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Effects of climate-smart agriculture on agricultural production, GHG emissions and livelihoods in agro-pastoral and mixed farming systems in southern Ethiopia

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Yonas Berhanu Jagisso

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Part II: Compilation of papers

Paper I

Berhanu, Y., Angassa, A. and Aune, J.B. 2019. A system analysis to assess the effect of low-cost agricultural technologies on productivity, income and GHG emissions in mixed farming systems in southern Ethiopia (Manuscript).

Paper II

Jagisso, Y., Aune, J. B. and Angassa, A. 2019. Unlocking the agricultural potential of manure in agro-pastoral systems: Traditional beliefs hindering its use in southern Ethiopia. *Agriculture,* 9(45): 1-17. doi:10.3390/agriculture9030045

Paper III

Berhanu, Y., Olav, L., Nurfeta, A., Angassa, A. and Aune, J. B. 2019. Methane emissions from ruminant livestock in Ethiopia: Promising forage species to reduce CH4 emissions. *Agriculture*, 9 (130). doi:10.3390/agriculture9060130

Paper IV

Berhanu, Y., Vedeld, P., Angassa, A. and Aune, J. B. 2019. The contribution of frankincense to the agro-pastoral household economy and its potential for commercialization – a case from Borana, southern Ethiopia. *Journal of Arid Environments*: Submitted.

Abstract

Changes in the agricultural sector are essential in order to mitigate and adapt to climate change, meet growing food demands, and improve the livelihoods of poor smallholder producers. Several studies have suggested that the adoption of sustainable agricultural practices is a crucial component of any strategy towards achieving this goal. This study concerns the multiple effects of climate-smart agricultural (CSA) technologies on agricultural productivity, farm income and the environment in agro-pastoral and mixed farming systems in southern Ethiopia.

The study applied a mixed methods approach. Data were obtained from on-farm and laboratory experiments, household surveys, key informants, focus group discussions and value chain analysis. The main results and findings are reported in four separate papers. The first paper shows that a combination of seed priming with micro-dosing could increase farm productivity (up to 45 % increase in grain yield), as well as income. A CSA model farm which was created using this technology, generated surplus grain production, improved food self-sufficiency, and reduced farm-level GHG emissions (Paper I). The second paper explores the potential of manure for increasing yields in semi-arid agro-pastoral systems in Borana, Ethiopia. Results of on-farm trials and manure analysis reveal that there is considerable scope for improving the productivity of these marginal lands by using manure. Manure is an underutilized resource in this area, but the study found that cultural barriers prevent agro-pastoralists from utilizing it. The third paper shows that the use of easily adapted, multipurpose fodder plants has the potential to reduce enteric methane emissions and simultaneously improve the production of ruminants in Ethiopia. The paper concludes that the promising species *M. stenopetala, C. juncea*, and *L. leucocephala* could be promoted as valuable feed resources for ruminants in the study area. The economic contribution of frankincense and its commercialization potential was researched and is reported in Paper IV. The paper shows that income derived from frankincense gathering constituted, on average, 35 % of the total annual income of people involved in harvest of the product. Results of the value chain analysis demonstrate that frankincense production and trade is profitable for many actors involved in the chain. The paper concludes that there is a scope to enhance commercialization of frankincense and its economic and environmental values in the study area.

In conclusion, various low-cost, climate-smart agricultural technologies are recommended as viable technologies for improving food and feed production, while reducing risk and contributing to mitigating GHG emissions. These include both existing (or internal to the farming system) resources such as manure, frankincense and farm-grown forages, and newly adapted technologies such as micro-dosing and seed priming. The findings highlight possible areas for intervention to address emerging livelihood issues, and food and feed security demands, through the adoption of practices that can increase yield, improve resilience and reduce GHG emissions in smallholder systems in southern Ethiopia.

Sammendrag

Forandringer i landbrukssektoren er viktig for å redusere utslipp av klimagasser og tilpasse landbruket til klimaendringer, produsere nok mat og forbedre levevilkårene for fattige småbønder. Flere studier har vist at bruk av bærekraftige klimatilpassede jordbruksmetoder er avgjørende for å nå dette målet. Denne studien omhandler effektene av klima-smart jordbruksteknologi på landbruksproduktivitet, inntekter, og miljø i agro-pastorale og jordbruks- og husdyrsystemer i det sørlige Etiopia.

Denne studien bruker en ulike forskningsmetoder (mixed methods). Data ble samlet fra felt- og laboratorieforsøk, husholds undersøkelser, nøkkel informanter, fokus gruppe diskusjoner og verdi-kjede analyse. Hovedresultatene er presentert i fire artikler. Den første artikkelen viser at en kombinasjon av forspiring av frø, sammen med mikrotilførsel av gjødsel kunne øke landbruksproduktiviteten (opptil 45% avlingsøkning) og samtidig øke inntekter. Et klimasmart modelbruk som ble dannet ved bruk av denne teknologien produserte et overskudd av korn, økte selvforsyningsgraden med mat og reduserte gårdens klimagassutslipp (artikkel 1). Den andre artikkelen undersøkte potensialet til husdyrgjødsel for å øke avlinger i det semi-aride Borana området i det sørlig Etiopia. Feltforsøk på en gård og analyser av husdyrgjødsla viste at det er store muligheter for å bedre produktiviteten i dette marginale området med bruk av husdyrgjødsel. Husdyrgjødsel er i liten grad brukt i dette området, men studien viser at det er kulturelle barrierer som hindrer agro-pastoralistene i å bruke denne gjødsla. Den tredje artikkelen viste at bruk av fôrvekster med stort bruksområde har et potensiale i å redusere metan-produksjon i vomma hos drøvtyggere i Etiopia og samtidig øke produksjonen fra drøvtyggere i Etiopia. Artikkelen konkluderer at de lovende treslagene *M. stenopetala*, *C. Juncea* and *L. Leucocephala* kan bli fremmet som verdifulle fôrressurser for drøvtyggere i området. Det økonomiske utbytte av produksjon av røkelse fra trær og omsetting av dette produktet ble studert og er presentert i artikkel 4. Artikkelen indikerer at inntekter fra innsamling av røkelse i gjennomsnitt utgjorde 35% av de totale årlige inntektene til dem som var involvert i høsting av produktet. Resultatene fra verdikjedeanalysen viser at produksjon og handel av røkelse er lønnsom for mange aktører involvert i verdikjeden. Artikkelen konkluderer at det finnes muligheter for å forbedre kommersialiseringen av røkelse og dens økonomiske og miljømessige verdier i studieområdet.

Konklusjonen er at ulike lavkostnad og klimasmarte landbruksteknologier kan anbefales som bærekraftige teknologier for å bedre mat og fôrproduksjon og samtidig redusere risiko og bidra til å redusere klimagassutslipp. Dette inkluderer både eksisterende (eller interne ressurser) som husdyrgjødsel, røkelse og dyrking av fôrvekster and nyutviklede teknologier som mikrogjødsling og forspiring av frø. Funnen fra studien peker på tiltak for å bedre levevilkår inkludert mat- og fôrbehov gjennom å ta i bruk teknologier som kan øke avlinger, bedre resilience og redusere klimagassutslipp jordbrukssystemer blant småbønder i det sørlige Etiopia.

Abbreviations

C	Carbon
CA	Conservation Agriculture
CGIAR	Consultative Group for International Agricultural Research
CH_4	Methane
CP	Crude protein
CRGE	Climate-resilient green economy
CSA	Climate Smart Agriculture
DFID	Department for International Development
ETB	Ethiopian Birr
FAO	Food and Agricultural Organization of the United Nations
FDG	Focus Group Discussion
GHG	Greenhouse gas
IAASTD	International Assessment of Agricultural Knowledge, Science and Technology for Development
IFAD	International Fund for Agricultural Development
IPCC	Intergovernmental Panel on Climate Change
KII	Key Informant Interview
MPR	Montpellier Panel Report
N	Nitrogen
NAS	the National Academy of Sciences
NGO	Non-governmental organization
NTFP	Non-Timber Forest Product
P	Phosphorus
SI	Sustainable Intensification
SLA	Sustainable livelihood approach
SL	Sustainable livelihood
SSA	sub-Saharan Africa

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Part I: Synthesizing paper

1. Introduction

Agriculture is one of the most important and vulnerable economic sectors in Ethiopia, given its climate-sensitivity, share of the economy, the number of people employed in the sector, and its importance in terms of food security. Agriculture accounts for about 50 % of the gross domestic product of the country, provides employment for 80 % of the population, generates about 90 % of the export earnings, and supplies about 70 % of the country's raw material to secondary activities (McIntosh et al., 2013). Crop production is estimated to contribute on average around 60 %, livestock to around 27 %, and forestry and other subsectors to 13 % of the total agricultural value. Over 95 % of the cultivated land is under smallholder (less than 1 ha) peasant agriculture (FAO, 2018; McIntosh et al., 2013).

Even though agricultural development has brought about major improvements in food security and rural livelihoods over the last few decades (Diao et al., 2012), smallholders in Ethiopia – and elsewhere in the developing world – are exposed to multiple production challenges. These challenges are often linked to limited resources such as land, labour and capital, and limited access to livelihood enhancement opportunities, including access to inputs, technologies, knowledge and markets. The situation is exacerbated by external factors such as increasing climate variability marked by frequent dry spells, environmental degradation, and low levels of public or private investment (Demeke et al., 2006; Niang et al., 2014; USGS, 2012). These constraints result in limited growth in the agricultural sector and exposure of smallholders to food insecurity (CRGE, 2011; McIntosh et al., 2013). Also, the fast population growth (2.5 % per year) (FAO, 2018) makes it necessary to increase food production in the country. As a fundamental first priority, any prospects for growth in Ethiopia – especially of the pro-poor nature – must deal with improving productivity on smallholder farms.

Agriculture needs to address enormous environmental challenges. The environmental impacts of the agricultural sector include those caused by expansion (when croplands and pastures extend into new areas, replacing natural ecosystems), and intensification (when existing lands are managed to become more productive, often using fertilizers, irrigation and mechanization) (Foley et al., 2011). Costly agricultural inputs and lack of capital make farmland expansion the main option for many smallholders in Ethiopia (CRGE, 2011) (e.g. a 15 % increase in expansion of agricultural land was recorded between 2005 and 2010) and elsewhere in Africa to increase production. However, increasing agricultural production through area expansion is often unsustainable, because farmers face diminishing land productivity and adverse environmental impacts of land-use change (Ngoma & Angelsen, 2017; Wood et al., 2004).

Similarly, although intensive agriculture has resulted in increased productivity, it is often at the expense of nature. The extensive use of agro-chemicals and mechanization has caused global water degradation, increased energy use, and widespread pollution, adversely affecting both the environment and the agricultural economy (FAO, 2006; Foley et al., 2011). Agriculture (both intensive and extensive) is also a significant contributor to climate change. It is responsible for about 23 % of global greenhouse gas (GHG) emissions (IPCC, 2019), mainly from tropical deforestation, methane (CH_4) emissions from livestock (enteric and manure), biomass burning, and nitrous oxide emissions from fertilized soils (FAO, 2014).

A challenge for the research and development community is to find more sustainable approaches or options to increase agricultural production, while simultaneously reducing agriculture's environmental footprints, including combating the effects of climate change (Foley et al., 2011; Godfray et al., 2010). Looking forward, smallholder agriculture in Ethiopia in particular and elsewhere in Africa, may have to deal with the double challenge of producing sufficient food and minimizing environmental damages associated with the extensive farming system. The adoption and ongoing use of sustainable agricultural technologies such as climate-smart agricultural (CSA) practices is one approach in addressing this challenge (FAO, 2010; FAO, 2013; Harvey et al., 2014).

This study examines various approaches to using climate-smart agriculture to increase production and reduce the environmental impacts of agricultural production in smallholder systems in southern Ethiopia. Specifically, the aim is to address the following explicit objectives, which correspond to the four papers included in this thesis:

- Investigate the short-term effects of alternative CSA technologies and identify the best-fit technologies that can increase yield, food security, feed production and income; enhance carbon (C) stocks; and reduce GHG emissions at the farm level;
- Examine the agricultural potential of cattle manure in semi-arid agro-pastoral systems;
- Identify promising fodder plants that can reduce CH_4 emissions and simultaneously improve animal productivity; and
- Quantify the economic contribution and commercialization potential of frankincense in drought-prone areas in southern Ethiopia (practicing income diversification to address climate change).

2. Theoretical perspective and conceptual bases

2.1 Sustainable agricultural development and the African smallholder

The concept of sustainability in farming systems and related practices arose from concerns about limits to the availability and carrying capacity of land resources; as well as concerns about the environmental, economic and social impacts of agriculture (FAO, 1993; NAS, 2010). Climate change has affected agricultural production systems significantly, thus explaining the current interest in sustainable agricultural development (FAO, 2006; Niang et al., 2014). Conventional agricultural practices (both intensive and extensive) contribute to climate change mainly through GHG emissions via livestock, deforestation, and the application of fertilizers (FAO, 2006; Foley et al., 2011; IPCC, 2019). Agriculture, in turn, is also affected by shifts in climate. In Ethiopia, where the data for this thesis were collected, climate change has been linked to the increased frequency and duration of droughts (USGS, 2012), which create severe farming conditions and increased vulnerability (Mahoo et al., 2013; USGS, 2012). Therefore, agricultural systems need both to adapt to climate change and reduce emissions. These adaptions require significant changes in production technologies and farming methods (Campbell et al., 2014; FAO, 2013).

Given the decline in available cultivable land globally, the world's food supplies will depend increasingly on raising production per unit area of farmed land. The need now, therefore, is for farmers to take up more sustainable, productive and profitable ways of production that do not damage the soil, the land or the environment. However, the land management systems practiced in many areas of the world – and particularly in tropical, subtropical and semi-arid regions – are damaging soils and limiting their capacity to generate rising yields on a sustainable basis. Particularly in sub-Saharan Africa (SSA), where agriculture makes up 20 to 40 % of the gross domestic product (Godfray et al., 2010), improving the productivity, profitability and sustainability of smallholder farming under adverse climatic conditions is seen as the main pathway out of poverty and food insecurity. At the same time, it is also understood that agricultural systems must play a key role in reducing GHG emissions (Campbell et al., 2014; FAO, 2013; Thornton & Herrero, 2010).

The major principles for developing productive and environmentally friendly agricultural practices are: (1) Designing and adapting agricultural systems to suit the environment of the region; this means, for example, cultivating crops and/or forages (for livestock) that are ecologically adapted to the soil, water, climate and biota present at the site. (2) Optimizing the use of biological, physical and chemical resources in the agro-ecosystem; this includes making effective use of genetic improvements to crops and livestock, using organic and mineral fertilizers, integrating forms of pest management, and improving the management of agricultural wastes and other biological resources. (3) Developing strategies that induce minimal changes in the natural ecosystem, protect the environment, and minimize the use of fossil energy in manipulating the agro-ecosystem (Pimentel et al., 1989).

2.2 Climate-smart approach for sustainable agricultural production and livelihoods

Climate-smart agriculture (CSA) – which is defined by its intended outcomes, rather than by specific farming practices – integrates the three dimensions of sustainable development (economic, social and environmental). The concept was first launched in 2009 by the FAO to draw attention to linkages between achieving food security and combating climate change through agricultural development, and the opportunities for attaining substantial synergies in doing so (FAO, 2009). CSA, as defined by the FAO is: "agriculture that sustainably increases productivity and incomes, resilience (adaptation), reduces/removes GHGs (mitigation), and enhances achievement of national food security and development goals" ((FAO, 2013), p. xi).

CSA is an approach to developing the technical, policy and investment conditions to meet the challenges presented by climate change, thus collectively transforming agricultural and food systems towards sustainability goals (FAO, 2013; IAASTD, 2009; NAS, 2010). The immediate goals of CSA include increasing the productivity of land, water, labour and capital to meet human needs, while preserving the functions of both natural and agricultural ecosystems (FAO, 2013), thus building natural capital; and reducing trade-offs involved in meeting these goals (Steenwerth et al., 2014). This approach also aims to strengthen livelihoods and food security, especially of smallholders, by improving the management and use of natural resources, and adopting appropriate methods and low-cost technologies for the production, processing and marketing of agricultural goods. Although CSA aims to attain all three intertwined pillars (or objectives) (economic, social and environmental), the relative priority of each pillar varies with locations and situations. For example, low-input smallholder farmers in least-developed countries need to put more emphasis on improving productivity, farm incomes and adaptive capacity; whereas farmers in developed countries must focus more strongly on mitigating GHG emissions from agriculture (Campbell et al., 2014; Lipper et al., 2014; Neufeldt et al., 2013; Steenwerth et al., 2014). Therefore, an essential element of CSA is to identify potential synergies and trade-offs between the pillars (Campbell et al., 2014), depending on local conditions and constraints.

Climate-smart agriculture is a new and evolving concept that captures basic ecological principles and promotes the use of innovative technologies. The agricultural technologies and practices that constitute a CSA approach are – in most cases – not new, and coincide largely with those of sustainable agriculture and sustainable intensification (Campbell et al., 2014; Garnett & Godfray, 2012; MPR, 2013; Singh & Singh, 2017). However, under a CSA approach, these practices are evaluated for their resilience, capacity to generate increases in productivity, and mitigation potential in specific locations, given the expected impacts of climate change (FAO, 2013; Williams et al., 2015). As such, CSA focuses on the prioritization of a range of options (existing and newly adapted) and the development of locally suited ones (FAO, 2013; Williams et al., 2015). Some proven CSA technologies that can help meet the goals mentioned above include: conservation agriculture; enhanced water and nutrient management; intercropping; mulching; livestock diet intensification through agro-forestry (for example, feeding the leaves of trees such as *Leucaena leucocephala*); integrated crop-livestock farming; agro-forestry; and weather forecasting practices such as early warning systems (FAO, 2013).

This study attempts to show how a range of low-cost climate-smart technologies (existing and newly adapted) can contribute to the development of more sustainable agricultural production practices and livelihoods in smallholder systems in southern Ethiopia. Paper I deals with the effects of climate-smart crop technologies and multipurpose trees on farm-level productivity, incomes and GHG mitigation; Paper II identifies fodder plants that can reduce enteric CH_4 emissions while simultaneously increasing ruminant productivity; Paper III demonstrates the potential of cattle manure in improving agricultural production in dryland systems; and Paper IV investigates the contribution of frankincense (an abundant non-timber forest product in southern Ethiopia) to household economies in drought-prone areas in southern Ethiopia.

2.3 Climate-smart agriculture: as an agent for improving mitigation and adaptation strategies

The relationship between vulnerability, adaptation and resilience is crucial to CSA (Lipper et al., 2018; Steenwerth et al., 2014), and has become central to the scientific debate in the global scientific community and among development practitioners (Obrist et al., 2010). Vulnerability describes exposure, sensitivity and capacity to respond to adverse impacts of climate change (Beichler et al., 2014; Brooks et al., 2005). Hence, the response to vulnerability is to reduce exposure, enhance coping capacity, strengthen recovery potential and minimize destructive consequences (Watts & Bohle, 1993). Adaptation refers to how to reduce vulnerability.

