biochar amendment on fertility of a southeastern coastal plain soil. *Soil science*, *174*(2), pp.105-112.

Nzuma, J.K., Murwira, H.K., 2000. Improving the Management of Manure in Zimbabwe. Managing Africa's Soils, vol. 15. IIED-Drylands Programme, London, UK.

Okello, B.D., O'connor, T.G. and Young, T.P., 2001. Growth, biomass estimates, and charcoal production of Acacia drepanolobium in Laikipia, Kenya. *Forest Ecology and management, 142*(1-3), pp.143-153.

Onduru, D.D., Snijders, P., Muchena, F.N., Wouters, B., De Jager, A., Gachimbi, L. and Gachini, G.N., 2008. Manure and soil fertility management in sub-humid and semi-arid farming systems of Sub-Saharan Africa: Experiences from Kenya. *Int J Agric Res*, *3*(3), pp.166-187.

Oteng-Peprah, M., Acheampong, M.A. and deVries, N.K., 2018. Greywater characteristics, treatment systems, reuse strategies and user perception—a review. *Water, Air, & Soil Pollution*, *229*(8), p.255.

Our World in Data 2018. *Water use stress.* (https://ourworldindata.org 2/water-use-stress). [2019-09-02]

Paff, K. and Asseng, S., 2019. Comparing the effects of growing conditions on simulated Ethiopian tef and wheat yields. *Agricultural and Forest Meteorology*, *266*, pp.208-220.

Patzel, N., Sticher, H. and Karlen, D.L., 2000. Soil fertility—phenomenon and concept. *Journal of Plant Nutrition and Soil Science*, *163*(2), pp.129-142.

Pedroso-Junior, N.N., Adams, C. and Murrieta, R.S., 2009. Slash-and-burn agriculture: a system in transformation. In *Current trends in human ecology* (Vol. 12, No. 34, pp. 12-34). Cambridge Scholars Publishing in association with GSE Research.

Prüss-Ustün, A., Bartram, J., Clasen, T., Colford Jr, J. M., Cumming, O., Curtis, V., ... & Freeman, M. C. 2014. Burden of disease from inadequate water, sanitation and hygiene in low-and middle-income settings: a retrospective analysis of data from 145 countries. *Tropical Medicine & International Health*, *19*(8), pp. 894-905.

Qi, G.H., Diao, Q.Y., Tu, Y., Wu, S.G. and Zhang, S.H., 2004. Nutritional evaluation and utilization of quality protein maize (QPM) in animal feed. *FAO Animal Production and Health Proceedings. Protein Sources for the Animal Feed Industry*, p.188.

Qin, J., Hovmand, M.F., Ekelund, F., Rønn, R., Christensen, S., de Groot, G.A., Mortensen, L.H., Skov, S. and Krogh, P.H., 2017. Wood ash application increases pH but does not harm the soil mesofauna. *Environmental pollution*, *224*, pp.581-589.

Richard, L.A., 1954. Diagnosis and improvement of saline and alkaline soil. *USDA*, *Washington*.

Rodhe, L., Stintzing, A.R. and Steineck, S., 2004. Ammonia emissions after application of human urine to a clay soil for barley growth. *Nutrient Cycling in Agroecosystems*, *68*(2), pp.191-198.

Rufino, M.C., Rowe, E.C., Delve, R.J. and Giller, K.E., 2006. Nitrogen cycling efficiencies through resource-poor African crop–livestock systems. *Agriculture, ecosystems & environment*, *112*(4), pp.261-282.

Ryden, J.C. and Whitchead, D.C., 1988. Some relationships between denitrification potential and fractions of organic carbon in air-dried and field-moist soils. *Soil Biology and Biochemistry*, *20*(5), pp.737-741.

Sanchez, P.A., 2019. *Properties and management of soils in the tropics*. Cambridge University Press.

Schachtman, D.P., Reid, R.J. and Ayling, S.M., 1998. Phosphorus uptake by plants: from soil to cell. *Plant physiology*, *116*(2), pp.447-453.

Šebek, L.B., Bikker, P., van Vuuren, A.M., van Krimpen, M. 2014 *Nitrogen and phosphorous excretion factors of livestock* Task 2: In-depth analyses of selected country reports.

Sene, M., Hijikata, N., Ushijima, K. and Funamizu, N., 2013. Effects of extra human urine volume application in plant and soil. *Int Res J Agric Sci Soil Sci*, *3*(6), pp.182-191.

Serrasolses I., Diego V., Bonilla D. 1999. Soil Nitrogen Dynamics. In: Rodà F., Retana J., Gracia C.A., Bellot J. (eds) Ecology of Mediterranean Evergreen Oak Forests. *Ecological Studies (Analysis and Synthesis), vol 137*. Springer, Berlin, Heidelberg.