Resilience is regarded as the capacity to tolerate disturbance, undergo change and retain the same essential functions, structure, identity and feedbacks (Folke et al., 2010; Walker et al., 2004) and is not indicative solely of returning to the same state that existed before a disturbance (Cabell & Oelofse, 2012; Steenwerth et al., 2014). Resilience and resource-use efficiency are included as guiding principles for CSA, presented by Lipper et al. (2014). The authors claim that "CSA pathways result in higher resilience and lower risks to food security", whereas business-as-usual approaches lead to higher risks to food security and lower resilience of agricultural systems ((Lipper et al., 2014), p. 1068).

The increasing diversity of production at farm and landscape level is an important way to improve the resilience of farming systems (FAO, 2013). As discussed above, one of the three components of CSA is building adaptive capacity (resilience), so that farmers may respond effectively to longer-term climate change, and be enabled to manage the risks associated with increased climate variability (Campbell et al., 2014). Adaptive capacity can be built through (among other strategies) improving crop productivity and diversifying farm enterprises (including mixed crop and tree systems) (Bennett et al., 2014; FAO, 2013; Singh & Singh, 2017). Observations and research suggest that farmers who increase diversity suffer less damage during adverse weather events, compared to conventional farmers planting monocultures (Altieri & Koohafkan, 2008; Altieri et al., 2012). Strategies to enhance agricultural diversity in time and space include crop rotations, cover crops, intercropping, crop/livestock mixtures, agro-forestry, composting and green manuring (Campbell et al., 2014; FAO, 2013; Lipper et al., 2018).

Along with these adaptive actions, CSA seeks to contribute to the mitigation of GHG emissions (mainly nitrous oxide (N_2O) and CH_4), and to balance trade-offs with food security and livelihoods (Valin et al., 2013). For example, integrating trees within faming systems to meet food demand will help to mitigate GHG emissions, support biodiversity and concomitantly preserve ecosystem services (FAO, 2013; Steenwerth et al., 2014).

2.4 Sustainable intensification (SI) and CSA

CSA is not the only concept that associates sustainability with agricultural production. There is a substantial overlap between CSA and other terms and concepts, such as sustainable intensification (SI), ecological intensification, agro-ecology, organic agriculture, permaculture, and eco-efficiency. Among these, SI has recently gained much attention, given the population pressure, adaptation and mitigation challenges facing society (Garnett et al., 2013; MPR, 2013; Vanlauwe et al., 2014).

SI is defined as "producing more output from the same area of land while reducing the negative environmental impacts and at the same time increasing contributions to natural capital and the flow of environmental services" ((Pretty et al., 2011), p. 7). Some authors (Campbell et al., 2014) conclude that SI and CSA are closely interlinked concepts. The main difference is the focus of CSA on outcomes related to climate change adaptation and mitigation. Capacity building through improving ecosystem services, diversity of agricultural systems, and information provision are key issues emphasized by the CSA approach. With such an emphasis, CSA provides the foundations for incentivizing and enabling intensification. SI also links to adaptation through its effects on diversifying farm incomes (Campbell et al., 2014).

The CSA approach, with its focus on improving the efficiency of production, is also crucial to the mitigation objective of SI: achieving lower N_2O and CH_4 emissions per unit of product. It is important to stress that SI entails the utilization of existing farmland to produce greater yields, better nutrition and higher incomes while reducing over-reliance on external inputs, and without exacerbating any environmental impact (MPR, 2013); this implies that all cases of CSA always prove to be cases of SI by default. Nevertheless, both SI and CSA are evolving concepts, and thus their meaning, objectives and approaches are subject to debate and contest (Garnett et al., 2013; Lipper & Zilberman, 2018; Neufeldt et al., 2013; Sumberg & Thompson, 2012).

2.5 Contestation of the CSA approach

The CSA approach was initially developed to address the need for a strategy to manage agricultural and food systems facing climate change. It has received considerable support from institutional actors such as the World Bank, IFAD and FAO as well as agricultural research organizations, governments, NGOs and private sector companies. An important feature of the CSA concept is that its ‘triple wins’ agenda, i.e. working simultaneously to achieve its three objectives (or pillars): enhancing adaptation, improving mitigation and increasing food security compared to a business as usual approach (Lipper et al., 2014; Lipper et al., 2018). However, CSA has also received criticism, with some authors suggesting that there is a need to be attentive to ecological limits and social inequalities, as well as to clarify the specific practices associated with the term, and recognize its synergies, tradeoffs, and limitations (Neufeldt et al., 2013). CSA has been criticized on the following ethical grounds: failure to exclude participation in the carbon market; emphasis on technology development and transfer; prevalence of support for agro-industrial expansion; and the exclusion of smallholder voices and priorities (Anderson, 2014; Atela, 2012; Newell & Taylor, 2018).

CSA has often been associated with conservation agriculture (CA). CA is said to increase yields, reduce labour requirements, improve soil fertility, and reduce erosion. Critics argue that it remains unclear which of the principles of CA contribute to the desired effects (Giller et al., 2009; Whitfield et al., 2018); also the suitability and applicability of CA in highly diverse smallholder farming systems remain contested (Sumberg & Thompson, 2012).

Comparisons of zero (or minimum) tillage and conventional tillage yields play a central role in this debate (Giller et al., 2009; Sumberg & Thompson, 2012). One of the main arguments against promoting CA in Africa is that CA was successfully applied within large-scale, mechanized commercial farming systems in the Americas, where the effects of tillage were mitigated by heavy dependence on herbicides and fertilizers. Little is known about the potential of CA to increase productivity, improve soil fertility and reduce erosion within smallholder farming systems in Africa (Giller et al., 2009; Whitfield et al., 2018); in the African context, small and fragmented landholdings are common, and the farming systems are generally more complex (Vanlauwe et al., 2014).

Critics are of the view that although CA has been proposed as an approach to increase the productivity of smallholder agriculture in Africa, the inherently poor soil fertility is a significant constraint to implementing CA in the continent (Giller et al., 2009; Giller et al., 2011). Further challenges to the adoption of CA include increased labour requirements when herbicides are not used, increased labour burden for women, and a lack of mulch due to poor productivity and the priority given to feeding livestock with crop residues (Giller et al., 2009).

Returning to the CSA approach in general, it is important to note that it is not limited to agricultural technologies; it includes the need to build climate information services, responsive governance systems, data processing systems, and education services. Such broad conceptualizations of CSA have been met by both praise and criticism – evidence of the persistent tension between the value of holistic and non-prescriptive approaches (Whitfield et al., 2018). The scope for research and evidence building is boundless because, under CSA, combinations of practices are coupled with combinations of objectives; and also because of the heterogeneity of agro-ecological conditions under which sophisticated technologies are advocated and applied. Hence, it is challenging to clarify the boundaries of CSA concepts (Sumberg & Thompson, 2012; Whitfield et al., 2018). Furthermore, some argue that it is even difficult to analyze claims about the universality of technology and such approaches (Sumberg et al., 2012).

Conservation agriculture is a good case in point. Whitfield et al. (2018) conclude – on the basis of an extensive study conducted in Africa – that it is not yet clear what forms of CA work, for whom, under what circumstances, and how CA is performed in the real world. Moreover, in evaluating CSA, "there is often a lack of clear metrics of success: can a yield increase that contributes little to GHG mitigation, or an overall emissions reduction that reduces water use efficiency be considered 'climate-smart'? Should we give more weight to one priority over the others?" ((Whitfield et al., 2018), p. 3). Sumberg and Thompson (2012) make a related criticism of the context in which agronomic research is conducted in developing countries. They criticize the implementation of CA in Africa, suggesting that the actual adoption of CA will be patchy at best, since it is suited to the circumstances of only a limited number of farmers and farming systems.

As mentioned in section 2.2, CSA stresses the simultaneous fulfilment of three pillars. However, some argue that there is an apparent discrepancy between these three pillars, underlining the fact that CSA is regularly perceived as addressing only adaptation, while neglecting mitigation and food security (Saj et al., 2017). According to (Harvey et al., 2014), research on CSA to date does not exhibit an appropriate equilibrium between the three CSA pillars: how different management practices, systems and landscape configurations affect mitigation and adaptive benefits, agricultural yields, food security, and biodiversity conservation.

Perhaps inevitably, the evidence base for CSA technologies has lagged behind their promotion and advocacy, sometimes resulting in unmet expectations and criticisms of the CSA concept (Whitfield et al., 2018). In particular, there has been limited research on the conceptual basis for CSA (Torquebiau et al., 2018). This lacuna suggests the need for more site-specific investigations that consider the existing political, socio-economic and agro-ecological context of the area. In this regard, some authors (Harvey et al., 2014; Whitfield et al., 2018) suggest that more studies are needed that improve our understanding of when and in which farming systems and at which scales pursuing adaptation and mitigation simultaneously is more beneficial and cost-effective than implementing them separately, thus facilitating identification of what constitutes 'climate smartness' in different biophysical and socioeconomic contexts (Lipper et al., 2014). However (Lipper et al., 2014) insist that although CSA aims to attain all three pillars, it does not imply that every practice applied in every location should generate 'triple wins' .

Nevertheless, according to (Lipper et al., 2014), CSA often requires consideration of all three pillars, from local to global scales, and over short and long-time horizons, in order to identify locally acceptable solutions. Reliable indicators (e.g. of agricultural production and resiliency, adaptive capacity, mitigation potential, ecosystem services, and human wellbeing) are also required to track the suites of synergies or tradeoffs that result from different agricultural development scenarios and be used to inform decision-making (Harvey et al., 2014). For this, the development of consistent CSA metrics is essential. The recognition of trade-offs is particularly crucial in developing countries, where agricultural growth and adaptation for food security and economic growth are priorities, and where poor farmers are the most affected by – but have contributed least to – climate change (Lipper et al., 2014; Lipper et al., 2018).

2.6 Sustainable livelihoods approach (SLA)

Farming systems in Ethiopia exhibit a high degree of heterogeneity, livelihood strategies, population pressures, and agro-ecological conditions (Chamberlin & Schmidt, 2010; Mengistu, 2006). This heterogeneity is reflected in the wide institutional variation in, for instance, access to markets, physical and knowledge infrastructure, service provision, and policy environments (CRGE, 2011; Vanlauwe et al., 2014). Heterogeneity in the economic, cultural and social status of households influences their access to livelihood assets such as land, labour and capital, which may in turn cause them to vary their livelihood strategies – that is, to seek various additional activities that can generate a means of living (Ellis, 2000; Scoones, 1998). The term 'livelihood' attempts to capture not just what people do to make a living, but the resources that provide them with the capability to build a satisfactory life; it also encompasses the risk factors that they must consider in managing their resources, and the institutional and policy context that either helps or hinders them in their pursuit of viable or improved living standards (Ellis & Allison, 2004). A sustainable livelihood is one which "can cope with and recover from stress and shocks, maintain or enhance its capabilities and assets, and provide sustainable livelihood opportunities for the next generation; and which contributes net benefits to other livelihoods at the local and global levels and in the short and long term" ((Chambers & Conway, 1991), p. 6).

The heterogeneity of smallholder farmers in Ethiopia suggests that pathways towards the development of sustainable production systems such as CSA need to be flexible in practice and adapted to local agro-ecological conditions at region, village, farm and plot levels. Such flexibility extends to crop choice and cropping patterns, a farmer's ability and willingness to invest, and specific institutional issues that can enable adoption and reduce risk (Scherr et al., 2012; Vanlauwe et al., 2014). Within any given community, variation in household-level characteristics (income, asset holdings and access to assets, and availability of household labour) and contextual variables, and production objectives will also impact the likelihood of adopting agricultural technologies (Giller et al., 2009; Vanlauwe et al., 2014). This implies that knowledge of various existing perspectives (economic, socio-organizational and environmental) is essential for exploring and designing appropriate agricultural technologies compatible with those circumstances or contexts (DFID, 1999; Vanlauwe et al., 2014).

A CSA strategy may be viewed as a concept of sustainable agriculture, since it can provide three types of benefits: (i) financial benefits for farmers (e.g. improved stability in yields; higher ratios of outputs to inputs; reduced demands for labour, much lower costs of farm power; and resilience to drought); (ii) benefits to communities and society (e.g. improved fodder and fuel wood supply); and (iii) ecological benefits (including increased carbon sequestration and retention in soils; reduced GHG emissions; conservation of soil and water), thus building natural capital and reducing the trade-offs involved in meeting these benefits. The sustainable livelihoods approach (SLA) may therefore be an essential tool in understanding how different CSA technologies could contribute to households' livelihoods and wellbeing, while also preserving the environment. The sustainable livelihoods approach or framework is illustrated in Figure 1.

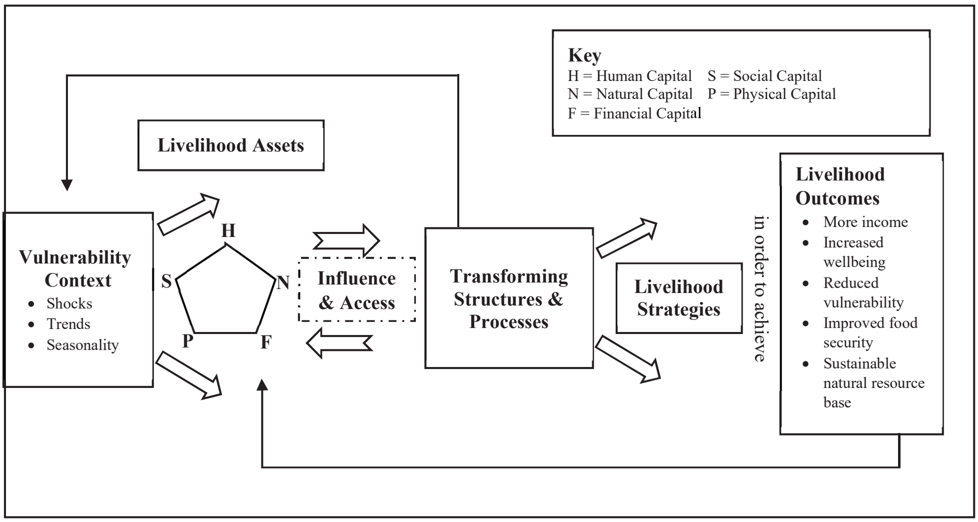

Figure 1 Sustainable livelihoods framework.
Source: (DFID, 1999).

The SLA is based on a set of six principles: (1) sustainable – find a balance between the social, economic and ecological components of sustainability; (2) people-centered – focus on the needs of the people (and different groups) in terms of poverty elimination and food security; (3) policy arena – formulate multilevel policies; (4) dynamic – recognize the dynamic nature of livelihood strategies; (5) participatory – people themselves must identify their livelihood priorities; (6) conducted in partnership – both the public and private sectors should get involved and interact with each other (Ashley & Carney, 1999; Toner, 2003). Thus, the SLA draws attention to people's capabilities, assets and activities, as well as to transforming structures and processes in order to pursue positive outcomes such as higher income, improved food security, or more sustainable use of natural resources (Kanji et al., 2005).

2.7 Effectiveness of the SLA in assessing the effects of CSA interventions

The sustainable livelihoods (SL) perspective seeks to develop strategies that enhance the five types of assets (human, social, natural, physical or produced, and financial capital) (Figure 1) that households can exploit. Sustainable agricultural interventions, for example CSA (as investigated in the present study), are different from conventional ones, in that they a) contribute to the accumulation of the different types of capitals; and b) they integrate improvements that have synergistic effects (Pretty & Hine, 2001). The SL framework appears relevant to this study in that it is rooted in the aim of improving food security and environmental health. It pays attention to the five types of capitals that make up livelihood assets; how they are transformed through the farm, livelihood or community system; and the outcomes of that transformation (e.g. more income, increased wellbeing, reduced vulnerability, improved food security, more sustainable use of the natural resource base).

Studies (Nkala et al., 2011) indicate that by availing households of opportunities to improve their livelihood strategies through the use of agricultural technologies (e.g. CSA), development interventions can improve household wellbeing. The SL framework also highlights the vulnerability context, policies and local institutions – and the fact that all these (including assets) interact with each other (Carney, 2001). The framework has conceptual roots in various traditions, including applied social science, agro-ecosystems/farming systems analysis, and uniquely participatory approaches to rural development.

For this study, it helps to re-orient our thinking towards sustainable agricultural interventions such as CSA that are designed to enhance smallholders' existing livelihood strategies. In this regard, Ramírez (Ramírez, 2002) for instance, provides evidence that the contribution and effectiveness of agricultural interventions can be best appraised within a sustainable livelihoods framework. The SL offers an analytical framework and the tools and experience to link agricultural interventions with food security and environmental objectives. Such an agricultural strategy holds promise in being able to address the various assets from which different product streams are derived and livelihoods are constructed (Ramírez, 2002), while at the same time realizing environmental benefits.

In this thesis, the SL framework was used to generate an understanding of the effects of low-cost and low-risk climate-smart technologies (both newly adapted and locally available) on improving agricultural productivity, farm income, and reducing environmental damage. The investigation relied on a range of data collection methods – including a combination of quantitative and qualitative methods – and varying indicators (e.g. increased farm yield, more income, improved food security, and increased carbon sequestration). The following section provides an overview of the study areas and research approaches adopted in the four constituent studies. Further details on data sources, methods of data collection and analysis employed per study are provided in the separate research papers.

3. Materials and methods

3.1 Study area and research approaches

This study was conducted in southern Ethiopia (Figure 2). A mixed methods approach was applied, depending on the scope and objectives of the individual papers. The study combined farm survey questionnaires, semi structured interviews, focus group discussions (FGDs), key informant interviews (KIIs), field observations, on-farm and laboratory experiments. The data in all the studies were analysed using SPSS ver. 25 (IBM Corp, USA).

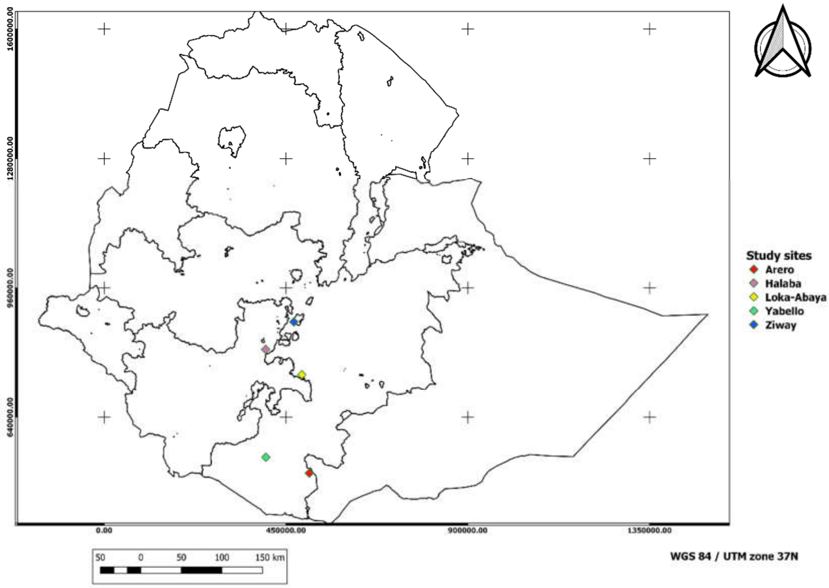

Figure 2 Ethiopia and the study sites

Paper I reports on a study which included on-farm trails conducted at three sites (Ziway, Halaba and Loka-Abaya) for two consecutive cropping seasons (2015 and 2016). It explores the effects of CSA technologies (5 treatments) on farm productivity and income. The treatment that resulted in better yields and profitability compared to the others was selected as the 'best-fit' or 'promising technology'. A conceptual (model) CSA farm was developed using the 'best-fit' CSA treatment and compared to conventional practice, which involve growing an improved maize variety (BH-540), no use of nutrient inputs, and an animal ploughing system. The analyses assessed the consequences of this best-fit CSA strategy for household food self-sufficiency, feed security, income and environmental impacts compared to the conventional practice.