Shen, J., Yuan, L., Zhang, J., Li, H., Bai, Z., Chen, X., Zhang, W. and Zhang, F., 2011. Phosphorus dynamics: from soil to plant. *Plant physiology*, *156*(3), pp.997-1005

Snijders, P.J.M., Davies, O., Wouters, A.P., Gachimbi, L., Zake, J., Ergano, K., Abduke, M. and Van Keulen, H., 2009. *Cattle manure management in East Africa: Review of manure quality and nutrient losses and scenarios for cattle and manure management* (No. 258). Wageningen UR Livestock Research.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., De Vries, W., De Wit, C.A. and Folke, C., 2015. Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223), p.1259855.

Sutton, M.A.; Bleeker, A.; Howard, C.M.; Bekunda, M.; Grizzetti, B.; de Vries, W.; van Grinsven, H.J.M.; Abrol, Y.P.; Adhya, T.K.; Billen, G.; Davidson, E.A.; Datta, A.; Diaz, R.; Erisman, J.W.; Liu, X.J.; Oenema, O.; Palm, C.; Raghuram, N.; Reis, S.; Scholz, R.W.; Sims, T.; Westhoek, H.; Zhang, F.S.. 2013 *Our nutrient world: the challenge to produce more food and energy with less pollution.* Edinburgh, NERC/Centre for Ecology & Hydrology, 114pp

Tilman, D., Balzer, C., Hill, J. and Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*, *108*(50), pp.20260-20264.

Tittonell, P., Van Wijk, M.T., Herrero, M., Rufino, M.C., de Ridder, N. and Giller, K.E., 2009. Beyond resource constraints–Exploring the biophysical feasibility of options for the intensification of smallholder crop-livestock systems in Vihiga district, Kenya. *Agricultural systems*, *101*(1-2), pp.1-19.

Tittonell, P., Muriuki, A., Klapwijk, C.J., Shepherd, K.D., Coe, R. and Vanlauwe, B., 2013. Soil heterogeneity and soil fertility gradients in smallholder farms of the East African highlands. *Soil Science Society of America Journal*, *77*(2), pp.525-538.

USDA Food Composition Databases (2019) https://ndb.nal.usda.gov/ndb/ [2019-05-19]

World Health Organization, WHO/UNICEF Joint Water Supply and Sanitation Monitoring Programme, 2017. *Progress on sanitation and drinking water: 2017 update and MDG assessment.* World Health Organization

World Population Review 2019. *Ethiopia population 2019* http://worldpopulationreview.com/ [2019-02-15]

Virmani SM, Sahrawat KC and Burford JR 1982 Physical and Chemical properties of Vertisols and their management in Vertisols and Rice Soils of the Tropics, Transactions of the Twelfth International Congress of Soil Science, Symposia Papers II, 8–16 Feb, 1982, pp. 94–118.

White, P.J. and Brown, P.H., 2010. Plant nutrition for sustainable development and global health. *Annals of botany*, *105*(7), pp.1073-1080.

World Health Organization and UNICEF, 2017. Progress on drinking water, sanitation and hygiene: 2017 update and SDG baselines.

Winblad, U. and Simpson-Hebert, M. eds., 2004. *Ecological sanitation*. EcoSanRes Programme.

World Bank, "Fertilizer consumption (kilograms per hectare of arable land)", accessed May 27, 2019, https://data.worldbank.org/indicator/AG.CON.FERT.ZS?locations= ZG

Moller, L. C. 2015. *Ethiopia's great run : the growth acceleration and how to pace it (English)*. Washington, D.C. : World Bank Group.

World Population Review (2019) http://worldpopulationreview.com/countries/ethiopia-population/ [2019-02-18]

Yimer, F., Ledin, S. and Abdelkadir, A., 2007. Changes in soil organic carbon and total nitrogen contents in three adjacent land use types in the Bale Mountains, south-eastern highlands of Ethiopia. *Forest Ecology and Management*, *242*(2-3), pp.337-342.

Zingore, S., Murwira, H.K., Delve, R.J. and Giller, K.E., 2007. Soil type, management history and current resource allocation: Three dimensions regulating variability in crop productivity on African smallholder farms. *Field Crops Research*, *101*(3), pp.296-305.

Zbíral, J., Smatanová, M. and Němec, P., 2018. Sulphur status in agricultural soils determined using the Mehlich 3 method. *Plant, Soil and Environment*, *64*(6), pp.255-259.

Zelleke, G., Agegnehu, G., Abera, D. and Rashid, S., 2010. Fertilizer and soil fertility potential in Ethiopia: Constraints and opportunities for enhancing the system. *International food policy research institute (IFPRI), Washington, DC, USA*.

Unpublished material

Buta, Teshome. 2019. Personal communication.

Bolo Silasie Kebele Statistics. 2019. Received through Buta, T. and Hailegiorgis, Y. Bolo Silasie. March-April 2019.

Dagerskog, L.2014. *Unpublished data on compost and farmyard manure quality.*

Dagerskog, L. 2017 *Evaluating the potential of productive sanitation in Bolo Silasie village, Ethiopia.* Poster presentation at Agri4D conference. 2017.

Dagerskog, L. 2018. *Green participatory assessment – « Flux des Ressources (FdR) ».* Unpublished manuscript.

Dagerskog, L. 2019 Personal communication.

Appendix 1: Interview manual

Names of respondents: ____

Household code: ____

Date(s):____

Oral and written information about the study is provided: ☐ **Yes** ☐ **No**

The consent form is presented and signed: ☐ **Yes** ☐ **No**

General information of household

- Number of household (hh) members: _____________
- Number of women in hh: _______________________
- Age distribution in hh:

  0-5 y:______________ 6-18 y:___________ 19-60 y:_____________ 60+ y: __________
- Years of experience in farming: _____________

Main assets

- Number of timads:

  Owned: ______ Borrowed/Rent: ______ Lent/Rent out: ______ Sharecropped: _______
- Livestock, number of:

  Oxen: ____________ Cows: ____________ Donkeys: _____________ Sheep: _________

  Goats: ____________ Poultry: ______________ Camels: ____________
- Number of productive trees (for firewood, construction):____________
- Number of ponds: with geomembrane: ___________ without geomembrane: ________
- Vehicles: ________________________________
- Other assets: _____________________________

Sources of income:

☐ Cereals ☐ Seedlings ☐ Onion ☐Tomato ☐ Gesho

☐ Egg ☐ Meat ☐ Skin ☐ Milk ☐ Butter

☐ Tella ☐ Areke ☐ Other foods,_________________

☐ Firewood ☐ Charcoal ☐ Kubet ☐Fug ☐ Compost ☐ Straw

☐ Livestock fattening of: _________________

☐ Remittance (money from abroad)

☐ Manual labour, ________________

☐ Other profession, ______________

☐ Others,_________________

The resource flow map

Objectives

- Understanding what relevant activities and processes, from a nutrient flow perspective, that occur in the farm household. This includes production, consumption, purchase, selling, re-utilization and discard of products.
- Defining the limits and features of the "system": the farm household

Materials needed

Item	Purpose
Large white papers (A0)	Constitute the "fond" to the resource flow map, were pictures can be placed and lines and arrows can be drawn
Pedagogical photos or drawings picturing farm household objects and activities	Symbolizes objects and activities related to resource flows onto and out from the farm household, such as animals, foods and waste fractions. Can be re-organized on the paper until a satisfactory map is on place.
White small-sized (A6) papers	For making new drawings if other objects and activities than the already pictured are brought up in the discussion.
Marker pens	For drawing lines and arrows representing borders and relations between objects and activities on the nutrient flow map.
A pre-made risks and values chart with the listed waste fractions	To evaluate perceptions on the potential use of different waste fractions.
Pebbles, sticks or beans	To mark what alternative is most accurate in the risks and values chart.

Methodology

1) Drawing the nutrient flow map

i) A large white paper is placed on the ground and will constitute the fond to the map.

ii) Pictures and drawings displaying objects and activities are spread out around the map.

iii) A square is drawn, symbolising "the household". Within the household images symbolising all the consumers of products are placed, namely family members and the kinds of animals that belongs to the farm.

iv) Another square is drawn, symbolising the farms fields and grazing lands. The household is asked to place everything that is grown on the fields in terms of crops and trees in this square.

v) A vertical line in drawn on the right side of the page, symbolizing the market and the commons (from where products are imported and exported)
vi) Inputs to the production are illustrated with pictures and arrows. The source of water (rainfed, irrigated from well, from water harvesting tanks etc) is indicated with an image as well as purchased amendments (chemical and organic fertilizers).
vii) Are there any products sold or given away? Such products are marked with an arrow from products to market. What is consumed in the household? Draw arrows from products in the field to the household.
viii) If water is bought/brought from the commons, mark the input of water from the commons to the household.
ix) All consumption activities are shown with images in the “household square”: construction, food preparation, food consumption, animal feeding, water consumption (for dishing, washing, dishing, beverage preparation, water for animals etc).
x) The animals also bring products of all kinds, which are they? (Skin, milk, eggs, meat…). Are they sold or consumed within the household? Draw arrows back to household or out to the market.
xi) At some time during the year the household also needs to buy food. What kinds? Show with pictures placed in the market, draw arrows to household.
xii) Almost all activities generate some kinds waste fractions. Which are the wastes from the different activities? (Like from food preparation, cooking on the stove, food consumption, coffee making, talla production, slaughter, body-washing/dishing/doing laundry). Are any of these waste fraction seen as products and reutilized? Where do they go? Show with arrows.
xiii) All living beings also produces excreta. Where does it end up? Show with arrows for every animal (including humans) where excreta end up.