Paper II examines the production, management and agronomic effectiveness of manure in semi-arid settings in southern Ethiopia. Semi-structured interviews (n=30), and manure sampling and analyses were used to collect data on cattle and manure management. Analysis of manure production was conducted in two ways: potential manure production was estimated based on the relationship between live animal weight and excretal output, following (Fernandez-Rivera et al., 1995); and on-farm measurements of manure production were taken, as suggested by (Brodie, 1990). An on-farm experiment was also undertaken to assess the effects of manure on maize yields in semi-arid agro-pastoral settings.

Paper III reports on a laboratory experiment that was conducted to identify forages with low CH_4 production, combined with adequate forage quality. Six tropical multipurpose forages (*Leucaena leucocephala* (Lam.) de Wit, *Moringa stenopetala* (Bak.f.) Cuf., *Sesbania sesban* (L.) Merr*., Cajanus cajan* (L.) Millsp., *Crotalaria juncea* L., and *Lablab purpureus* L. (Sweet)) and maize stover were studied. Maize stover served as a control in the experiment. The forages species were analyzed for chemical composition and their potential for reducing CH_4 production.

Paper IV examines the frankincense value chain and its contribution to the agro-pastoral household economy in southern Ethiopia. Semi-structured interviews (n=61) were conducted. The study applied a combination of sustainable livelihood and value chain frameworks. The study was conducted in two districts (Yabello and Arero) (Figure 2) where frankincense is actively collected and marketed. Due to the semi-nomadic nature of the pastoral populations in these areas, a respondent-driven sampling (RDS) approach was employed to select respondents.

3.2 Research reliability and validity

The research applied a mixed-methods approach. Combining multiple methods – both in data collection and analysis – improves the overall strength of the inquiry process, as well as the validity and reliability of the research results (Creswell, 2014). Reliability refers to how stable and reproducible the results are (Creswell, 2014). Reliability is fundamentally concerned with issues of replicability or repeatability of observations or measures, as supported by a positivist epistemology (Bryman, 2012). In quantitative research, for instance, to assure the reliability and confidence of results, treatments must be replicated or assigned repeatedly to similar experimental units, in sufficient quantities. Related to the reliability, is validity. It is concerned with the integrity of the conclusions that are generated from the research (Bryman, 2012). Validity reveals the level of accuracy to which outcomes or research results correspond with reality (i.e. how the data support conclusions), and is based on determining whether the findings are accurate from the standpoint of the researcher, the participants (or the farmers in this study), or the readers of an account (Bryman, 2012; Creswell, 2014).

The primary objective of agricultural research, such as the present study, is to obtain valid, defensible answers to the questions being studied. To achieve valid answers, one must adhere to basic principles of scientific inquiry, maintain the integrity of the research, and pay attention to procedures (Johnston et al., 2003). Multiple strategies were employed to ensure the reliability and validity of results in this research study. Threats to validity were minimized through the use of appropriate research design, careful selection of representative sites and participants, replication and randomization of treatments, valid and reliable instruments for data collection, and proper analytical tools (Creswell, 2014). Furthermore, triangulation of data from farm and household surveys was conducted using field observations, interviews and discussions. In this regard, my long-term involvement with the research project and the participants in all the study sites has made it easier to repeatedly observe and collect data on the topics being studied at each site over the study period.

3.3 Ethical considerations

In this research, ethical issues were considered at every stage of the project. Before the start of the study, permission was granted by the district agricultural offices at each site and a consultation workshop was held to brief all participants on the objectives and purposes of the research project. The farmers (engaged in the on-farm experiments) were selected after due consultation with extension staff at district and *Kebele* level (the lowest administrative unit), and only after the farmers expressed willingness to participate in the project. Initially the farmers attended an introduction to the research project (objectives and purposes), where the procedures to be followed were explained. The farmers were involved in most phases of the on-farm experiments, from the design of the project to checking interpretations and inferences.

Informed consent was obtained from respondents participating in household surveys, KIIs and FGDs. They were assured of their anonymity and that the information gathered was to be used for academic purposes only. I protected the identity of the respondents by assigning a code to each interviewee. Other ethical issues, such as involving village leaders and respecting local values and norms, were also recognized and respected.

4. Summary of papers

Paper I

A system analysis to assess the effect of low-cost agricultural technologies on productivity, income and GHG emissions in mixed farming systems in southern Ethiopia

This paper explores the effect of climate-smart agricultural (CSA) practices on agricultural productivity and farm incomes in smallholder mixed systems in southern Ethiopia. Five CSA treatments were tested in an on-farm experiment, with the current recommended practice (as a control). The study reveals that although all tested CSA treatments resulted in better yields, one of the investigated treatments was clearly better than the others in terms of effect on maize yield. This treatment involved a combination of seed priming (soaking seeds in water prior to sowing) with micro-dosing (the point application of a small amount of fertilizer – 0.5 g per pocket, corresponding to 27 kg ha^{-1}). It resulted in the highest maize grain yield (an increase of up to 45 %) compared to the control that had received the recommended rate of fertilizer. Another result was that the highest gross margin (net benefit) was obtained from the combined use of primed seed and micro-dosing. This technology was therefore identified as 'best-fit' and used to develop a conceptual CSA farm which was further compared with the conventional practice (receiving no nutrient inputs).

This study identifies a locally specific CSA treatment option that could simultaneously improve farm productivity, enhance adaptive capacity, and mitigate against climate change at the farm level. The analysis provides evidence that, relative to the conventional practice, combining primed seed with micro-dosing has the potential to generate higher farm incomes due to improved productivity. This practice also demonstrated higher fodder production than the conventional farm. It generated a grain surplus that can be sold, as well as an increase in stover production that can be used for fodder. Further important factors contributing to better grain yields observed in the CSA farm were better precision of fertilizer application and rapid seedling emergence. The micro-dosing also reduces risk for farmers compared to conventional practice, thereby making farms less vulnerable, for example in the case of drought. The results further suggest that food security was enhanced on the CSA farm compared to the conventional farm, due to the surplus grain production (more than three-fold higher). Furthermore, the CSA farm performed better than the conventional farm with regard to GHG mitigation. Soil carbon sequestration more than compensated for emissions related to production and use of mineral fertilizer.

In conclusion, the paper shows that low-cost technologies may offer a unique starting point to develop sustainable agricultural production systems (both environmentally and economically) in southern Ethiopia. By combining low-cost and resource-efficient technologies such as seed priming and micro-dosing of fertilizer, farm productivity can be increased with minimal environmental damage (lower GHG emissions and minimal use of chemical fertilizers). The increased farm incomes could allow farming households to build up their assets for use in times of stress (this is an essential element of adaptive capacity) or change their development trajectory altogether. Furthermore, the paper reveals that on-farm development of multipurpose trees can greatly contribute to carbon sequestration at the farm level; and thus, introducing agro-forestry is far more efficient in improving carbon sequestration than the changes obtained when introducing new crops or fertilizer management.

Paper II

Unlocking the agricultural potential of manure in agro-pastoral systems: Traditional beliefs hindering its use in southern Ethiopia

A climate-smart agricultural approach to sustainable food production emphasizes the effective utilization of resources that are internal to the agro-ecosystem. One such resource in the agro-pastoral areas of southern Ethiopia is cattle manure. Paper II presents information on the status of manure use, manure nutrient supply, and its implications for agricultural production in the semi-arid agro-pastoral systems of southern Ethiopia. Results show that, on average, more than 74 tons of manure containing 667 kg nitrogen (N) had accumulated per farm. This manure has an economic value, in terms of N supply, equivalent to ETB (Ethiopian Birr) 16,452 (US$ 802). The results further suggest that about 613 % of the N and 16.7 % of the phosphorus fertilizer needs could theoretically be met with manure if all the available manure were to be used to fertilize maize croplands.

Furthermore, this study shows that the application of manure can improve agricultural productivity in these marginal lands (manure alone increased yield by 51 % compared to non-use of inputs). It was found that nearly two-thirds (63 %) of the croplands were less fertile and degraded, and the agro-pastoralists in the study area generally use neither fertilizer nor manure. The application of external input-based alternatives might be difficult in the study area due to their cost, accessibility and the risks of failure. Instead, manure is relatively free than purchasing chemical fertilizer, and environmentally sound.

In the study area, crop yields are low due to the inherent low fertility of soils and no use of fertilizer. The large amount of manure currently available and the observed yield response represent an opportunity to increase crop production in a sustainable way. It is therefore a great paradox that manure is left unused despite the fact that its use could greatly increase crop yields. The paper shows that the traditional beliefs linking manure use to misfortune and loss of livestock have a negative influence on manure use and management. These beliefs are understood to be key causes for not realizing the potential of manure to support crop production in the study area.

Paper III

Methane emissions from ruminant livestock in Ethiopia: Promising forage species to reduce CH_4 emissions

There is increasing interest in the tropics in optimizing animal production while also reducing CH_4 emissions. Paper III quantifies the amount of enteric CH_4 produced from ruminant livestock in Ethiopia, and identifies promising fodder plants that can reduce CH_4 emissions while simultaneously improving nutrient supplies for ruminants. Results show that enteric CH_4 emissions from ruminant livestock in Ethiopia are increasing considerably, in particular, by 12 % or ≈ 6,197 Gg CO_2-eq. between 2011 and 2017. This corresponds to an annual growth rate of nearly 2 %, which is higher than the global average experienced between 1961 and 2010 (0.95 %).

In low-input production systems such as in Ethiopia, the utilization of easily adapted multipurpose forages grown by small-scale farmers could help to mitigate CH_4 emissions and produce economic benefits (Buddle et al., 2011; FAO, 2013). CH_4 concentration (%) was used as a potential indicator to determine the capacity of a plant to lower CH_4 production. The results show that, among the studied species, *L. purpureus* has the highest CH_4 reduction potential (16 %), followed by *C. juncea* (23.45 %), *M. stenopetala* (24.2 %), and *L. leucocephala* (25.5 %). The results further suggest that *Moringa s.* is the most frequently preferred by the farmers, followed by *C. juncea* and *L. leucocephala*. These multipurpose fodder species are significantly different in chemical composition and predicted feeding values compared to the control and among each other. They are rich in crude protein (CP) which makes them important as supplementary feed, since the native forages are CP-deficient and supplementation with conventional feeding concentrates is generally too costly and therefore rare.

The paper concludes that *M. stenopetala*, *C. juncea*, and *L. leucocephala* greatly reduce CH_4 emissions, contain high CP content, and are preferred by farmers. The use of these species can therefore be a promising pathway for sustainable intensification of the mixed farming system in southern Ethiopia. The results indicate that the promising fodder plants identified not only mitigate GHG emissions, but can be economically acceptable. Therefore, they appear to offer an additional benefit for risk-averse, resource-poor livestock producers in southern Ethiopia.

Paper IV

The contribution of frankincense to the agro-pastoral household economy and its potential for commercialization - a case from Borana, southern Ethiopia

In recent years, the desire to promote the adoption of locally specific development options, along with global concerns over rural poverty and the negative effects of climate change, have led to renewed interests in the commercial extraction of non-timber forest products (NTFPs). In the drylands of Africa, NTFP commercialization has been actively promoted as a strategy for improving rural livelihoods and an approach to foster resilience (De Leeuw et al., 2014; Lemenih & Kassa, 2011). This study (Paper IV) examines the frankincense value chain and its contribution to the household economy in southern Ethiopia.

Frankincense is a widely used and traded product in Ethiopia. The results show that income from frankincense, on average, makes up 35 % (4 to 77 %) of total household (n=34) cash income, supporting the notion that many rural populations are highly dependent upon forest resources for their livelihoods. Poorer households derive nearly 50 % of their income from frankincense, almost as much as from livestock production and non-farm revenues combined. Due to their low adaptive capacity and risk-prone production environments, the communities in the study area are vulnerable to the effects of drought and climate variability, which means that they are exposed to severe food and feed insecurity. Frankincense income therefore functions as an economic safety net in difficult times for the households. More importantly, this forest resource is vital even for medium wealth groups, for whom relative frankincense income (i.e. frankincense income as share of total income) reaches nearly 30 %, well above the global average (22 %) estimated in an early synthesis of 54 case studies from developing countries (Vedeld et al., 2007).

While harvesting frankincense is only one activity within a diversified household livelihood strategy, the cash it generates can play an important role as an economic safety net, in sustaining and improving the economy of households in the study area. Results of the value chain analysis show that frankincense production and trade are profitable for many actors and the price increases by 450 % in the value chain. By comparing the values obtained by various actors, it appears that the extractors achieve a lower benefit (in terms of price) than other actors. However, they receive a higher profit margin than other actors along the value chain because they incur no cash cost and the alternative value of family labor is arguably extremely low.

The study concludes that due to the abundance of the resource, and a stable and growing domestic market (Lemenih & Kassa, 2011), the possibility exists to enhance commercialization of frankincense in southern Ethiopia by providing an incentive for increased production, hence leading to increased income and more diversified livelihoods.

5. Synthesis and conclusions

The general objective of this study was to examine the effects of climate-smart agriculture on increasing agricultural production, reducing GHG emissions, and improving farm income in smallholder systems in southern Ethiopia. The objective was tested in four individual but interrelated research studies that investigated various CSA technologies and their impacts. This section offers a reflection on the contributions of this research to existing knowledge and it also discusses the limitations of the study, and avenues for further research. The section also synthesizes the research results of the associated papers. Differences and similarities are established, and the section closes by outlining final remarks.

5.1 Contribution of the thesis

The thesis contributes methodologically and empirically to the body of knowledge on conceptual and practical implications of the CSA approach. It shows that locally available technologies and resources can be integrated with new technologies to promote agricultural production and address economic and environmental constraints at a local level. Although the CSA approach stresses the simultaneous fulfillment of its three pillars, research on CSA in developing countries often concentrates on adaptation, rather than mitigation or food security, sometimes resulting in criticisms of the CSA concept (Neufeldt et al., 2013; Saj et al., 2017; Whitfield et al., 2018). To the best of my knowledge, this is the first empirical study to simultaneously address the three pillars of the CSA approach, as it demonstrates how the CSA approach can simultaneously improve food security, enhance adaptation to climate change, and reduce GHG emissions in smallholder systems in southern Ethiopia.

The study employed different approaches and methodologies, thus promoting the use of interdisciplinary approaches and mixed research methods. Using methods such as farm survey questionnaires, FGDs, KIIs, field observations and on-farm experiments was found to be essential. These are robust and well-established methods for such field investigations, and they are relevant for our objectives, as they are at the interface between the social and natural sciences. This allows a more balanced and integrated assessment of the situation in the study area.

Because the pastoral populations in the study area are dispersed in time and space and are very mobile, it is difficult to find a reasonable sampling frame, and it is uncertain and difficult to assert and correctly identify respondents using conventional household-based sampling strategies. This study is the first to employ a respondent-driven sampling approach to overcome these difficulties and access such hard-to-reach populations in southern Ethiopia.

5.2 Limitations of the study and avenues for further research

The study has several limitations which may affect the quality and external validity of the conclusions. The causes and consequences of the limitations of this study are discussed in this section, as well as considerations to prevent similar limitations in future research.

Based on experimentation and household surveys, we explored the effects of CSA technologies on the production and livelihoods of smallholder farmers and herders in four representative sites in southern Ethiopia: three sites represent the mixed farming system and the fourth is based on the agro-pastoralist system. Analyses, results and findings in this study apply only for parts of this region – that is, they cannot necessarily be generalized to other locations. However, farming systems in Ethiopia exhibit a high degree of diversity in terms of farm characteristics, livelihood strategies, agro-ecological conditions (Chamberlin & Schmidt, 2010; Mengistu, 2006), and institutional factors (CRGE, 2011). The performance and applicability of the technologies identified in this study need to be evaluated at different scales in the country, from village to sub-national or national level; further investigations may be model-assisted explorations, complemented with experimentation, and farmers' observation and experience.

Model-based studies that capture more extensive datasets might be essential to help identify and (when possible) fill critical gaps in the current knowledge of the CSA approach, as well as measures and/or opportunities to promote the promising technologies at the national scale. Furthermore, the model farm that represented the CSA approach was developed based on a combination of only two CSA technologies, which may not be sufficient to study the full potential in developing a CSA farm. There might also be some uncertainties in the interpretation of GHG emissions data because the model was run using default factors or emission coefficients from the literature.

Due to time limitations, farmers engaged in the on-farm experiments were "model" or "good" farmers who were willing to participate in the research project. These farmers were selected in the first year of the project using KIIs, community meeting (at Kebele level) and observations. Despite this, however, picking only "model" farmers might restrict the recommendation domain. Complementary follow-up research to understand the potential impacts of CSA technologies on the performance of farmers and herders in different groups (e.g. men, women, different age or wealth groups) of the population would expand the recommendation domain and allow a better understanding of the likely effects of CSA-based interventions.

In study IV, the data were collected, through a single case study, from a limited number of frankincense gatherers and market actors. Furthermore, due to time and financial constraints, the market survey did not include national and international frankincense markets. The data presented should thus be considered as a pilot case study in obtaining insights in the commercialization of frankincense that originates from the southern Ethiopia. In this regard, future research on frankincense resources (including the regeneration capacity and domestication potential of frankincense yielding trees) and analysis of overall livelihoods of the agro-pastoral population would allow for a more complete and accurate assessment of the sector, and thus increase the external validity of the results. In addition, value chain analysis that considers the national harvest and trade, and international markets could enhance the wider validity of conclusions.

5.3 Synthesis and final remarks

This study shows that low-cost and context-specific technologies need to be implemented to address existing socio-economic and agro-ecological contexts in the study area. This thesis contributes to global and local knowledge about how a combination of CSA technologies can enhance farm-level productivity (generate surplus production); diversify and improve household income (build up adaptive capacity); and reduce GHG emissions in southern Ethiopia. More importantly, the thesis attempted to show how different CSA technologies can be used as a starting point to develop sustainable agricultural production and livelihood systems in smallholder contexts.