2) Discussing the current waste management

The identified household waste and excreta fractions are discussed. The household is asked to answer if the fraction is currently used or not. If it used, for what purpose, and by whom?

3) Charting values and risks with human excreta and waste fractions

A prepared chart with the major waste and excreta fractions is placed on the ground. The waste fractions are first discussed in to what extent they are considered a risk. There are four alternatives provided, all in separate boxes. The household members are asked to choose the alternative that suits best and place a pebble/stick in the corresponding box. After finishing this section, the same waste fractions are discussed in to what extent they are considered to be an asset/have a value.

4) **Estimating farm production**

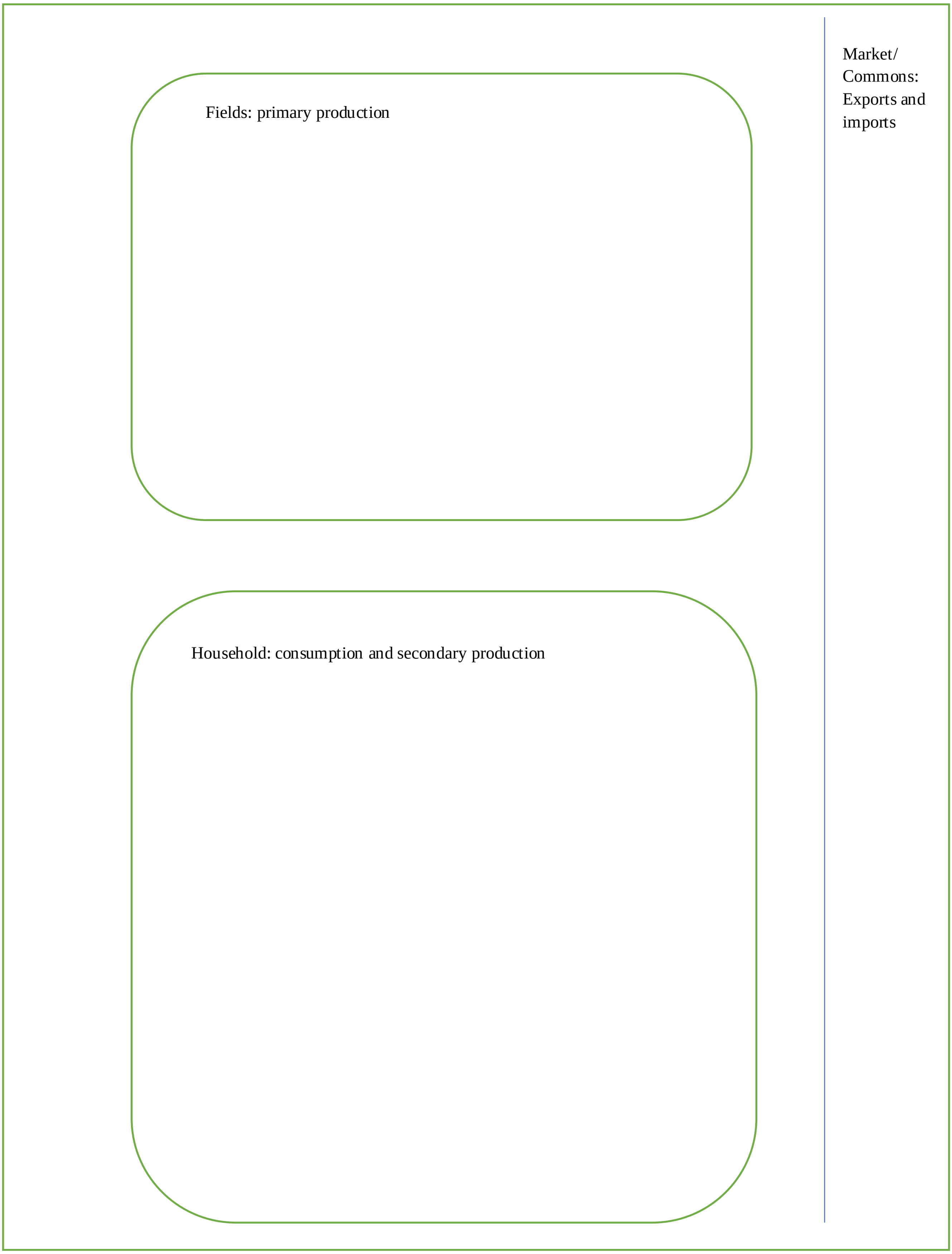
The primary and secondary production taking place in the household are summed up and recorded.

5) **Estimating human consumption of foods and water**
The consumption of products from the own household, identified in the map, are summed up by asking the household to estimate quantities and sources.

6) **Discussing animal husbandry practices**
The household is asked to estimate the quantities of fodder and water given to the live-stock, as well as explain their practices around manure management. This questionnaire is preferable done together with a weighing of volumes and quantities.

7) **Discussing current sanitation practices**
Questions are asked about basic sanitation practices.

The resource flow map



Current waste management

Origins of waste	Wastes	Current use (if any)	Who manages?
Human foods	Urine		
	Faeces		
	Waste from food preparation		
	Food leftovers (from eating)		
	Rests from Tella production		
	Rests form coffeemaking		
	Rests from grinding grain to flour		
	Others		
	Others		
	Others		
Stove fuel	Charcoal		
	Ashes		
	Others		
Livestock feed:	Cattle faeces		
	Goat and sheep faeces		
	Camel faeces		
	Poultry faeces		
	Donkey faeces		
	Others		
	Animal urine		
Water usage	Shower water		
	Laundry water		
	Dish water		

Identified risks and value in the usage of household waste and excreta

Waste fraction	Value					Risks			
	No value	Small value	Moderate value	High value		No risk	Small risk	Moderate risk	High risk
Human faeces									
Human urine									
Goat and sheep faeces									
Cattle faeces									
Donkey faeces									
Camel faeces									
Cat and dog ex-creta									
Poultry excreta									
Animal urine									
Ashes									
Food leftovers									
Compost									
Laundry water									
Dishing water									
Body-washing water									

Primary and secondary production

Category	Item	Quantities	Unit
Yields in major crops	Teff		
	Wheat		
	Corn		
	Chickpeas		
	Onion		
	Tomato		
	Straw		
	Firewood		
Plant-based products	Charcoal		
	Tella		
	Areke		
Livestock raising and fattening	Cattle		
	Donkey		
	Sheep		
	Goat		
	Poultry		
	Camel		
Livestock products	Meat		
	Milk		
	Butter		
	Egg		
	Skin		
	Kubet		
	Fug		
	Compost		

Human consumption of foods, water and stove fuel

Category	Item	Quanti-ties	Unit	Sources: Mark one alternative			
				Always from own produce	Always purchased	Purchased some months (record no)	Other, de-scribe:
Foods	Teff						
	Wheat						
	Sorghum						
	Barley						
	Corn						
	Pea						
	Lentil						
	Chickpea						
	Broad bean						
	Phaseolus bean						
	Onion						
	Garlic						
	Potato						
	Cabbage						
	Tomato						
	Beetroot						
	Carrot						
	Green pepper						
	Berbere						
	Gesho						
	Oil						
	Chicken						
	Lamb or beef						
	Egg						
	Milk						
	Butter						
	Sugar						
	Salt						
	Tella						
Stove fuel	Firewood						
	Charcoal						
	Fug						
	Kubet						
Others	Straw						

Households consumption of water for human activities

Water consumption activity	Quantity (in jerrycans or litres)	Frequency
Total weekly consumption		
Cooking		
Dishing		
Laundry		
Injera preparation		
Tella preparation		
Drinking water		

- How much manure do you use for construction and maintenance?
- How much do you use for threshing?
- Do you produce your own charcoal? How often? How much FYM do you use?
- Are there any storage losses of foods or grains? How much? Related to what?
- Do you use electrical stove?

Recording 1.6: Animal husbandry

Feed

Livestock	Months of only grazing	Months with mixed feed	Months with only supplementary feed and fodder	Feed types	Estimated quantity/ volume	Measured mass	Purchased?
Cattle							
Donkey							
Sheep and goats							
Camel							
Poultry							

Water

Livestock	Water sources	Quantities (per day or week)
Cattle		
Donkey		
Sheep and goats		
Camel		
Poultry		

Additional questions on livestock husbandry

- Where do your livestock spend the night? (differentiate between animals)
- Where do they spend the day?
- For how many hours daily are they away from the homestead?
- From what animals do you collect manure?
- How do you collect manure, and how do you decide upon what it should be used for?
- From where do you collect animal manure?
- Where do you store manure?
- For how long do you store manure before using it?
- Do you use any bedding material for the livestock? If yes, what kind, and about how much?
- Do you add urine to straw improve palatability for livestock?
- Do you have cat/dog? What do they eat?

Recording 1.7: Current sanitation practices

- What kind of latrine do you have in your household?
  ☐Have no latrine ☐ arborloo/other eco-san solution
  ☐ deep pit with cement slab ☐ deep pit without cement slab
- When was it installed?
- Are you satisfied with the solution?
- What will happen when the latrine fills up?
- Do small children use the latrine? If not, what happens with their excreta?
- To urinate only, where do men go?
- To urinate only, where do women go?
- When having people visiting you, would they use the latrine?