The combined application of seed priming with fertilizer micro-dosing (presented in Paper I) has the potential to improve productivity and economic returns, and promote environmental sustainability (less use of chemical fertilizers and improved soil C sequestration) in smallholder systems, relative to conventional practice. The use of easily adapted multipurpose fodder plants i.e. *M. stenopetala*, *C. juncea* and *L. leucocephala* (Paper III) might be potentially efficient in increasing ruminant productivity in a sustainable way. These fodder plants can be promoted as valuable feed resources, not only to provide high-quality feed to complement low-quality native forages, but also to mitigate CH_4 emissions from ruminant livestock in the region. Agro-pastoralists in the drylands of southern Ethiopia do not apply manure to crops, and awareness about its potential benefits is non-existent. Nonetheless, the results from this study (Paper II) indicate that the application of manure has the potential to improve the productivity of dryland systems without much investment. The utilization of such resources that are internal to the agro-ecosystem can have a positive effect, especially where farmers cannot afford to purchase mineral fertilizers (Rufino, 2008), and the risk of failure is high. Frankincense production and sales (explored in Paper IV) can be promoted in the region to diversify household economies and reduce the risks associated with frequent crop and pasture failures.

The technologies tested and explored in this study are low cost, productive and profitable, and can be easily adapted to the agro-ecological and socio-economic settings of southern Ethiopia. While some of the studies combine different technologies (e.g. Paper I), others concentrate on individual practices (e.g. Paper II and Paper IV); the findings from all four studies complement each other and highlight different approaches to, and effects of climate-smart agriculture technologies and practices.

Finally, the thesis shows that both existing resources (that is, internal to the farming system), such as manure, frankincense, farm-grown forages – and newly adapted technologies, such as micro-dosing and seed priming – can serve as an entry point for the sustainable development of local farming systems. If implemented, the technologies studied will have a positive impact on environmental health (mitigation benefits), food and feed security, and improved livelihoods in smallholder systems in southern Ethiopia. In conclusion, this study contributes to the growing national and global knowledge base on context-specific sustainable agricultural development options that could lead to a sustainable future at local and national scales.

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Part II: Compilation of papers

PAPER I

A system analysis to assess the effect of low-cost agricultural technologies on productivity, income and GHG emissions in mixed farming systems in southern Ethiopia

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-Manuscript-

Abstract

This study assessed the effects of various low-cost climate-smart agricultural (CSA) technologies on farm productivity, farm income and greenhouse gas (GHG) emissions in smallholder farming systems in southern Ethiopia. On-farm trials were conducted at three study sites/districts (Ziway, Halaba and Loka-Abaya) during the 2015 and 2016 cropping seasons. The experiment compared five climate smart treatments against existing recommended practice. Three farms were selected at each site. Each farm hosted one full experimental repetition, thus functioning as an experimental block. The average data of the two seasons were taken from each farm and means were calculated per site and over the study sites as well. The on-farm trails were established to identify a CSA technology that can improve yields and economic returns, while simultaneously reduce GHG emissions at the farm level. Averaged over the three sites, a combined application of seed priming with micro-dosing (0.5 g of fertilizer per pocket) was identified as the best-fit technology in terms of farm productivity and farm income. Results show that this technology increased maize grain yield by up to 45 % (compared to the recommended practice). A model CSA farm was then created using this technology which was compared with the performance of the farmers' current system (conventional farm). It generated surplus production of both grain (more than three times higher) and fodder. The CSA farm produced 84 % of dry matter fodder (DM) requirements and 60 % of livestock crude protein (CP) needs respectively, while the conventional farm produced 30 % DM and 48 % of CP needs. Furthermore, the CSA farm demonstrated reduced GHG emissions compared to the conventional farm which grows maize without the use of mineral fertilizers. Our estimates indicate that due to the establishment of multipurpose trees on the CSA farm, the total on-farm C stock was about 29 Mg ha^{-1}, that is 24 % higher than the conventional farm. In conclusion, we recommend the combined application of seed priming and micro-dosing as a strategy for improving economic returns and promoting environmental sustainability in maize systems in southern Ethiopia. The on-farm development of multipurpose trees can further enhance sustainability, as demonstrated in one of the study sites.

Key words: Low-cost technologies; farm productivity; economic returns; conventional farm; climate-smart agriculture; greenhouse gas emissions; southern Ethiopia

1. Introduction

Smallholder farmers in Ethiopia are under severe pressure to increase productivity and farm income, and to feed a growing human population. They are confronted by a number of livelihood challenges, including low incomes, food insecurity, natural resource constraints (such as rainfall variability marked by frequent dry spells), inadequate resource allocation, technological limitations and land degradation (Baye, 2017; McIntosh et al., 2013; USGS, 2012). Furthermore, poor management of soil fertility and continuous cropping exacerbate soil nutrient depletion, placing many smallholder farmers in a vulnerable position.

In Ethiopia and elsewhere in Africa, costly agricultural inputs and limited access to credit imply that the main option for many smallholders to increase agricultural production is farmland expansion (Ngoma & Angelsen, 2017; Wood et al., 2004). However, this is often unsustainable because it may result in diminishing land productivity and adverse environmental impacts of land-use change (Ngoma & Angelsen, 2017; Wood et al., 2004). With the growing human population, impacts of climate change, and decreasing arable areas, there is a need to transform agricultural systems into production systems that are productive, stable, climate neutral, and environmentally sound.

In response, climate-smart agriculture (CSA) has been developed and promoted as an approach to agricultural development in smallholder farming systems in the tropics (FAO, 2010; FAO, 2013; Lipper et al., 2018; Steenwerth et al., 2014). This approach is especially relevant in Ethiopia, a country very vulnerable to climate change and strongly dependent on the agricultural sector. CSA is defined as a set of farming principles and practices aimed at increasing productivity and income, enhancing farmers' resilience to climate change, and reducing greenhouse gas (GHG) emissions from agricultural activities (FAO, 2010; FAO, 2013). Examples of CSA technologies that increase yield while reducing GHG emissions in agricultural systems include water management, intercropping, conservation agriculture, integrated nutrient management, mulching, improved agronomic practice, integrated crop-livestock management systems, and agroforestry (FAO, 2013; Lipper et al., 2014).

The principal advantage of the CSA approach is that it offers an attractive framework for reorienting and transforming production systems in response to climate change (Khatri-Chhetri et al., 2017; Khatri-Chhetri et al., 2019; Scherr et al., 2012). Adopting CSA technologies can provide an array of benefits to smallholder farming systems in terms of reduced soil degradation, adaptation to climate change, improved food security, and reduced poverty levels (FAO, 2013; Steenwerth et al., 2014). However, benefits offered by CSA interventions may vary across locations and situations (Lipper et al., 2014). CSA therefore needs to be tailored to local conditions and focus on developing locally suitable options (FAO, 2013; Williams et al., 2015).

This paper shows how different CSA technologies may be combined in order to increase farm level productivity and farm income, whilst reducing GHG emissions in smallholder farming systems in southern Ethiopia. The objectives of this study were i) to examine the short-term effects of different CSA technologies and identify those that provide greater yield and profitability, and reduced GHG emissions; ii) to demonstrate whether the CSA approach has the potential to develop a sustainable production system at the farm level in southern Ethiopia.

2. Materials and methods

2.1 General approach

The methods used in this study included (i) on-farm experiments to determine yield response of maize to CSA treatments; (ii) an assessment of profitability and comparison of GHG emissions under CSA and conventional systems. These methods were used in combination with a farm survey to assess the viability of CSA technologies and their prospects at the farm level. Socio-economic and farm characteristics were collected from the farmers who hosted the experiment. Details are discussed below.

2.2 Study sites

This study was conducted during two consecutive cropping seasons (2015 and 2016) at three sites in southern Ethiopia: Ziway, Halaba and Loka-Abaya. The on-farm trials with CSA practices were conducted in relatively similar agro-ecological settings. Ziway is located at 7°58’19” N and 38°37’59” E; Halaba is located at 7°18’25” N and 38°00’44” E; and Loka-Abaya is located at 6°45’07” N and 38°20’01” E; at altitudes of 1,643 m, 1,810 m and 1,630 m above sea level respectively. The study sites are characterised by a bimodal rainfall pattern (short rains in March and April, followed by the main rainy season from June to October). Farm holdings are small, generally less than 2 ha of cultivated land. Farming is carried out in mixed crop-livestock production systems and, as in most mixed farming systems in the country, large proportions of crop residues are used as feed (Tsigie et al., 2011). Crop production in the study sites is mainly rain-fed and threatened by problems of frequent dry spells, droughts and declining soil fertility (Biazin & Stroosnijder, 2012; Biazin & Sterk, 2013; Kassie et al., 2014; USGS, 2012). Furthermore, the use of improved inputs, such as fertilizer and improved seed, is very limited.

These problems contribute to low agricultural growth and food insecurity. In general, farmers practise animal-drawn tillage, but some farmers in Ziway make use of tractors for ploughing. The principal crops are maize (*Zea mays* L.), teff (*Eragrostis tef* (Zucc.)), wheat (*Triticum aestivum*. L.) and pulses such as haricot beans (*Phaseolus vulgaris* L.). Maize is the predominant cereal crop and is used for home consumption as well as being sold in local markets. Maize crop residue (stover) is an important by-product, primarily used for feed, often as *ex situ* forage and/or through *in situ* stubble grazing. The stover may also be used for fuel. Due to free post-harvest grazing practices and human export of crop residues, hardly any residue is left on the field. Recommended fertiliser rates for the study sites are 100 kg diammonium phosphate (DAP) ha^{-1} and 100 kg urea ha^{-1}. However, due to economic constraints and the lack of supply, most farmers in these areas are not able to apply these levels of mineral fertilizers. As in many farming systems in Ethiopia, increasing risks of crop failure due to irregular rainfall also hinder farmers' use of the recommended rates of fertilizer (Alemu et al., 2014; Kassie et al., 2013; McIntosh et al., 2013). Cattle represent a major asset for farmers in the study sites, providing food, income, draught power, and a hedge against risk.

2.3 Experiments and measurements

On-farm experiments were conducted during the 2015 and 2016 cropping seasons, with three farmers at each site, making a total of nine farmers hosting the tests. Each farm hosted one full experimental repetition, thus functioning as an experimental block. The purpose of this trial was to compare the yield responses of five CSA treatments against the recommended levels of treatment (the control). The treatment that resulted in greater yields and economic returns over the years was considered the best-fit option and was later used to evaluate the effect of CSA on household food self-sufficiency, income, and environmental benefits. Treatments were selected based on the outcomes of a stakeholders' workshop, as well as a comprehensive review of the literature on CSA technologies that have been tested in similar agro-ecosystems in sub-Saharan Africa (SSA) (Aune et al., 2012; Camara et al., 2013; FAO, 2013; Sime & Aune, 2014).

The treatments were:

1. Recommended fertilizer levels, i.e. 100 kg diammonium phosphate (DAP) ha^{-1} and 100 kg ha^{-1} urea at 30 days after planting (53,333 plants ha^{-1}).
2. Fertilizer micro-dosing (MD) (point application of 0.5 g of DAP (equivalent to 26.7 kg ha^{-1}) at planting and 0.5 g of urea (equivalent to 26.7 kg ha^{-1}) 30 days after planting per pocket), equivalent to 17.3 kg N/ha (53,333 plants ha^{-1});
3. Maize seed primed (SP) in water for eight hours, + 3 Mg of mulch (M), + 100 kg DAP ha^{-1} and 100 kg ha^{-1} urea (53,333 plants ha^{-1});
4. MD + maize/sunnhemp (SH) intercropping (53,333 and 266,666 plants ha^{-1});
5. MD + maize/lablab (LL) intercropping (53,333 and 66,666 plants ha$^{-1)}$;
6. SP + MD (53,333 plants ha^{-1}).

On each of the nine farms, a plot size of 420 m^2 was divided into six plots (treatments) each covering an area of 70 m^2 (7 x 10 m). All the plots were maintained for the entire study period. In the intercrop plots, single rows of large-seeded legume (LL) were planted in between the maize rows at an intra-row spacing of 0.20 m, while sunnhemp was planted at an intra-row spacing of 0.10m. In all the treatment plots, maize was planted at an inter- and intra-row spacing of 0.75 and 0.25 m, respectively. One seed per hill was used for maize and lablab, while two seeds per hill were used for sunnhemp.

Farmers conducted all the required management tasks. Yield measurements were taken from each plot. Agronomic and socio-economic data on the conventional farm (i.e. representing the farmers' current system), which grows maize without the use of mineral fertilizers, was estimated based on on-farm surveys. Yield and biomass data were collected from each farm and an average value was taken per site which was then compared with the average CSA farm developed at each site based on on-farm trials. In order to estimate yields of the conventional system, on each of the nine participant farms, a plot size of $70m^2$ was randomly placed adjacent to the experimental plot. On each plot, yield measurements (grain and stover) were taken by harvesting three 5.63 m^2 random sub-plots, excluding the border rows (in cases where the main 70 m^2 plot is set close to the border). The average of the three sub-plots was taken and used to compute the yield per ha for each farm. Socio-economic and farm characteristics were collected from the farmers who hosted the experiment. Data on land and livestock holdings, household size, cropping and feed practices, input use and accessibility were collected using a questionnaire and field observations. A tree inventory was conducted at the start and end of the field work. Initial soil samples were taken at a depth of 15 cm from five points on each farm to characterise the soil in the experimental sites. Soil samples were analysed according to the recommended methods (Anderson & Ingram, 1993; van Reeuwijk, 2002). Soil characteristics of the study sites are given in Table 1.

Table 1. Soil characteristics at 0-15 cm depth for the experimental farms at the three sites (Mean±standard deviations)

Site	% Sand	% Clay	% OC	% TN	Av. P (mg/kg)	pH (H_2O)
Ziway	22.67±1.15	34.67±1.53	2.29±0.44	0.17±0.03	9.68±0.54	7.42±0.22
Halaba	28.33±10.60	33.33±8.39	1.72±0.30	0.13±0.02	19.33±5.65	7.45±0.36
Loka-Abaya	25.33±5.77	38.00±4.00	1.93±0.48	0.16±0.05	11.62±3.37	6.34±0.50

Key: organic carbon (OC), total nitrogen (TN), available phosphorous (Av. P)

2.4 Economic analysis

Economic performance of studied practices was evaluated based on gross margin (GM) (net returns) (CIMMYT, 1988). The GM ha^{-1} was calculated as the difference between total revenue and total variable costs (TVC). TVC was calculated as the sum of labour and input costs (seed and fertilizers); the latter were obtained from local markets. Total revenue was estimated as the sum of maize yield (grain and stover) and legume biomass (kg ha^{-1}). Revenue obtained from each crop (maize and legume) was calculated by multiplying yields/biomass (kg ha^{-1}) with average farm gate price recorded at each site during the two cropping seasons. Monetary values were converted to USD at the rate of USD 1.0 = Ethiopian Birr (ETB) 22.91.

2.5 Analysis of biomass carbon and carbon input from maize and trees planted on-farm

In order to quantify the short-term effects of CSA treatments on soil carbon sequestration, we estimated the carbon content in the aboveground parts and in the roots on each of the nine experimental farms. The aboveground carbon (C) biomass (in carbon, $C_{biomass}$) was estimated by multiplying harvestable aboveground yields of grain and stover (Y_{grain} and Y_{stover}, t ha^{-1}) with the carbon concentration of plant biomass (equation 1). We assumed that maize crop biomass contains 44 % C. Thus, aboveground C biomass was calculated as:

$$C_{biomass} = (Y_{grain} + Y_{stover}) \times 0.44 \quad (1)$$

The belowground carbon biomass was determined based on the assumption that roots and shoots have similar carbon content. The belowground root biomass of maize was calculated from shoot: root ratios. Evidence (Zhang et al., 2015) suggests that the root biomass of a maize crop is 19 % of the total aboveground biomass. Accordingly, maize-derived carbon input into the soil ($I_{maize–C}$) was calculated as:

$$I_{maize–C} = 0.19 \times C_{biomass} \quad (2)$$

The contribution of maize-derived carbon (maize-derived C retention in roots) was estimated by assuming that, on average, 24 % of maize-derived carbon in roots is converted to soil organic carbon, as suggested by (Zhang et al., 2015). Thus, the contribution of root carbon to soil organic carbon (SOC) was calculated as follows:

$$SOC\ (t\ C\ eq.\ ha^{-1}) = I_{maize–C}\ x\ 0.24 \quad (3)$$

In order to assess the potential of establishing agroforestry as a CSA technology, multipurpose trees were planted in one of the study sites (i.e. Ziway) on farmers' crop fields in 2014. Biomass carbon stocks for each farm were calculated as the product of dry matter biomass and carbon content. Furthermore, the carbon sequestration potential of trees grown on the farm was estimated from farm inventory data and allometric biomass functions. The aboveground biomass (ABG) of the trees was estimated using equation 4 (Kuyah et al., 2012a) and the belowground biomass of the trees and/or saplings was estimated using equation 6, as recommended by (Kuyah et al., 2012b).

$$AGB = 0.0905 * DBH^{2.4718} \quad (4)$$

where AGB is the estimation of the aboveground biomass (kg dry matter/plant) and DBH is the diameter (cm) at breast height (1.3 m).

Then the tree biomass was converted to carbon (assuming 50 % carbon content) by using equation 2 (MacDicken, 1997). Thus:

Aboveground carbon (AGC) or belowground carbon (BGC) = AGB or BGB *0.5 (5)

$$BGB = 0.490 * AGB^{0.923} \quad (6)$$

where BGB is the belowground biomass.

Total carbon stock (from trees grown on farm) was calculated by summing the individual carbon pools as suggested by (Pearson et al., 2005). Thus, the carbon stock density of the study area is TC = AGC + BGC, where TC is total carbon, AGC is aboveground carbon, and BGC is belowground carbon.

2.6 Determination of GHG emissions from fertilizer production and application

The amounts of GHG emissions (CO_2 and N_2O) in terms of CO_2 equivalents associated with fertilizer production and application were estimated by multiplying the application rates with their corresponding C emission coefficients (IPCC, 2006; Ledgard et al., 2011). This analysis includes emissions from urea and DAP fertilizers, with average emission factors (i.e. 0.91 kg C eq. kg^{-1} urea and 0.73 kg C eq. kg^{-1} DAP) being taken from (Ledgard et al., 2011):

Emissions (kg C eq. ha^{-1}) = Application rate in kg N ha^{-1} * EFsynthetic fertilizer (7)

where EFsynthetic fertilizer is an emission factor for fertilizer applied.

Synthetic N fertilizer applied to soil can be nitrified or denitrified by micro-organisms, thus contributing directly and indirectly to N_2O emissions. The amount of such emissions is related to the quantity of N applied, timing, spreading techniques, and prevailing environmental conditions (FAO, 2001). In this study, direct N_2O emissions from the on-farm experiment arising from N fertilizer application were determined based on guidelines proposed by IPCC (IPCC, 2006) (equation 8). The method includes a direct contribution from N_2O produced from added N in the soil system, and an indirect contribution of N_2O produced from N that escapes the cropping system via NH_3 volatilisation, N leaching, and surface runoff; however, the present study focused merely on direct N_2O emissions induced by the application of chemical N fertilizer. According to the IPCC methodology, direct N_2O emissions from N fertilizer constitute 1% of the total N fertilizer applied.