Questionnaire on soil management

Tilling

- How deep do you till your soil?
- What tools do you use?
- When do you till your soil, and how to you decide upon a date?
- How many times to you till?

Sowing and weeding

- When do you sow your crops?
- Do you buy seeds or save your own for sowing?
- When and how and how many times do you weed?
- What do you do with the weeds?

Fertilization management

- In bags (50 kg) or quintals (100 kg), how much did you apply last season of following:
  - DAP:________________________
  - Urea: _______________________
  - Compost:___________________
  - Other:_______________________
- When do you apply fertilizer?
- What do you base your fertilization management strategies on?

Irrigation

- Do you irrigate any field crops, vegetables or fruit trees? What kinds? For subsistence or for selling?
- When do you irrigate?
- What water source do you use? What technique? How much water do you use?

Water availability

- Is water scarcity a threat for good yields?
- Is standing water or surface runoff a problem during the rainy season?

Other farming practices

- Do you practice crop rotation? If yes, in what way, with what crops and why?
- Do you leave any land fallow? If yes, why?
- Do you burn crop residues? If yes, why?

Perceptions on fertility and fertilizers

- How would you describe your land in terms of fertility?
  ☐ Very poor ☐ Poor ☐ Medium ☐ Good ☐ Very good

- How satisfied are you with the yields that you get?
  ☐ Not satisfied ☐ Somewhat satisfied ☐ Very satisfied

- Is there any variation in yields from your different fields?

- How has the fertility of your soils changed since you started farming?
  ☐ Become more fertile ☐ Become less fertile ☐ No change

- If changing, how do you experience it?

- What do you think is the reason?

Access to resources

- What is the distance (in minutes walking) to your…
  closest field: ________________ field farthest away: _________________

- How do you transport fertilizers, grain and straw to and from your fields?

- How is your access to livestock for farming (cattle, donkeys)?
  ☐ Good, I own all the livestock I need
  ☐ Medium, I do not own all the livestock I need, but can borrow or hire for a low cost.
  ☐ Poor, I do not own the livestock I need, and it causes problems in my farming, such as:
  ____

- Are you content with the amount of land that you have access to farm?

- Can you afford the amount of mineral fertilizer (DAP and Urea) that you would like?
  ☐ Yes. Last year I paid all the fertilizer I needed with cash.
  ☐ Yes, but I had buy __________ bags with credit.
  ☐ No, I cannot afford to buy as much mineral fertilizer as I would like

- Do you practice composting?
  ☐ Yes – using the composting practice recommended by the government (composting pit)
  ☐ Yes – using the traditional composting way of piling up manure and organic waste in the compound
  ☐ No

- If yes, where do you practice composting?
- Would you like to produce and apply more compost than today? ☐ Yes ☐ No
  If no, why not? If yes, what is the main constraint/difficulty for you?

Section 3: The seasonal calendar

Objective

Understanding seasonal variations in:

- Rainfall and temperature
- Crop production and post-harvest activities
- Animal production events, activities and sites.
- Food availability
- labour or levels of work activity
- Income, expenses and credits

Materials needed

Item	Purpose
Large white paper with a pre-drawn timeline including the 13 months of the Ethiopian calendar.	Represents a timeline of one year, to which all activities can be related.
Pedagogical photos or drawings picturing relevant objects and activities	To place on the timeline were best suited and serve as a base for further discussion.
White papers in smaller size (1/4 or 1/8) of a normal paper	To make new drawings if new objects and activities are mentioned
Marker pens	To mark major events
Peanuts and sticks	To mark relative availability of food

Methodology

1) **The seasonal calendar**

I) The four seasons Kiremt, Tseday, Bega and Belg are identified and marked in the calendar, as well as the major rains, draughts etc.

II) The activities of the cropping year are placed in the calendar (soil preparation, sowing dates and fertilization events for the different crops, eventual irrigation events, harvesting dates, post-harvest activities etc)

III) The livestock related activities are placed in the calendar (births, slaughter, purchase, selling, fed by grazing, fed by fodder, etc). Done with all different kinds of livestock.

IV) Food availability is marked by placing beans or other item symbolizing food in quantities according to availability (1-3 peanuts per month). Months where food needs to be purchased are indicated by placing small sticks.

V) The months when the household is in debt are market, as well as the months with major incomes.

2) **In relation to the discussions, the recording 3.2 is filled out according to the questionnaire.**

Recording 3.1: The seasonal calendar

Recording 3.2: Complementary questionnaire on seasonal activities

Approximate dates for farming activities

Crop	Sowing	Fertilizing	Weeding	Harvesting

- Do any household member go elsewhere for a longer period any time during the year? If yes, for how long, for what reason and for what months?