Thus, direct N_2O emissions (kg CO_2 eq. ha^{-1}) were calculated as:

N_2O (direct) = FSN × EFN × 44/28 x 298 (8)

where N_2O represents direct N_2O emissions from the application of N fertilizer (kg CO_2 eq. ha^{-1}); FSN = Amount of synthetic fertilizer applied (kg N ha^{-1}); EFN = IPCC emission factor for added nitrogen (0.01 kg N_2O-N/kg N); 44/28 presents the molecular weight of N_2 in relation to N_2O; and 298 is the global warming potential (GWP) for N_2O over a 100-year horizon (IPCC, 2007).

Emissions of CO_2 and N_2O were summed in terms of their 100-year global warming potentials (CO_2-equivalents), i.e. 1 for CO_2 and 298 for nitrous oxide. The total amount of GHG emissions associated with fertilizer use was calculated by summing the individual emission sources considered in the study, as follows:

Total GHG emissions (t C eq./farm) = CO_2 emissions from fertilizer production (ton C eq./farm) + $N_2O_{(direct)}$ emissions from fertilizer application (t C eq./farm).

2.7 Calculating energy needs per adult equivalent unit (AEU) and feed needs for livestock

Other than economic and environmental outcomes**,** our study considers the food and feed security implications of implementing CSA technologies. The dietary requirement of animals was calculated based on the tropical livestock unit (TLU), which corresponds to a mature zebu weighing 250 kg, with daily maintenance needs of 6.25 kg of dry matter (DM) and 156 g of digestible protein (Le Houerou & Hoste, 1977).

Household food self-sufficiency was determined using suggested conversion factors of household members' consumption levels, based on the daily energy requirements per adult equivalent unit (AEU) (Deaton, 2003) and an energy content for maize whole grains (Latham, 1979). The AEU scales the consumption level of household members of different ages to the equivalent consumption level of an adult (Deaton, 2003). Accordingly, as suggested by that author, adults (over 18 years of age) were given a weight of 1 while children (under 18) were given a weight of 0.3.

2.8 Statistical analysis

Analysis of variance was done using SPSS ver. 25 (IBM Corp, USA) to determine the effect of treatments on grain and stover yields, and economic responses. The means were separated using the least significant difference (LSD) test. A probability level of 0.05 was used in all the tests. The average data of the two-year experiment are presented in this paper. The data were analysed separately for each site. The treatment that resulted in the highest yield in terms of grain and fodder production (coined as 'best-fit' in this paper**)**, was used to analyse the consequences of CSA strategies for household food self-sufficiency, feed security, income, and environmental impacts. Finally, a model CSA farm was developed with the 'best-fit' CSA option, and was compared with the conventional (i.e. the farmers' system) practice—which involves growing improved maize variety (BH-540), oxen for ploughing, and no use of fertilizer. In each study area, the CSA farm was developed with the same household and farm characteristics as the conventional farm, but with the best-fit technology.

3. Results and discussion

3.1 Characterising conventional and CSA farms

The characteristics of an average farm in each site were described based on the average socioeconomic data from each three farms and the farm survey. The average CSA farm (hereafter CSA farm) was developed with the same households and farm characteristics as the average conventional farm (hereafter conventional farm), but with CSA technologies. To ensure similar biophysical conditions (soil type, climatic and topographic conditions), experimental plots on the CSA farm were established adjacent to the conventional fields. Table 2 describes the main features of an average conventional farm in each of the three study sites.

The conventional farm in Ziway (representing traditional practice) is 2.5 ha under maize/bean intercropping, with 10.97 TLU cattle, 0.13 TLU local chickens, *teff*, wheat, and eucalyptus and acacia trees. Maize is the major staple crop in Ziway, with an average maize yield of about 1.2 Mg ha^{-1}. The grain yield on the conventional farm was estimated based on the on-farm survey, whereas the yield for the CSA farm was obtained from the on-farm trials. The average milk yield for farms in Ziway is 2.0 litres day^{-1}. The annual maintenance dietary needs of a cattle TLU in Ziway are 2,281 kg (25,023 kg per farm) of dry matter (DM) and 109.5 kg (1,201 kg per farm) of crude protein (CP). The average household size in Ziway is 2.7 AEU and the annual food energy requirement per family is 640 kg (237 kg per AEU), assuming a daily energy requirement of 2,330 k cal per AEU and an energy content for maize whole grain of 359 cal per 100 g edible portion (Latham, 1979).

The conventional farm in Halaba is 1.5 ha in size, with 6.5 TLU cattle and 0.37 TLU local chickens. Farmers here produce the staple crops (maize, beans, wheat); horticultural crops (peppers); and they grow trees (eucalyptus, *Cordia Africana* and *Albizia gummifera*). The average maize yield for farms in Halaba is 2.0 Mg ha^{-1}. The average milk yield in the area is 1.9 litres per cow day^{-1}. The average annual maintenance dietary needs of cattle in Halaba are 14,827 kg of DM and 712 kg of CP per farm. The average household size in Halaba is 3.0 AEU and the annual food energy requirement per family is 711 kg (237 kg per AEU).

The conventional farm in Loka-Abaya is 0.18 ha in size, with around one TLU cattle and 0.1 TLU local chickens. Farmers here produce staple crops (maize and enset); cash crops (coffee and chat); and they grow trees (Eucalyptus, *Cordia Africana* and *Albizia gummifera*). The average maize yield for farms in Loka-Abaya is 2.0 Mg ha^{-1}. The average milk yield in the area is 1.9 litres per cow day^{-1}. The average annual maintenance dietary needs of cattle in Loka-Abaya are 2,281 kg of DM and 109.5 kg of CP per farm. The average household size in the area is 1.3 AEU and the annual food energy requirement per family is 308 kg (237 kg per AEU).

Table 2 Main features of the conventional farms

Variables	Ziway	Halaba	Loka-Abaya	Overall average
Family size (AEU)[a]	2.70	3.00	1.30	2.33
Cropped area (ha)[b]	2.50	1.50	0.18	1.39
Maize grain yield (Mg ha^{-1})	1.17	2.00	2.00	1.71
Fertilizer use	None	None	None	None
Cattle holding (TLU)[c]	10.97	6.53	0.93	6.14
Local chicken holding (TLU)	0.13	0.37	0.07	0.19
Forage area	None	None	None	None
Average maintenance dietary needs (kg per TLU per year)				
Dry matter (DM)	2281	2281	2281	2281
Crude protein (CP)	109.50	109.50	109.50	109.50

Milk yield (l/cow/day)	2.00	1.90	1.90	1.93

[a]adult equivalent units; [b]cropped area comprises cereals; [c]TLU: tropical livestock units, equivalent to an animal of 250 kg weight (Cattle: 0.7; Chicken: 0.01)

In contrast to the national average of 4.6 person per household (UN-DESA, 2017), the households that participated in the present study have smaller family size (on average, 4.33 person/household or 2.33 AEU), partly because some women are widows while in other cases, the children have grown up and left the household. In all the study sites, the conventional livestock feeding system is based on natural pasture and maize residue. Herd composition and herd size remained unchanged in both conventional and CSA systems.

3.2 Yield results

3.2.1 Maize grain and stover yields

Maize grain yield (averaged across seasons) showed significant ($p < 0.05$) differences between treatments at all sites. Results for the tested CSA technologies and the control are shown in Table 3.

Table 3 Average maize grain and stover yield (kg ha^{-1}) in response to different CSA practices

	Ziway		Halaba		Loka-Abaya		Overall	
Treatments	Maize grain	Stover	Maize grain	Stover	Maize grain	Stover	Maize grain	Stover
Control[1]	3564^{a}	4812^{a}	4034^{a}	7034	5293^{a}	7081	4297^{a}	6309
MD[2]	4211^{ab}	7230^{cd}	3957^{a}	8196	5312^{a}	7914	4493^{a}	7780
SP+M[3]	4663^{bc}	5846^{ab}	5154^{ab}	8996	6827^{b}	8418	5548^{ab}	7753
MD+SH[4]	3891^{ab}	6439^{bc}	4302^{a}	7896	5282^{a}	6990	4492^{a}	7108
MD+LL[5]	4255^{ab}	5914^{ab}	4630^{a}	8578	5683^{a}	6788	4856^{ab}	7093
SP+MD[6]	5259^{c}	8296^{d}	5955^{b}	9375	7440^{b}	9668	6218^{b}	9113
Average	4307	6423	4672	8346^{ns}	5973	7810^{ns}	4984	7526^{ns}
$LSD_{5\%}$	774	1271	1564	4800	1180	3845	1611	3312

1 100 kg DAP ha^{-1} and 100 kg ha^{-1} urea at 30 days after planting
2 Micro-dosing (0.5 g of DAP at planting and urea at maize jointing per pocket 30 days after planting)
3 Primed maize seed + 3 Mg/ha mulch + 100 kg of DAP and urea
4 Micro-dosing (0.5 g DAP and urea per pocket) + sunnhemp intercropping
5 Micro-dosing (0.5 g DAP and urea per pocket) + lablab intercropping
6 Water primed seed + micro-dosing (0.5 g DAP and urea per pocket)
ns Not significant. [a,ab,b,bc,c]Different letters indicate significant differences across treatments (Fisher's LSD test, $p < 0.05$)

In Ziway, all CSA treatments recorded significantly higher maize grain yields than did the control that received the recommended rate of fertilizer. At this site, primed seed combined with micro-dosing (SP+MD) produced 48 % higher maize grain yields than the control over the study period. In Halaba, maize grain yields were significantly greater in SP+MD and SP+M treatments than the control, whereas no differences were observed between MD, MD+SH and MD+LL treatments and the control. In Loka-Abaya, SP+MD and SP+M gave similar maize grain yields (averaged over two seasons), which were significantly higher than the control. At this site SP+MD and SP+M increased maize grain yields by 2,147 kg ha^{-1} (or 41% higher) and 1, 534 kg ha^{-1} (or 29 % higher) respectively, relative to the control. However, no significant differences were seen between MD, MD+SH and MD+LL treatments and the control.

Average stover yields in Ziway showed significant differences between CSA treatments and the control. At this site, all CSA treatments produced a significantly higher stover than the control, with highest yields obtained in SP+MD (8,296 kg ha^{-1}). No significant differences were observed in average stover yields among treatments at Halaba and Loka-Abaya. In both these sites, however, seed priming combined with micro-dosing (SP+MD) recorded the highest stover yields compared to the control and the other CSA treatments (Table 3).

The overall maize grain yields, averaged over the three sites, showed significant differences between treatments, with SP+MD producing the highest yield, followed by SP+M and MD+LL, with no significant difference of grain yields between SP+M and MD+LL. Overall, of the tested CSA treatments, primed seed combined with micro-dosing of fertilizer resulted in a robust increase in maize grain yields at the three sites, thus appearing to be a promising technology to improve food production in these locations. The application of a small quantity (0.5 g per pocket, corresponding to 27 kg ha^{-1}) of fertilizer, combined with seed priming, improved maize grain and stover yields by 45 % and 44 % respectively over the control. This is in close agreement with observations made in Mali (Aune et al., 2012) where seed priming combined with micro-dosing of fertilizer resulted in a substantial increase in grain yields over the other treatments. Although no significant differences between treatments were found in overall stover yields, all CSA treatments showed higher yields than the control, with highest being obtained with SP+MD.

Better yields due to priming and micro-dosing might be attributed to better precision in fertilizer application and rapid seedling emergence, as reflected by improved crop establishment and better crop performance (Aune & Coulibaly, 2015; Aune et al., 2017; Harris, 2006). Poor crop establishment under unpredictable and limited soil moisture, and poor soil conditions are major obstacles to obtaining reasonable yields in many farming systems in the tropics (Harris, 2006; Reynolds et al., 2015). Given its low cost and lower risk of failure, a combination of on-farm seed priming and the application of small amounts of fertilizer (micro-fertilization) therefore appears to give an additional benefit for risk averse, resource-poor farmers in the study areas.

3.2.2 Legume yields

Legume biomass yield in intercropping with maize is presented in Table 4. Averaged over the three sites, sunnhemp intercropped with maize produced 6.5 Mg ha^{-1} of green forage over two consecutive seasons, whereas lablab intercropped with maize produced 2.7 Mg ha^{-1} of green forage over the two seasons.

Table 4 Sunnhemp and lablab green forage yield (Mg ha^{-1}), grown in association with maize in the study sites. Standard deviations are shown by '±'

Treatments	Ziway	Halaba	Loka-Abaya	Overall mean
[1]MD + SH/maize intercropping	3.43±1.12	7.39±2.5	8.7±3.43	6.5±2.7
[2]MD + LL/maize intercropping	3.01±1.63	3.31±2.1	1.76±0.7	2.70±0.8

[1]fertilizer micro-dosing + sunnhemp; [2]fertilizer micro-dosing + lablab

Earlier research from Ethiopia (Berhanu et al., 2019) has shown that sunnhemp and lablab have a protein content of 15 % which is above the threshold level of 7 % for animal feed; these CSA treatments could enable greater utilization of protein-deficient native forages, which otherwise would be consumed less and with less benefit to livestock. Thus, both the current and Berhanu et al. (2019) studies show that these intercropping forage legumes (sunnhemp and lablab) can produce a high yield of good quality feed. Thus, such legume-based cropping systems are promising for resource-poor crop-livestock farmers, since more livestock fodder (in the form of maize stover and legume biomass) and increased maize grain yield can be produced from the same piece of land.

3.3 Economic returns

An economic analysis based on the calculation of gross margins for tested CSA practices was undertaken to determine whether these technologies provide sufficient incentives (in the form of increased income) to encourage their adoption by farmers. Separate profitability analyses for the sites are presented in tables 5 to 8. There were notable differences in net benefits between treatments at Ziway and Halaba, whereas no significant differences were seen among treatments at Loka-Abaya. In Ziway, MD+SH resulted in an overall increase in net benefits by 80 %, relative to the control, followed by SP+MD and MD+LL that increased net benefits by 74 % and 67 % respectively. However, these three CSA treatments did not differ significantly among themselves. The total variable costs were significantly higher in MD+LL and MD+SH compared to SP+MD (Table 5). In Halaba, the highest benefits were obtained when fertilizer micro-dosing was combined with sunnhemp intercropping (i.e. MD+SH). At this site, MD+SH more than doubled net benefits over the control (USD 5,684 versus USD 2,815 ha^{-1}) (Table 6). In Loka-Abaya, although no significant differences were seen among treatments, SP+MD provided the largest net benefits compared to the control and the other CSA treatments (Table 7).

Averaged over the sites, significant differences were seen among treatments in net benefits, and all CSA treatments gave significantly higher net benefits than the control (Table 8). This economic response could be ascribed mainly to yield improvements in the CSA practices, relative to the control. Averaged over the three sites, MD+SH gave the highest net benefits (4,615 USD ha^{-1}), followed by SP+MD (4,126 USD ha^{-1}) and MD+LL (3,865 USD ha^{-1}). Increased net benefits in MD+SH and MD+LL were the result of biomass yields of forage legumes. However, the increase in net benefits was accompanied by an increase in costs.

Higher total variable costs were recorded for MD+SH than for SP+MD (USD 184 versus USD 131), due to the higher cost of legume seeds in the former treatment. Considering the dominance of maize in the study sites, it is important to find low-cost options for increasing the net returns from maize.

Under the current situation in the study context, cropping systems based on forage legume intercropping might not be an attractive option, given the higher cost and inaccessibility of legume seeds for the farmers. Due to a lack of supply, the price of legume seeds is very high (5.24 USD kg^{-1}) in the study sites. Furthermore, farmers in all the sites are cash constrained and vulnerable (McIntosh et al., 2013). In such an environment, increased production costs might be a barrier to farmers in adopting this technology (Giller et al., 2011; Khatri-Chhetri et al., 2017; Stonehouse, 1997). Thus, it is likely that farmers will prefer low-cost treatments, rather than those that yield higher net benefits (by incurring higher costs) (CIMMYT, 1988).

Furthermore, the prime aim of the CSA approach is to reduce inputs (costs) without reducing yields (FAO, 2013). From our experiment, SP+MD was able to maintain yields (Table 3) while also allowing a considerable reduction in production costs (Table 8). It also produced higher stover biomass of high economic value. This technology is also easy to introduce, since it does not require any major shift in the conventional farming system. Thus SP+MD is considered to be the best option. This CSA technology was analysed further to study its effect on food self-sufficiency, feed security, income, and environmental impacts (discussed in section 3.4).

Table 5 Costs and benefits analysis for CSA practices and the control at Ziway

Gross income (USD)	Price per unit (USD)	Treatment					
		Control	MD	SP+M	MD+SH	MD+LL	SP+MD
Yield (kg/ha)							
Maize grain	0.24	3564	4211	4663	3891	4255	5259
Stover	0.31	4812	7230	5846	6439	5914	8296
Legume biomass	0.31	-	-	-	3495	3010	-
Revenue (USD/ha)							
Maize grain		855±60^{a}	1011±23^{ab}	1119±157^{bc}	934±97^{ab}	1021±80^{ab}	1262±83^{c}
Stover		1493±357^{a}	2241±124^{cd}	1812±152^{ab}	1996±192^{bc}	1833±69^{ab}	2572±199^{c}
Legume		-	-	-	1083	933	-
Total revenue (TR)		2347	3252	2931	4013	3788	3834
Input costs (USD/ha)							
Maize seed	1.08	27.00	27.00	27.00	27.00	27.00	27.00
Legume seed	5.24	-	-	-	52.39	89.05	-
DAP	0.64	63.77	17.00	63.77	17.00	17.00	17.00
Urea	0.50	49.80	13.27	49.80	13.27	13.27	13.27
Total input costs		140.57	57.27	140.59	109.69	146.37	57.31
Total variable costs (TVC)*		219±6.12^{b}	136±6.20^{a}	219±6.12^{b}	188.04±6.20	225±6.20^{b}	136±6.20^{a}
Returns (USD/ha)							
Gross margin (TR-TVC)		2128±365^{a}	3116±107^{bc}	2712±390^{ab}	3825±567^{c}	3563±549^{c}	3698±289^{c}

*Labour costs not shown in the table. ^{a,ab,bc,c}Different or no letters (maize grain and stover revenue, TVC and gross margin) indicate significant differences across treatments (Fisher's LSD test, $p < 0.05$). Standard deviations are given by signs '±'. ^{ns} Indicates not significant. MD: fertilizer micro-dosing; SP+M: seed priming + mulch; MD+SH: fertilizer micro-dosing + sunnhemp; MD+LL: fertilizer micro-dosing + lablab; SP+MD: seed priming and fertilizer micro-dosing

Table 6 Costs and benefits analysis for CSA practices and the control at Halaba

Gross income (USD)	Price per unit (USD)	Treatment					
		Control	MD	SP+M	MD+SH	MD+LL	SP+MD
Yield (kg/ha)							
Maize grain	0.21	4034	3957	5154	4302	4630	5955
Stover	0.31	7034	8196	8996	7896	8578	9375
Legume biomass	0.34	-	-	-	7396	3321	-
Revenue (USD/ha)							
Maize grain		847	831	1082	903	972	125[ns]
Stover		2181	2541	2789	2448	2659	2906[ns]
Legume		-	-	-	2515	1129	-
Total revenue (TR)		3028	3372	3871	5866	4761	4157
Input costs (USD/ha)							
Maize seed	1.08	27.00	27.00	27.00	27.00	27.00	27.00
Legume seed	5.24	0.00	0.00	0.00	52.40	89.08	0.00
DAP	0.64	64.00	17.00	64.00	17.00	17.00	17.00
Urea	0.50	50.00	13.34	50.00	13.34	13.34	13.34
Total input costs		141.00	57.40	141.00	109.80	146.50	57.40
Total variable costs (TVC)*		212.80±4[b]	129.20±4[a]	212.80±4[b]	181.61±4	218.30±4[b]	129.20±4[a]
Returns (USD/ha)							
Gross margin (TR-TVC)		2815±697[a]	3242±705[ab]	3658±890[ab]	5684±452[c]	4543±929[bc]	4028±1284[ab]

*Labour costs not shown in the table. [a,ab,b,bc,c]Different or no letters (for maize grain and stover revenue, TVC and gross margin) indicate significant differences across treatments at $p < 0.05$. Standard deviations are given by signs '±'. [ns] Indicates not significant. MD: fertilizer micro-dosing; SP+M: seed priming + mulch; MD+SH: fertilizer micro-dosing + sunnhemp; MD+LL: fertilizer micro-dosing + lablab; SP+MD: seed priming and fertilizer micro-dosing

Table 7 Costs and benefits analysis for CSA practices and the control at Loka-Abaya

Gross income (USD)	Price per unit (USD)	Treatment					
		Control	MD	SP+M	MD+SH	MD+LL	SP+MD
Yield (kg/ha)							
Maize grain	0.24	5293	5312	6827	5282	5683	7440
Stover	0.31	7081	7914	8418	6990	6788	9668
Legume biomass	0.14	-	-	-	7743	1705	-
Revenue (USD/ha)							
Maize grain		1270 ± 164^{a}	1275 ± 100^{a}	1638 ± 151^{bc}	1268 ± 158^{a}	1364 ± 142^{ab}	1786 ± 217^{c}
Stover		2195	2453	2610	2167	2104	2997^{ns}
Legume		-	-	-	1084	239	-
Total revenue (TR)		3466	3728	4248	4519	3707	4783
Input costs (USD/ha)							
Maize seed	1.08	27.00	27.00	27.00	27.00	27.00	27.00
Legume seed	5.24	-	-	-	52.4	89.08	-
DAP	0.64	64.00	17.07	64.00	17.07	17.07	17.07
Urea	0.50	50	13.34	50	13.34	13.34	13.34
Total input costs		141.00	57.40	141.00	109.80	146.48	57.40
Total variable costs (TVC)*		213.24 ± 4.1^{b}	129.65 ± 4.1^{a}	213.24 ± 4.1^{b}	182.05 ± 4.1	218.73 ± 4.1^{b}	129.65 ± 4.1^{a}
Returns (USD/ha)							
Gross margin (TR-TVC)		3253 ± 976	3598 ± 679	4035 ± 220	4336 ± 529	3488 ± 868	4653 ± 1054^{ns}

*Labour costs not shown in the table. ^{a,ab,b,bc,c}Different or no letters (for maize grain and stover revenue, TVC and gross margin) indicate significant differences across treatments at $p < 0.05$. Standard deviations are given by signs '±'. ^{ns} Indicates not significant. MD: fertilizer micro-dosing; SP+M: seed priming + mulch; MD+SH: fertilizer micro-dosing + sunnhemp; MD+LL: fertilizer micro-dosing + lablab; SP+MD: seed priming and fertilizer micro-dosing

Table 8 Overall summary of costs and benefits of the CSA practices and the control, averaged over the three sites

Gross income (USD)	Price per unit (USD)	Treatment					
		Control	MD	SP+M	MD+SH	MD+LL	SP+MD
Yield (kg/ha)							
Maize grain	0.24	4297	4493	5548	4492	4856	6218
Stover	0.31	6309	7780	7753	7108	7093	9113
Legume biomass	0.31	-	-	-	6211	2679	¨
Revenue (USD/ha)							
Maize grain		991±236^{a}	1039±213^{ab}	1280±293^{ab}	1035±224^{ab}	1119±237^{ab}	1433±318^{b}
Stover		1956±641	2412±434	2403±649	2204±515	2199±689	2825±764^{ns}
Legume		-	-	-	1560±856	767±592	-
Total revenue (TR)		2947	3451	3683	4799	4085	4258
Input costs (USD/ha)							
Maize seed	1.08	27.00	27.00	27.00	27.00	27.00	27.00
Legume seed	5.24	-	-	-	52.40	89.07	-
DAP	0.64	63.92	17.05	63.92	17.05	17.05	17.05
Urea	0.50	49.93	13.32	49.93	13.32	13.32	13.32
Total input costs		140.86	57.37	140.86	109.77	146.44	57.37
Total variable costs (TVC)*		215±5.14^{b}	131.51±5.3^{a}	215.00±5.1^{b}	183.90±5.3	220.58±5.2^{b}	131.51±5.3^{a}
Returns (USD/ha)							
Gross margin (TR-TVC)		2732±796^{a}	3319±538^{ab}	3468±772^{ab}	4615±945^{b}	3865±859^{ab}	4126±942^{b}

*Labour costs not shown in the table. ^{a,ab,b}Different letters (for maize grain and stover revenue, TVC and gross margin) indicate significant differences across treatments at $p < 0.05$. Standard deviations are given by signs '±'. ^{ns} Indicates not significant. MD: fertilizer micro-dosing; SP+M: seed priming +mulch; MD+SH: fertilizer micro-dosing + sunnhemp; MD+LL: fertilizer micro-dosing + lablab; SP+MD: seed priming and fertilizer micro-dosing

3.4 Farm productivity, food/feed self-sufficiency, and profitability potential of CSA systems

As shown in tables 9 and 10, the CSA system increased maize yield, gross margins, food and feed supply in all three study sites. The discussion in this section is based on the results of the combined analysis (overall summary). In each study area, the CSA farm was developed with the same household and farm characteristics as the conventional farm, but with the best-fit technology, i.e. primed seed combined with 0.5 g of fertilizer (based on farm trials from the three sites). The grain yield on the conventional farm was estimated based on the on-farm survey from the crop field adjacent to the experimental plot, whereas the yield for the CSA farm was obtained from the on-farm trials. The CSA system was far more productive and profitable, despite cultivated areas remaining the same size. On average, on-farm seed priming combined with micro-dosing of fertilizer increased maize grain yields by 260 % on the CSA farm compared to yield on the conventional farm (Table 10).

Averaged over the sites, the total grain production on the conventional farm and the CSA farm was 2 Mg and 7.8 Mg respectively. In order to fulfil the annual food requirements of a household size of 2.3 AEU (Table 2), grain production of 0.50 Mg (0.24 per AEU) is required. The conventional farm produced 1.6 Mg of surplus grain, whereas the CSA farm yielded a grain surplus of 7.3 Mg. Such grain surpluses are high, due to the small family sizes in this study. The CSA farm also improved livestock feed supply. The average annual maintenance dietary requirements of a TLU are 2,281 kg (on average, 14,012 kg per farm) of DM and 109.5 kg (on average, 715 kg per farm) of CP respectively (see Table 2). As shown in Table 10, maize stover production was about 4 Mg in the conventional farm and 12 Mg on the CSA farm.

Livestock plays a critical role in the mixed smallholder farming systems of Ethiopia as a source of income, a source of protein, and a buffer against adverse weather patterns for cropping. However, in the country's conditions of land scarcity, it is difficult to grow sufficient fodder to feed the livestock. Concentrates are expensive and seldom used in Ethiopia (Assaminew & Ashenafi, 2015). Thus, in the face of decreasing grazing lands, many farmers rely on crop residues as an increasingly important ruminant feed resource (Duncana et al., 2016). As illustrated in Table 10, improved livestock production is possible through increased production of stover in the study sites. Although it was not sufficient to meet all the maintenance energy needs of the animals (i.e. cattle), the CSA farm produced significant quantities of maize stover that could cover, on average, 83.6 % of DM and 59.3 % of CP needs per year. The conventional farm could supply only 30.2 % of DM demand and 59 % of CP demand. This result indicates that available fodder resource in the CSA farm might be sufficient in contributing to the 50 % cover by natural pastures in the feed supply in mixed systems in Ethiopia (Mengistu, 2006). Furthermore, the increased stover production in the CSA farm could enable farmers to recycle some of the surplus stover as mulch, thereby contributing to soil carbon sequestration and the maintenance of soil fertility.

Uncertainty regarding the economic advantages of new technologies is often cited as one of the major limitations to their wide-scale uptake in sub-Saharan Africa (Giller et al., 2009).

This study has shown that the CSA system tested (i.e. primed seed combined with fertilizer micro-dosing) contributed to higher gross margins (by 218 %) compared with conventional practice (Table 10), because a high yield was obtained at a low cost (Table 8). The CSA farm can sell 7 Mg of maize grain and generate a total income of USD 1754. The cost of fertilizing 1.4 ha with 27 kg of DAP and 27 kg of urea ha^{-1} would be USD 24.2 and USD 19 respectively (Table 8). It is therefore possible to fund the fertilizer using income earned from the maize grain sale. The economic surplus created can also allow the farmers to make further investments in their farm. This finding also demonstrates the value of stover. Due to a shortage of fodder, farmers use all the stover to feed their livestock. However, as natural pastures covering up to 50 % of the feed supply in mixed systems (Mengistu, 2006), the increased stover biomass in the CSA farm might enable farmers to sell produce. Seed priming and micro-dosing therefore can generate a positive development spiral characterized by increased grain production, enhanced food and feed supply, and improved income.

Table 9 Productivity, food and feed self-sufficiency, and economic contributions of the conventional farm and the CSA farm at the three study sites

	Ziway		**Halaba**		**Loka-Abaya**	
Output	Conventional Farm	CSA Farm	Conventional farm	CSA farm	Conventional farm	CSA farm
Average cultivated area, ha	2.50	2.50	1.50	1.50	0.18	0.18
Maize grain production, Mg per farm	2.90	13.2	3.00	8.94	0.37	1.34
Stover production, Mg per farm	5.83	20.7	5.40	14.1	0.73	1.74
Maize grain yield, Mg/ha	1.17	5.26	2.00	5.96	2.00	7.44
Maize grain production supply (% of demand) per AEU per year	566	2469	518	1511	127	472
Maize stover DM supply (% of demand) per TLU per year	21.20	84.52	45.1	84.8	24.4	81.7
Maize stover CP supply (% of demand) per TLU per year	33.80	59.9	72	60.1	39	58
Gross margin (USD) (per ha)	852	3698	1532	4028	1514	4653

Table 10 Summary of potential contributions of the conventional farm and the CSA farm at the three sites

	Overall	
Output	Conventional farm	CSA farm
Average cultivated area, ha	1.39	1.39
Maize grain production, Mg per farm	2.09	7.81
Stover production, Mg per farm	3.99	12.2
Maize grain yield, Mg ha^{-1}	1.72	6.22
Maize grain production supply (% of demand) per AEU per year	404	1484
Maize stover DM supply (% of demand) per TLU per year	30.2	84
Maize stover CP supply (% of demand) per TLU per year	48.2	59.3
Gross margin (USD) (per ha)	1299	4126

3.5 Contribution of the CSA farm to carbon sequestration and reduced GHG emissions

We quantified GHG emissions and soil carbon sequestration for the conventional and the CSA farms. Table 11 shows estimates of CO_2 and N_2O emissions from N fertilizer production and application, expressed as Mg CO_2 eq per farm, and the farm-GHG balance. These calculations take into consideration emissions from nitrogen fertilizer. Overall, the CSA farm had a slightly better GHG balance (0.23 Mg) than the conventional farm (0.12 Mg).

The findings show that the total maize-derived C retention (C retained from belowground biomass) on the CSA farm was 0.40 Mg CO_2 eq. per farm, while it was 0.12 Mg C on the conventional farm. The CSA farm thus contributed to a net sequestration of 0.23 Mg C per year.

Table 11 Average GHG farm-balance for conventional and CSA farm on a yearly basis

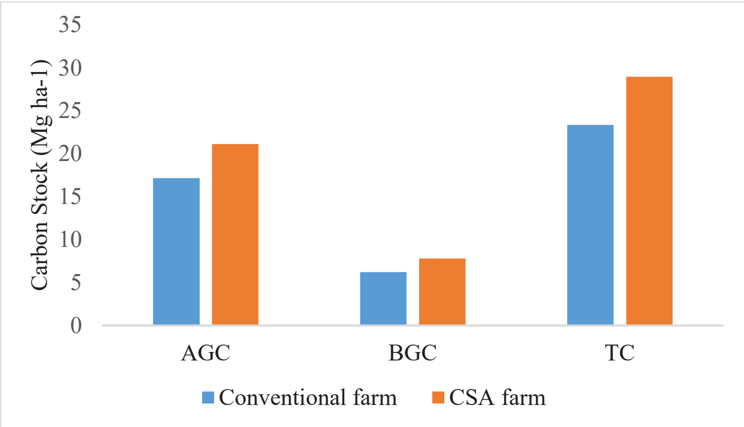
Output	**Overall**	
	Conventional farm	CSA farm
Average cultivated land, ha	1.39	1.39
Maize grain production, Mg per farm	2.09	7.81
Stover production, Mg per farm	3.96	12.18
Total aboveground biomass production, Mg per farm	6.05	19.99
Root biomass production, Mg per farm	1.15	3.80
Belowground (roots) carbon biomass, Mg per farm	0.51	1.67
Carbon in roots transformed to soil organic carbon (C retention in roots), Mg per farm	0.12	0.40
CO_2 emissions from fertilizer production, Mg C eq./farm		
Urea, Mg C eq./farm	0	0.03
Diammonium phosphate (DAP), Mg C eq./farm	0	0.03
Total N applied (Urea + DAP), kg N per farm	0	23.79
N_2O emissions from fertilizer application, Mg C eq./farm	0	0.11
Total GHG emissions from fertilizer production and application	0	0.17
Farm-GHG balance (difference between C gains (SOC retention) and losses/emissions)	**0.12**	**0.23**

Results from the study illustrate that the CSA technology (combined application of fertilizer micro-dosing with seed priming) not only improved plant biomass production (discussed in Section 3.2.1), but also demonstrated a more positive GHG balance than the conventional farm.

3.6 Abatement potential of agroforestry-based climate-smart technologies

In 2014 (at the beginning of the experiment) selected multipurpose trees (*Moringa stenopetala*, *Sesbania sesban* and *Carica papaya* L.) were planted in one of the study sites (Ziway) to test the GHG mitigation potential of agroforestry-based CSA technologies. The total carbon stock is the sum of the carbon equivalent of aboveground biomass and belowground biomass produced by the tree. Total C present in biomass was estimated by multiplying the total biomass with 50 % C, as it was assumed that biomass contains 50 % C (MacDicken, 1997). Figure 1 shows tree biomass-derived C in both conventional and CSA systems. Our estimates indicate that the total on-farm C stock due to the establishment of multipurpose trees on the CSA farm (calculated from tree biomass carbon stock) was about 29 Mg ha^{-1}, that is, 24 % higher than the conventional farm (four years after establishment).

The increase in C stock on the CSA farm is due to an increase in woody biomass as a result of a change in species composition. Our results show that the carbon sequestration potential of introducing agroforestry is much higher than what can be obtained by introducing seed priming and micro-dosing alone. Another study (Eagle et al., 2012) revealed that agroecosystems with a broader diversity of plant species and production activities may achieve higher levels of productivity in the long term, while maintaining larger and more stable C stocks. Biodiversity in agroecosystems may also contribute to diversification of products and diets, and to income stability (Brookfield et al., 2002)—a win-win alternative for smallholder farmers in sub-Saharan Africa (FAO, 2013; Henry et al., 2009). These (*M. stenopetala, S. sesban and C. papaya*) tree species also provide the additional benefit of high quality and palatable fodder. The leaves and fruits of *M. stenopetala and C. papaya* are also rich in protein and minerals and can augment household nutrition and income.



AGC: Aboveground carbon; BGC: Belowground carbon; TC: Total carbon

Figure 1 Average farm-level carbon stock in multipurpose trees growing under conventional and CSA farms in Ziway, four years after establishment (2018)

4. Conclusions

From the results obtained in this study, we can conclude that climate-smart agricultural practices (as compared to conventional practices) yield multiple benefits in the form of increased food and feed production, GHG mitigation, and improved economic returns. The results demonstrate the effects of promising CSA technologies that can be well adapted to the physical and economic conditions of smallholder farmers in southern Ethiopia. This study found that using seed priming and micro-dosing can generate a high economic benefit, while also contributing to enhanced food self-sufficiency, increased feed supply, and improved household economy. The economic surplus created can also allow the farmers to make further investments in their farm. These findings are important, since the long-term sustainability of a practice depends on its profitability, affordability and feasibility for the farmers. By developing a farm model (a conceptual farm) it was shown that the CSA technologies also improved soil carbon sequestration and gave a slightly more positive GHG balance compared to the conventional farm.

Given its low cost and lower risk of failure, seed priming and the application of small amounts of fertilizer (micro-dosing) can provide additional benefits for risk averse, resource-poor farmers in the study areas. Major efforts should be directed into promoting the application of this best-fit technology. Furthermore, the study showed that agroforestry can contribute greatly to carbon sequestration at the farm level.

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PAPER II

agriculture

Article

Unlocking the Agricultural Potential of Manure in Agropastoral Systems: Traditional Beliefs Hindering Its Use in Southern Ethiopia

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Abstract: Manure is often considered a valuable resource for improving productivity in semi-arid tropics. This paper investigated agropastoralist knowledge of the use of manure and barriers that limit manure use in Borana, southern Ethiopia. The potential and actual amounts of manure available on-farm and its relative economic value were estimated. Yield response to manure application was also quantified. Data was gathered using on-farm surveys, focus group discussions, key informant interviews, field observation and on-farm experiments. We found that an enormous amount of manure with substantial fertilizer value and economic benefit had accumulated over the years in studied households in Borana. Our analysis revealed that, on average, more than 74 tons of manure containing 667 kg nitrogen (N)–more than five times the current requirements–had accumulated per farm. This manure has an economic value, in terms of N supply, equivalent to ETB (Ethiopian Birr) 16452 (US$802). On-farm trials showed that a considerable scope exists for increasing the yields of these marginal lands by using manure. However, because of the traditional beliefs and associated practices, which have prevailed for centuries in the community, this valuable resource is left unused. Having identified the link between traditional beliefs and non-use of manure, the paper sets out possible areas for intervention.