- For how many months:
- Can livestock rely only on pasture for feed?
- Are most vegetables bought on market?
- Is the household in debt (from credits)?

Questionnaire on daily activities

- How many hours a day do you spend outside the household (women)?
- How many hours a day do you spend outside the household (men)?
- How many hours do small children (0-5 y)
- How many hours do elder children and young (6-18 y) spend outside the household?
- Where do men, women and children you spend time outside the household?
- How does this vary over the year?
- Which are the main tasks, related to household, carried out by men?
- Which are the main tasks, related to the household, carried out by women?

<u>Additional checklist – To discuss if not already mentioned</u>

<u>Perceptions on:</u>

- ☐ Gender roles
- ☐ Prices (for selling and purchasing products)
- ☐ Access to water resources
- ☐ Access to markets
- ☐ Access to inputs, such as fertilizers, ploughing oxen etc
- ☐ Access to agricultural training
- ☐ Access to land

Appendix 2: Consent form

Participation in study on household waste as plant nutrient resources
Purpose with the study:

- To understand what plant nutrient value there is in different household wastes
- To chart the current farming and fertilizing practices in Bolo Silasie
- To evaluate the local soil status

What the study will include:

- Participatory interviews and participative mapping of resource and waste flows with the whole household.
- Soil sampling from fields belonging to the farm household
- Collection of household waste, manure and food/plant material in order to estimate masses and nutrient contents.

How the household can benefit from participating in the study:

- Information of soil status on the household's own fields
- Insight in the potential value and alternative use of household waste and excreta

Consent to take part in research

I, ____________________ and my household voluntarily agree to participate in this research study.

- I understand that even if I agree to participate now, I can withdraw at any time.
- I have had the purpose and nature of the study explained to me and I have had the opportunity to ask questions about the study.
- I understand that participation involves:
  - Participating in repeated interviews
  - That soil samples are taken from the fields that I farm
  - That small samples ash, plant material, foodstuff, manure, compost etc might be taken from my household for laboratory analysis, with my permission
  - That the student might be estimating masses of resources and wastes by weighing ashes, food leftovers, greywater foodstuffs, fodder, firewood etc.
- I understand that I will always be informed before soil or waste samples are collected.
- I understand that I will not be economically compensated from participating in this study, other than a small symbolic compensation for contributing with small shares of houeholds resources and wastes.
- I understand that the results from this study will be published.
- I understand that in any report on the results of this research my identity will remain anonymous.
- I understand that all information from the interviews and analyses will be coded and available only for the student.
- I understand that I will be given feedback on the soil status for the fields that I farm.

Contact information

Jorunn Hellman, student: [redacted]
Annika Nordin, supervisor: [redacted]
Linus Dagerskog, supervisor: [redacted]

Appendix 3a: MFA data for all hh groups

Goods	N ($kg\ y^{-1}$)			
Imports	Worse-off	Middle	Better-off	Average
Food from fields	11.7	16.3	26.4	18.1
Food from market	0.87	1.70	0.78	1.14
Corn from market (for tella)	17.0	16.8	6.68	13.5
Feed from fields	17.4	46.4	73.7	45.8
Purchased feed	6.21	36.5	60.8	34.5
Stove fuel from fields	20.6	23.5	23.1	22.4
Purchased charcoal	0.07	0.08	0.27	0.14
Water	0.00	0.0	0.0	0.0
SUM IMPORTS	**73.8**	**141**	**192**	**136**
Exports				
Manure excreted in fields	3.10	8.59	16.7	9.47
Manure for thresing pans	1.26	1.42	1.75	1.47
Compost	0.00	5.67	5.51	3.73
Human excreta	2.98	2.82	5.17	3.65
Tella	0.63	0.38	0.00	0.34
SUM EXPORTS	**7.96**	**18.9**	**29.1**	**18.7**
Transfers				
Manure for cooking	16.6	21.9	40.1	26.2
Construction material	1.03	2.49	0.72	1.42
Animal-based food	2.39	2.00	3.34	2.61
Food leftovers	2.01	2.01	2.01	2.01
Atella	9.47	10.8	1.96	7.40
Dishwater to livestock	0.34	0.34	0.34	0.34
Human excreta	12.7	12.0	22.0	15.6
Ashes	0.42	0.69	0.91	0.67
Discarded greywater water	0.37	0.37	0.37	0.37
SUM TRANSFERS	**45.4**	**52.5**	**71.9**	**59.6**
STOCK CHANGE	**+65.8**	**+123**	**+163**	**+117**