Keywords: non-use of manure; traditional beliefs; yield response to manure application; economic value; agropastoralists; southern Ethiopia

1. Introduction

This study was conducted in Borana, which is a lowland semi-arid region of southern Ethiopia. The area is largely inhabited by the Borana, a semi-nomadic people whose main economic activity is based on a combination of extensive livestock production and grain cultivation on small plots [1] Cattle comprise the largest share of livestock biomass and are the most highly valued animals in the area. They are a symbol of abundance, of social status and of community influence [2] while small ruminants are raised for cash income and meat [3]. Crop production in Borana is increasing in importance owing to human population growth, the falling availability of grain and increased demand, and frequent droughts which make livestock rearing challenging [2,4]. The Borana cultivate the land located in close proximity to their "olla"–a collective residential unit where extended families of close relatives reside [1].

Crop farming in Borana primarily involves cultivation of maize, wheat and "teff" and perennials such as sugarcane, banana and *Moringa stenopetala*. Yields are very low because of drought, floods and low inherent soil fertility [5,6], thus, improvement of soil fertility is essential to attain the desired levels of crop yield. Unfortunately, due to various constraints, there is no use of external inputs (e.g. chemical fertilizer); low input agriculture has been implemented in this part of Ethiopia.

The challenge in such drought-prone production environments is to enhance crop (both food and forage) productivity while preserving the sustainability of the land [6]. A feasible option friendly to the producer, soil and environment is needed and cattle manure, hereafter referred to as manure, is one possible option [7,8].

The merits of applying manure to depleted, low fertility and marginal soils has received a wealth of attention in the developed world [9] and the developing world [10,11]. Manure increase yields of crops and forages, and can sustain crop-rangeland integration in semi-arid sub-Saharan Africa (SSA) [12]. In many farming systems of SSA where fertilizer use is low, manure has been utilized as a valuable nutrient source for crops and this trend will most likely continue [13,14]. Because of the low cash requirements, manure is more affordable for poorer households than mineral fertilizer [8,12]. It is also clear that in resource-poor farming systems, the importance of manure will increase as more land is brought under cultivation [12,13]. However, despite all these merits, as a consequence of traditional beliefs that prevailed for centuries in the community, there is no tradition of using manure in Borana (this report). Farming systems and resource management practices in the Borana is strongly influenced by their indigenous religious beliefs and practices [15].

However, to our knowledge, no studies have been conducted on the attitudes, cultural perceptions and beliefs concerning manure in Borana, southern Ethiopia. Furthermore, no attempts have been made to investigate the barriers preventing manure use in the area. Moreover, the benefits of using manure as fertilizing material have not yet been investigated in semi-arid farming systems. Manure-based research in Ethiopia has been concentrated in medium to high rainfall areas of the country [16,17]. Even when such studies have been carried out, they have mainly focused on the availability and quality of manure and its effect on crop production. However, social and economic process, the knowledge or awareness about this resource, and farm-related features can influence the production, use and management patterns of manure in farming systems [18]. A growing body of literature has demonstrated the positive effects of manure application to different crops in agroecosystems across SSA [18]. Against this background, this study was conducted with the following objectives: (i) to assess the status of manure utilization and management (disposal, storage and handling), (ii) to assess agropastoralists' knowledge about manure use and barriers constraining its use, (iii) to quantify the potential and actual amount of manure produced, manure nutrients generated and its relative economic value, and (iv) to investigate, through on-farm experimentation, the effect of manure on maize yield.

This study is meant to inform scholars and practitioners through a quantitative and qualitative assessment of why manure is not used and its potential value in agropastoral systems of southern Ethiopia. Furthermore, by examining yield responses to manure, this study makes a contribution to the literature on the agronomic effectiveness of manure as a source of nutrient for maize production in semi-arid agropastoral setting in Ethiopia.

2. Methodology

To address its multiple objectives, this study applied a mixed method approach. Combining qualitative and quantitative methods provides a better understanding of the research problem or issues of concern than either method alone can provide. A combination of the two approaches is also essential, as each serves different but complementary roles within the overall research design [19]. The study has combined farm survey questionnaires, focus group discussions (FGDs), key informant interviews, field observation and on-farm experiments to determine the effects of manure on maize and stover yield.

2.1. The Study Site

The study was conducted in Yabello district of the Borana zone located in southern Ethiopia. The district was selected purposively as being representative of the extensive agropastoral farming systems of southern Ethiopia. The study area has a semi-arid climate with a highly unpredictable bimodal rainfall pattern [1,20], and an absence of permanent surface water [1]. Average annual rainfall at the study district during 2001–2015 ranged between 412 to 873 mm (with an overall average of 596 mm). The area is prone to periodic droughts [21]. The dominant soil types are shallow and sandy loam soils and Vertisols. The latter are restricted in valley bottoms, low-lying plains and on flat surfaces while upland soils occur elsewhere [1]. As in many parts of semi-arid eastern Africa, soils of the study area are regarded as having low inherent fertility [5]. However, according to Coppock [1], bottomlands and other sites with impeded drainage have better fertility and water holding capacity than soils on uplands. Animals graze freely on communal rangelands during the day, and are kept in kraals during the night. Though livestock production is the dominant farming practice, the pastoralists have gradually taken up crop farming since the mid-1980s drought [1], and crop cultivation is now expanding in valley bottom sites across the district, not merely for subsistence, but to diversify household income (see section 3.1. for detail).

2.2. Field Methods

The first study was an in-depth farm survey of agropastoral households of varying resource endowment to assess manure use and its management, identify farming orientation, farm characteristics and land use practices. These variables were collected using questionnaires aided by FGDs, unstructured key informant interviews and field observation. A multi-stage random sampling technique was employed to select the samples. In the first stage, one "kebele", the lowest administrative unit, was selected purposively based on its production orientation (i.e., widely known for its mixed crop–livestock farming practices). In the second stage, the households (159) in the selected kebele were grouped into permanent (93) and opportunistic (66) agropastorals. In this study, permanent agropastorals were defined as households where the main priority of the household head is crop-related activities, while herding is the responsibility of family members, particularly children. In the opportunistic agropastoral group, the household head's priority is livestock herding, while family labor and sometimes shared or hired labor is usually used to manage crop fields. Accordingly, 30 households were randomly selected from the list of all the households permanently engaged in mixed crop-livestock production at the third stage. As our attention was focused on the value of manure in relation to crop (food and forage) production in the agropastoralists systems, opportunistic agro-pastoralists were not included in the study. Key informant interviews with the kebele manager and extension agents were conducted to identify and categorize all the households engaged in crop farming. For analytical purposes, studied households were categorized into three resources groups based on cattle holding: resource-poor (0.7–14 tropical livestock units, TLUs), medium (14–21 TLUs), and resource-rich (above 21 TLUs). Cattle were considered the most important indicator of wealth status in the area. Nine of the 30 households were chosen for the on-farm manure measurement and nutrient analysis study.

2.3. Procedures to Estimate Manure Production

Analysis of cattle manure production was conducted in two ways: potential manure production estimation based on the relationship between animal live weight and excretal output, and direct manure measurement that is available in the farm. In theory, the amount of manure to be produced was estimated by multiplying the number of cattle with the assumed fecal output per day. Accordingly, we used the live weight and excretion figure of Fernandez-Rivera et al. [22], who assumed that cattle in semi-arid areas of the Sahel produce 0.8% of its live weight as fecal dry matter in a day. According to these authors, grazing ruminants under fluctuating feed supplies produce a constant amount of fecal output per unit live weight [22]. Livestock numbers were collected using the questionnaire. Additionally, the amount of manure currently available (i.e., piled) in the farm was estimated using direct manure measurements and calculations as suggested in Brodie [23].

2.4. Determination of Manure Quality and Its Economic Value

Manure samples from the nine farms were taken from the surface heap (30 cm depth) on eight random spots representing different ages and moisture conditions. The collected samples were thoroughly mixed and a composite sample of 1 kg was taken using a hand-in bag method and transported to the Hawassa University soil laboratory. There, it was air-dried and ground to pass through a 2 mm sieve. The manure was analyzed for organic matter content, pH, phosphorus (P), total nitrogen (TN) and potassium (K) according to the recommended methods [24,25]. Subsequently, the amount of nutrients available for crop production and their economic value was estimated. In an economic valuation of manure, the major emphasis was on the replacement value of N, P and K, as these nutrients are the limiting factors in crop production [26]. In the present study, the replacement cost of inorganic fertilizer (i.e., on an inorganic fertilizer-equivalent rate based on current agronomic recommendation and market value) was used to quantify the economic value of manure.

2.5. The Response of Maize Grain and Stover Yields to Manure

An on-farm experiment was conducted during the 2015/16 cropping season in a randomized complete block design with three replications. Two model agropastoralists were chosen purposefully to host all the treatments of the trial. The treatments were: (1) control receiving no manure and fertilizer (to show agropastorals' usual practice); (2) recommended practices (100 kg diammonium phosphate (DAP) ha^{-1} and 100 kg ha^{-1} urea at 30 days after planting); (3) manure micro-dosing (point application of 70 g (corresponds to 3.71 tons per ha) of manure per planting pocket); (4) five tons (equivalent to 35.45 kg of N ha^{-1}) of manure ha^{-1}; (5) five tons of manure plus intercropping; (6) manure micro-dosing plus fertilizer micro-dosing (i.e., point application of 70 g of manure plus 0.5 g of fertilizer per pocket); (7) manure micro-dosing plus intercropping. In each farm, a plot size of 43 × 26 m that was divided into three blocks was established. The plot size for each treatment was 40 m^2 (8 × 5 m). In plots receiving broadcasted manure, 20 kg $plot^{-1}$, corresponding to five tons per ha was spread over the plots and superficially incorporated into the soil with a long-handled hoe. All the cultural practices were carried out by the agropastoralists. Yield measurements were taken from each plot of both farms.

2.6. Statistical Analysis

Analysis of variance (ANOVA) was performed using SPSS (version 24) to determinate differences in land allocation for different enterprises, manure production potential and livestock to useable farmland ratio between the resource groups. A least significant difference at the probability level of 0.05 was used to delineate significant differences among the resource group means. Standard errors of means of the resource groups are presented. For the variables that did not show statistical differences, or in cases when it was difficult to compare, the results are presented in an illustrative form. Grain and stover yield data were also subjected to ANOVA and means were tested using least significant difference (LSD) at $p < 0.05$. The report was made based on pooled data.

3. Results and Discussion

3.1. Farm Characteristics, Manure Utilization and Opportunity for Pasture Development

The Borana agropastoralists are characterized by large livestock ownership and mixed land use (Tables 1a and 1b). On one hand, livestock farming was well established in the study area. On the other hand, crop cultivation has become an important component of the farming system in recent years. Generally, crop farming was expanding in many parts of the study area, not merely for subsistence but to diversify household income. The total farmland held by the households, excluding home compounds, was 2.15 ha (on average), and all the studied households were engaged in crop production on their private crop fields. The observed mixed farming system reflects the integration of crop–livestock production system primarily cattle, sheep and goats with annual and perennial crops (i.e., fruit trees and *Moringa stenopetala)* (see Table 1a), and suggesting the growing importance of crop cultivation in the study area.

Table 1a. Farm characteristics in Borana, southern Ethiopia.

		Mean	Resources groups (n = 30)		
			Rich (n = 9)	Medium (n = 7)	Poor (n = 14)
Farm skill training (% HH head)	None		26.7	23.3	46.7
	Short-term		3. 3	0	0
Education of HH head (%)	None		16.7	23.3	26.7
	Adult education		10.0	0	6.7
	Primary school		3.3	0	13.3
Farm assets					
Farm land (ha)		2.15 (0.24)	3.46 (0.33)	2.7 (0.37)	1.19 (0.19)
Livestock (TLU)[a]		24.09 (2.5)	41.60 (2.5)	24.90 (2.1)	12.44 (0.7)
Land allocation in %					
Cropped area (three major crops) [b, c]			64.41	51.69	57.14
Grass patch area			7.45	25.85	30.25
Cash cropped land[d]			10.47	13.56	10.10

[a] TLU: tropical livestock units, equivalent to an animal of 250 kg weight; [b] land allocated for mixed use not seen in the table, [c] maize, "teff" and wheat; [d] primarily sugar cane plot; HH: household; values in parenthesis are standard errors.

As in many parts of the country, maize, teff and wheat were allocated the largest share of the cultivated area of most farms. Almost all the crop fields were situated in valley bottom sites and along floodplains to make use of the seasonal flooding. Foot-slopes were also cultivated. The average livestock holding (TLU) per household in the study area was 24.09 TLU, higher than that reported by Yonas et al. [27] and Abate et al. [28] in agropastoral areas of southwest Ethiopia (22.31) and southeast Ethiopia (10.3), respectively. This large livestock holding could be an opportunity for increased manure supply.

Table 1b. Land allocation (in ha) for different enterprises.

Resource group	Total farmland	Cropped area [a]	Cash cropped area	Grazing pasture plot	Mixed plot
Rich	3.46	2.17	0.36	0.26	0.61
Medium	2.37	1.22	0.32	0.61	0.21
Poor	1.19	0.68	0.11	0.36	0.04
Mean	2.15	1.26	0.23	0.39	0.25
se±	0.24*	0.18*	0.05*n.s.*	0.11*n.s.*	0.10*
p-value	0.000	0.000	0.081	0.48	0.000

[a] Cropped area comprises cereals and common bean plots; *n.s.* and * indicate not significant and significant at $p \leq 0.05$, respectively.

Regardless of their wealth category, all the studied households used neither fertilizer nor manure. Absence of fertilizer use was related to the unfamiliarity and/or inaccessibility of fertilizer. In Borana, there is no tradition of using fertilizers in general [29]. In the study area, respondents stated that manure was stockpiled for periods of seven years or longer. The manures heaps were not considered by the agropastoralists as valuable source of nutrients owing to traditional beliefs, limited knowledge and lack of extension services (see details below in section 3.3). This is different from the situation in other parts of Ethiopia where manure is a highly appreciated and valuable resource in mixed farming systems [17,30]. Similarly, settled Fulani pastoralists in West Africa also depend on corralling cattle overnight on farmland to enrich the soil [13,18].

Households, particularly the resource-poor and medium group, were allocated more than a quarter of their farmland to fodder production (Table 1a) for grazing and fodder sale. During the study period (i.e. 2015/16), fresh cut grass forage was sold often at a price of 25 ETB (Ethiopian Birr) (US$1.22) per load. The habit of fodder sale by the producers might offer an opportunity to demonstrate the use of manure in the study area. If agropastoralists are shown the benefits of using manure, some may start to apply it to enhance their forage production, and thereby increase their income. Studies suggest that increased profitability is an incentive for adoption of an innovation or technology [18]. Furthermore, forage productivity, particularly the herbaceous layer, is low in Borana, see for example [31]. In this regard, the huge livestock population and substantial amount of manure available (see section 3.5.) would be a good opportunity for promoting pasture development using manure in the study area. The use of dung and urine on pasture plots to improve grass growth and productivity is a widely adopted practice in other parts of southern Ethiopia [17].

3.2. Agropastorals' Perception of Soil Fertility Status

In this study, soil fertility status of crop fields was explored through FGDs, and field visits. Participants involved in FGDs developed and prioritized indicators to evaluate soil fertility status of crop fields. Consequently, soil type (primarily its color, i.e., red versus black to brown colored soils) and the occurrence of weeds were used as the main indicators to distinguish between fertile, low fertility and degraded crop fields. According to the agropastoralists' judgment, the red colored soils were considered less fertile while black to brown soils were perceived as very fertile or productive. The water-holding capacity of the soil was also assessed based on its color. According to the perception of FGD participants, black-brown colored soils were the most appreciated soils in terms of water-holding status compared to red soils. This is in agreement with Gray and Morant [32] and Birmingham [33], who found that smallholders are knowledgeable with regard to defining major soil types and the fertility status of their farms by taking into account the color, texture and moisture retention of soil as a basis for their classification.

Of the observed farms, over half (53%) of the croplands were identified as less fertile, while 37% of the studied farms were perceived as fertile (Figure 1). The position of the cropping fields along the landscape might explain the observed fertility status of the studied farms. The majority of the crop fields in the study area were located in the bottom valley sites and flood plains. Cropping fields, which were perceived as degraded, were situated in uplands. It has been reported that soils located in valley bottom sites in semi-arid areas of southern Ethiopia are often poorly drained and are expected to have better fertility and water-holding capacity than hilltop soils [1]. This is in line with the current perceptions of agropastorals. Coppock [1] also notes that although water is assumed to be the major limiting factor for plant growth, in semi-arid areas, nutrient limitations could be an important constraint in run-on areas in drylands where water availability is less of a constraint. To confirm the perceived fertility status, scientific observations are required.

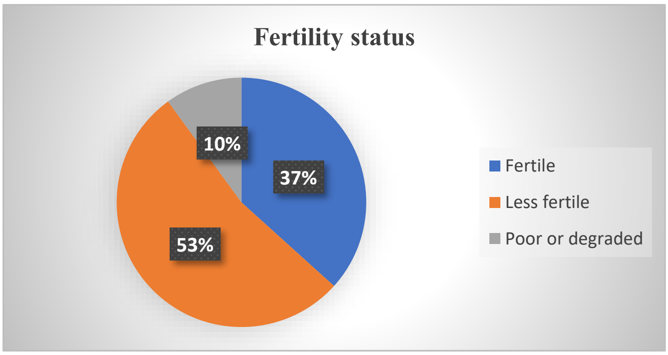

Figure 1. Perceived fertility status of soil.

3.3. Why the Borana Agropastoralists Do Not Use Manure: The Influence of Traditional Beliefs

As stated in section 3.1, there is no tradition of using manure in Borana. In many parts of Ethiopia, for example, [34] and other SSA countries [12,35], it is widely acknowledged that quantities of manure available to the farmers are limited because of low numbers of livestock per household, thus constraining crop production. Even in areas that have large livestock populations, and thus, large volumes of manure, labor requirements hamper manure utilization [17]. This is different from the situation that prevails in the study area, where manure does not have a value as a fertilizer. As compared to other agropastoralists of SSA, the Borana may be unique, to say the least, in possessing a large livestock population and an enormous amount of manure (see section 3.5.) without benefitting from this resource.

In order to understand the barriers to the use of manure, key informant interviews were carried out with five highly regarded elders independently. Our discussion with the elders revealed that the entire olla have to move to a new place every seven to ten years, as a result of the size of the manure heap. They move because dangerous animals such as 'python snake' are attracted to the heap. People associate this with misfortune or with bad things expected to happen in the community. Therefore, they move to another site. The occurrence of dangerous animals was seen as an indicator to move to another site, or as an expression of the necessary action (i.e., relocate the olla) to please the will of God. Dangerous animals are also seen as evil carriers that God uses to punish those who violate God's rules. According to the village elders, failure or delay to relocate one's olla despite having seen the indicators is seen as dishonoring God's will. The consequences are spiritual retribution, such as loss of livestock, illness, physiological disorders or sudden death. There were stories of such outcomes, according to the village elders.