Goods	P ($kg\ y^{-1}$)			
Imports	Worse-off	Middle	Better-off	Average
Food from fields	1.53	1.98	3.27	2.26
Food from market	0.11	0.24	0.10	0.15
Corn from market (for tella)	2.37	2.35	0.93	1.88
Feed from fields	2.54	6.70	11.2	6.81
Purchased feed	0.88	5.20	9.38	5.20
Stove fuel from fields	1.98	2.26	2.22	2.15
Purchased charcoal	0.01	0.01	0.02	0.01
Water	0.0	0.0	0.0	0.0
SUM IMPORTS	**9.42**	**18.7**	**27.1**	**18.4**
Exports				
Manure excreted in fields	0.45	1.25	2.43	1.38
Manure for thresing pans	0.18	0.21	0.26	0.21
Compost	0.00	4.40	4.28	2.89
Human excreta	0.64	0.60	1.11	0.78
Tella	1.09	0.66	0.00	0.58
SUM EXPORTS	**2.37**	**7.12**	**8.07**	**5.86**
Transfers				
Manure for cooking	3.45	4.55	8.32	5.44
Construction material	0.15	0.36	0.11	0.21
Animal-based food	0.29	0.10	0.52	0.31
Food leftovers	0.08	0.08	0.08	0.08
Atella	1.23	1.40	0.25	0.96
Dishwater to livestock	0.12	0.12	0.12	0.12
Human excreta	2.72	2.66	3.52	2.97
Ashes	3.23	5.33	7.05	5.20
Discarded greywater water	0.37	0.37	0.37	0.37
SUM TRANSFERS	**11.4**	**14.8**	**20.1**	**15.5**
STOCK CHANGE	**+7.05**	**+11.6**	**+19.0**	**+12.6**

Goods	OC ($kg\ y^{-1}$)			
Imports	Worse-off	Middle	Better-off	Average
Food from fields	312	432	698	480
Food from market	15.6	52.5	14.0	27.4
Corn from market (for tella)	620	615	244	493
Feed from fields	1720	4700	7910	4780
Purchased feed	110	480	930	507
Stove fuel from fields	1060	1160	1150	1110
Purchased charcoal	10.7	12.9	42.9	22.2
Water	0.0	0.0	0.0	0.0
SUM IMPORTS	**3810**	**7460**	**10 980**	**7420**
Exports				
Manure excreted in fields	85.2	236	459	260
Manure for thresing pans	34.5	38.9	48.1	40.5
Compost	0.00	107	104	70.1
Human excreta	7.26	6.88	12.6	8.92
Tella	0.00	0.00	0.00	0.00
SUM EXPORTS	**127**	**388**	**623**	**380**
Transfers				
Manure for cooking	583	773	1410	921
Construction material	28.4	68.4	19.9	38.9
Animal-based food	37.0	25.5	40.5	34.3
Food leftovers	51.3	51.3	51.3	51.3
Atella	134	152	27.6	104
Dishwater to livestock	0.72	0.72	0.72	0.72
Human excreta	31.0	29.3	53.8	38.0
Ashes	17.5	29.0	38.3	28.3
Discarded greywater water	0.16	0.16	0.16	0.16
SUM TRANSFERS	**883**	**1130**	**1640**	**1260**
STOCK CHANGE	**+3680**	**+7070**	**+10400**	**+7040**

Appendix 3b: Additional procedures and assumptions in the MFA calculations

∴ The sales of grain and pulses have been calculated by subtracting the reported consumption of own grains and pulses from the reported production of the same.

∴ The purchased food types considered are vegetables, grains other than teff and wheat, and pulses. Spices, coffee, oil and animal-based products are not included.

∴ Worse-off families are according to interviews expected to purchase all their vegetables, while middle and better-off families can support themselves with own produce for a quarter of a year.

∴ Meat, eggs, chicken and milk are products that the average hh both sell and purchase, and consume in quantities that resemble their own total yearly production. To simplify the calculations, the consumption of animal-based food has therefor been included exclusively as an internal flow.

∴ Straw and *kubet* are to some extent sold and purchased among neighbours but always stay within the local community. The average hh thus neither purchase nor sell straw or *kubet*.

∴ Areke is a distilled spirit and is presumed to contain negligible total amounts of N, P and OC.

∴ Complementary grazing of grass and shrubs from road and field edges is not included in the MFA since the amounts and N, P and OC concentrations remain unknown. Their contribution is assumed to be relatively small.

∴ No consideration was taken to differences in the amount of time the different hh groups spent home. All groups were assumed to stay home 81% of the day, just as the reported average hh.

∴ The average hh's daily production of food leftovers and greywaters was held to be valid for all hh groups. This assumption is probably not an appropriate reflection of reality, but the evidence was too small (based on 3 hh per group and only one round of collection) to display differences between the groups.