Above all, the communities in the study area believe that their animals die if their dung (from the heap) is used for any purpose other than plastering their house floor. During the fieldwork, informants often stated that there was a belief among the communities that if they used their animals' dung, they would offend the creator God and this could bring suffering or misfortune to the offender's animals, family and perhaps even to the whole olla and the village. In line with this, we observed that some of the households were not even willing to let their manure heap be measured and sampled, saying that God may be dissatisfied and punish them. Mather and Hart [36] in Kenya have made similar observation. These authors reported that there was believe among the Kikuyu tribes that cattle will become possessed of an evil spirit (thahu) and die if their dung is placed in the soil or removed.

In the present study, the observed unwillingness among some studied agropastoralists, together with the information obtained from elders can suggest that the traditional beliefs (and concepts regarding manure) appear to negatively influence the community's attitude towards manure. This can explain the observed non-use of manure in the area. Because all the elders gave an unambiguous answer regarding the use of manure, it is possible to assume that this observation is valid for the whole study area. Nevertheless, this information cannot be extrapolated to the whole agropastoral areas of southern Ethiopia, because such traditional beliefs are area-specific constructs influenced by local social, cultural, economic and biophysical circumstances [37,38]. Therefore, further investigations are necessary to substantiate the current observation.

In areas where application of scientific knowledge and educational services are lacking, people use their indigenous systems of beliefs to make choices, understand and interpret their biophysical environment, and make decisions [39] as seen in many instances in Africa [40,41]. Evidence suggests that although such beliefs and practices may have positive consequences [42], they can also generate unfavorable attitudes and anxieties towards innovation, restrict adoption of innovations, and impede economic progress [37,39]. For instance, from the analysis of panel data on 26 African countries, Nkamleu [43] reported that countries dominated by indigenous believers have shown lower rates of agricultural growth, particularly in terms of technological progress between 1970 and 2000, thus implying the possible negative effects of traditional beliefs.

Lack of knowledge or unfamiliarity with the use of manure was the second reason given for the non-use of manure in the study area. As it is a drought-stricken area, there are many non-governmental organizations (NGOs) working in the area. However, none of the organizations engage in manure research, technical support or promotion. This is most likely because their entire focus is on livestock production and/or rangeland management, in addition to ignorance of the potential use of manure. The observed lack of awareness of manure's potential may also be related to the households' low level of education. Two-thirds of the studied household heads had not attended school at all or had a very low level of formal education. Just under 17% of those surveyed household heads had basic (adult) education. Almost all of the households had no farm skill training at all, and had not attended pastoral-training centers (see Table 1a). This is contrary to the farmers in the highland areas of the country, who receive farm skill training once every year. Similarly, Megersa et al. [4] report a lack of formal education among the Borana agropastoralists.

3.4. Livestock Housing and Manure Management

No statistical analyses were performed as all the respondents had similar responses (no variation observed) to the questions asked about manure management and housing. Therefore, the results are presented in a descriptive form using figures for illustration. Animals in the study area were freely grazing during daytime (10–11 hours) and were corralled at night in a house or kraals (locally called “monaa”). Every Borana household had livestock kraals and manure heaping sites at the edge of the household’s compound. All the studied households had separate kraals for large cattle (Figure 2), mature sheep and goats (Figure 3c), calves (Figure 3d) and for lambs and goat kids (roofed and constructed 30–50 cm high above the ground) (Figure 3 a and b, respectively).

Figure 2. Large cattle kraal (locally called monna) in Borana, southern Ethiopia. Photograph by the first author.

The large cattle kraals are slightly sloping with a salt trough located in or outside the kraal. The Borana traditionally supplement livestock with crude salt mined from local volcanic craters. The composition of this salt was found to be 41% NaCl with minor quantities of macro and trace minerals [1]. We visually observed that manure was swept from the kraal and heaped in an open-air site (Figure 4) located outside the kraal. The studied households were observed to use their bare hands to remove manure accumulated in the kraal; cattle hide was used to throw manure onto the heap. None of the studied households had a defined time or number of intervals per week to collect and remove manure from their kraal. Rather, the amount of manure accumulating in the kraal determined when the manure was to be swept from the kraal – usually done daily or up to every fifth day. While manure sweeping is women’s duty, men are responsible for building and repairing kraals.

Figure 3. Kraal for goat kids (a) and lambs (b), matured sheep and goats (c) and calves (d) in Borana, southern Ethiopia. Photograph by the first author.

As with the kraals, the manure from cattle, sheep, goats and camels manures was heaped in separate sites. The informants explained that if heaped in the same sites, seedlings of weed species–especially acacia species such as *Acacia brevispica* Harms, A. *drepanolobium* and A. *seyal* Del–could establish themselves from within the intact dung pellets of sheep and goats. Separate heaping sites were used to avoid this perceived problem. Furthermore, almost all (29 of 30) respondents had only one cattle manure heap; the remaining respondent had two cattle manure heaps. According to the informants, establishing new heaping sites in the current olla is not part of their tradition. If there is a lot of manure, the practice is not to establish a new site, but to abandon the heap and move to a new place, leaving the old heap undisturbed. This is because prolonged practice of storing manure at the same site leads to large accumulations of dung. Informants further mentioned that the average age of a manure heap when it is abandoned, from their long experience, is around seven to ten years. When the manure heap reaches this age, dangerous animals are attracted to the heap.

On average, the manure heap was situated about 25 minutes' walk from the cropping fields and four minutes' walking distance from the owner's house, respectively. This could present an opportunity to encourage the use of manure for crop production. Since the heap is located near the cropping fields, transporting manure to the fields would then require less time and energy [44].

From our field observations, with the current management (storage and accumulation, Figure 4), nutrient losses and emissions of ammonia and of nitrous oxide from the manure are expected [45]. Research has shown that losses of nutrients, mainly due to leaching and volatilization, from cattle dung were much higher where dung was piled and remained uncovered [13,14]. Even though its effect was not examined in the current study, land application of manure, though varied with environmental conditions, application rates and spreading techniques, is associated with emissions that are responsible for a range of environmental damages [46,47]. Other possible problems related to utilization of manure on cropland include high costs associated with hauling and spreading the bulky materials [48].

Figure 4. Representative pictures showing cattle manure heaps (dunghills) in Borana, southern Ethiopia. Photograph by the first author.

3.5. Manure and Nutrient Production in Borana

Considering the large population of cattle and separate accumulation of manure in the study area, in the current study, we only measured the cattle manure. Table 2 and Table 3 show cattle population per cultivated area, theoretically estimated manure, farm-available manure and corresponding nutrient supply.

3.5.1. Theoretically Estimated Quantities of Manure

The average total (theoretically estimated) manure production per household of the studied households (30) was estimated to be 16.85 tons per year (Table 2). The quantity of manure produced varies considerably among the resource groups due to differences in herd size. Smaller manure production (8.9 tons) for the resource-poor households can be explained with small cattle herd size, see for example [49]. The cattle population to farmland ratio shows no significant variation among the resource groups.

Table 2. Average TLU per cultivated land and theoretically estimated amount of manure per household resource group in Borana.

Resource group	Farmland (ha)[a]	Cattle in TLU	Estimated manure (tons)	TLU per farmland
Rich	3.46	32.51	28.28	10.45
Medium	2.36	20.90	18.20	9.87
Poor	1.19	10.15	8.90	9.70
Mean	2.15	19.37	16.85	9.98
se±		1.90*	1.65*	0.97*n.s.*

[a] Farmland = land used for arable crops + cash crops + grazing pasture + mixed crops. *n.s.* and * indicate not significant, significant at $p \leq 0.05$, respectively.

3.5.2. Manure Available on Farm: A Hidden Resource

Besides the as-excreted estimate of manure that could be produced in the farm, we measured manure currently available in the farm from nine randomly selected farms. The average amount accumulated over the years in the heap was 74.1 tons. In Ethiopia, based on current agronomic advice, 100 kg of urea (expressed as 46-0-0) and 100 kg of DAP (18-46-0) expressed as 18% N, 46% P_2O_5 and

0% K_2O by weight is applied to maize per hectare. This corresponds to 64 kg N/ha. In this study, it was estimated that, on average, one ton of manure contains 9.03 kg of N (Table 3). Thus, 7.09 tons manure/ha corresponds to 64 kg/ha of N in the study area. With this application rate, the average amount of manure currently available in the farms would be sufficient for manuring more than 10ha of maize crop land which is five times greater than the land currently under cropping (Table 3). Assuming the studied households' response on the non-use of manure is representative of the whole study area, an enormous amount of manure is not made use of. This estimation did not consider potential losses due to management and soil application of manure which cannot be avoided [45,50].

Table 3. Manure production (ton) and nutrient contents (kg/ton) and total outputs in Borana, southern Ethiopia (based on nine farms).

	Cattle in TLU	CL (2015/16)	AM (ton)	MNC (kg/ton)			TO in kg per farm		
				TN	P_2O_5	K_2O	TN	P_2O_5	K_2O
Mean	**26.83**	**1.70**	74.11	9.03	0.12	3.98	667.87	9.14	320.53
Stdev	7.07	1.20	61.20	1.49	0.01	1.42	565.62	8.38	365.47

CL: Cropped land; AM: Amount of manure; MNC: Manure nutrient concentration; TO: total nutrient outputs.

3.5.3. Nutrients Potentially Available for Crop Production

The plant nutrients nitrogen (N), phosphate (P_2O_5), and potash (K_2O) are the most yield determining nutrient inputs in most farming systems [51]. Manure contains a substantial amount of these nutrients and others such as magnesium and sulphur. It was found that one ton of manure contains 9.03 kg N, 0.12 kg P_2O_5 and 3.98 kg K_2O (Table 3). As compared to the other two, phosphorus availability is very low which may be attributed to low P availability in the soil in the study area. Studies have shown that P content of the soil in the Borana rangeland was very low [5], which in turn affects plants' P level. As outlined in Table 3 above, the measured amount of mean total manure was 74.11 tons. From the analysis, the mean total available N was found to be 667 kg. The P_2O_5 output was 9.14 kg and K_2O output was 320 kg, found on average in each farm, though considerable numerical differences among the studied farms were found (see Supplementary material Table S1).

3.6. The Economic Value of Manure as Fertilizer (in Monetary Terms)

As a plant nutrient source, manure can provide an economical source of N, P and K for plant growth and reduce the cost for fertilizer (Newton et al., 2003). However, in the study area, manure does not have known economic value. Our analysis revealed that 667.87 kg of N, 9.14 kg of P_2O_5 and 320.53 kg of K_2O are, on average, available in each farm. In this study, the value of N was only used as indicator to estimate the fertilizer value of manure.

Table 4. The value (ETB) of nitrogen in manure produced on farms.

Nutrient	Nutrient price per kg	Total nutrients output	Total monetary value (ETB)
N	24.63	667.87	16452.84

**ETB (Ethiopian Birr) 20.52 (March-2016) = US$1.* The value of manure was estimated based on fertilizer-equivalent rate (N in urea and DAP and P in DAP) and value.

During the survey year of 2016, the price of mineral N fertilizer was ETB 24.63 per kg. The market price attached to the nutrients in this study was the price that the agropastoralists would have to pay if the produce were to be purchased. This is because manure in the study area does not have market value. Accordingly, if the agropastoralists were supposed to use N fertilizer, the above-measured nutrient is equivalent to an economic value of ETB 16452 (US$802), which could be attributable to N fertilizer. The economic value of manure N is shown in Table 4. Although manure utilization is not in practice, this analysis indicates that there is a considerable scope for using manure to increase yield and food security in the Borana agropastoral areas. However, the exact scope for improvement requires further quantification and detailed studies of the nutrient flow across the landscape.

3.7. Implications for Cropland Productivity and Nutrient Management

The agropastorals in the study area have sufficient manure N to apply to their croplands. In relation to the requirement, about 613% of the N and 16.7% of the P fertilizer needs can theoretically be met with manure if all the available manure (collected from the kraal) was used to fertilize maize croplands. Hence, manure could make a significant contribution to plant nutrient supply for the study area. From the analysis, the quantity of N to potentially be generated from manure was in excess of requirements (more than five times the current requirements), indicating considerable scope for the agropastorals to increase yield substantially by using manure, even if they lack access to fertilizers. The excess to N supply of what is currently needed suggests that an important role which government or another development organization could play, would be to facilitate and promote use of manure in the study area. However, crop P needs would not be met through manure applications alone.

3.8. Yield Responses for Manuring in Borana

Maize responded positively to manure application. Responses in grain and stover yield to manure and fertilizer application are shown in Table 5. All treatments recorded significantly higher grain and stover yield of maize than did the control treatment that received no nutrient inputs.

The highest grain and stover yields were achieved where micro-doses of manure were combined with micro-fertilizer, followed by the recommended dose of fertilizers. Application of 70 g (corresponding to 3.71 tons per ha) of manure, combined with a small quantity (0.5 g per pocket) of fertilizer, improved maize grain yield by 77% compared to non-use of inputs. Additionally, manure applied alone yielded 51% of grain compared to the control. This is in close agreement with the findings of Ademba [52] in South Western Kenya where animal manure applications resulted in a substantial increase in maize yield over the control. Maize stover yield followed similar trends to the grain yield (Table 5). Despite variation between treatments, the observed significant yield improvements compared to the usual non-use of manure shows considerable scope for increasing yields of these marginal lands by using manure. Thus, there is a potential to promote manure use in agropastoral areas of the Borana if the traditional beliefs withholding its use are eradicated. However, the observed yields at farm level are far below the potential (i.e., suggested to be 2000–3000 kg ha-1) [53], which require further investigation. An analysis of the cost-benefit ratio is also required to show the returns of manure for the agropastoralists.

Table 5. Yield responses of maize for manuring in Borana, southern Ethiopia.

Treatment	Grain yield (kg ha^{-1})	Stover yield(kg ha^{-1})
Control	701.00±46	2013.82±95
Recommended practice (mineral fertilizer)	1231.12±46bc	3181.58±95b
Manure micro-dose (3.71ton ha^{-1})	1015.00±46a	2684.87±95a
5 ton of manure†	1059.00±46ab	2546.49±95a
5 ton of manure + legume intercrop	929.70±46a	2572.15±95a
Manure micro-dose + fertilizer micro-dose	1240.60±46c	3386.62±95b
Manure micro-dose + legume intercrop	1015.60±46a	2564.69±95a
LSD	186.2	386.91
p-value	0.00	0.00

Standard errors are given by signs '±'; †: equivalent to 35.45 kg of N ha $^{-1}$. Means within a column with different or no letters are significantly different (p<0.05).

4. Possible Areas of Interventions

Despite the enormous potential manure has for smallholders, it remains un-utilized in the study area. The observed large amount of manure with substantial fertilizer value, high manure production potential, and unavailability of fertilizer could be seen as an opportunity for intensification using manure. Rogers [54] notes that personal characteristics such as an individual's values and beliefs, among others, can influence adoption decisions. Our results show that, indeed, traditional beliefs have negatively affected decisions to use manure by the agropastorals in Borana. These beliefs are enhanced by lack of awareness and knowledge limitations about the values and uses of manure. Addressing these factors could promote use of manure in the area. The following section gives an overview of the possible areas of interventions.

4.1. Institutional Support to Overcome the Barriers and Promote Manure Use

The barriers outlined above are all related to limited access to education, extension services and technical information regarding manure use and its management. Therefore, eradicating the barriers requires concerted efforts through cooperation and understanding of community leaders, research institutions, development agencies and decision-makers. Carefully planned information campaigns and education, which encourage adoption of manure use and counteract those factors that act as barriers, may change the current attitude towards manure. Community education (via local media), because it helps to promote a rational worldview, might be vital in increasing public awareness of the negative influences of the existing societal beliefs and associated practices. It may also enhance the level of awareness of the farming household about the virtues of manure use. In this regard, the growing use of mobile phones in the area might offer an opportunity for reaching agropastorals to access and spread (and share) information. Increased knowledge on the merits of manure can be achieved through radio programs addressing these issues. Working to increase the awareness about the merits of manure use would produce more change than would efforts to diminish objections to manure application. Farm skill training on manure use and management by the extension service can transform the attitude of the households' so that they can become adopters of the innovation. Extension services can further address the barriers to manure use. Studies have shown that producers use of manure was positively and significantly associated with the availability of training and of extension services [17,55], which must be emphasized in the study area.

4.2. Manure for Crop and Pasture Development

Agropastorals in the study area suffer from serious food and feed shortage problems [4,56]. This study has shown a large supply of manure that is left unused. This manure can potentially be used to promote maize production, which increases grain supply for human consumption and fodder (stover) for animals. Furthermore, there is a possibility of forage development by using manure. In this regard, agropastoralists in the study area are currently setting aside land for fodder production and this represents a niche for manure use. Manuring grasslands is widely practiced in some parts of southern Ethiopia [57].

4.3. Option to Enhance Use of Manure in Agropastoral Farming Systems in Ethiopia

Contemporary proposals for enhancing agricultural productivity on the African continent strongly support the introduction and expansion of sustainable agricultural practices. In this regard, currently, crop (both forage and food) productivity can be maximized within agropastoral systems in Africa through two basic alternative scenarios. The first involves the more effective utilization of resources internal to the agro-ecosystem, e.g., manuring, mulching and intercropping with leguminous plants), while the second is based on the increased use of external inputs (e.g., chemical fertilizers). This study shows, though nearly two-thirds (63%) of the croplands were as less fertile and degraded, the agropastorals in the study area used neither fertilizer nor manure. Application of external input-based alternatives might be difficult in the study area due to the cost of the input and accessibility. Instead, intensive utilization of manure is relatively cheaper than purchasing chemical fertilizer, more appropriate to the Ethiopian agropastoral systems and environmentally friendly. The large amount of manure currently available in the study area and the observed yield response represent an opportunity for intensification of crop production. In this regard, with the aim of increasing crop and pasture production, starting with a few agropastoralists, manure demonstration projects should be established at the village level to demonstrate its value. This could be undertaken as a collaboration between the local pastoral development office, research center, NGOs and with active involvement of the communities (using model farms or test agropastoralists). Such a community-based approach, which focuses on raising knowledge and participatory application/adoption of technologies at village level, has proved successful in the piloting of adaptation strategies in Kenya and Nepal [58,59].

5. Conclusion

This study has explored status of manure use, manure nutrient supply potential, and its implication for agricultural production in the semi-arid agropastoral systems of southern Ethiopia. Based on the findings of this study, it appears that crop yield from the nutrient-poor soils of the Borana can be substantially enhanced by using manure. However, despite this fact, manure is left unused in Borana, while the agropastoralists continue to suffer from the widening gap between food and feed production and population growth. The study shows that the potential of manure to improve crop yield in the study area is limited by traditional beliefs prevailing in the community. The traditional beliefs linking manure use to misfortune and loss of livestock have a negative influence on manure use and management. These beliefs are understood to be key causes for not realizing the potential of manure to support crop production in the study area. We believe that these beliefs have prevailed for years in the community because of factors such as lack of education, lack of manure research and the lack of extension service and technical support. Thus, there is a need for farm skill trainings and education programs or campaigns, combined with village-level manure demonstration projects to show the value of manure. These should be accompanied by community-level dialogue with the agropastoralists regarding the cultural issues and traditional beliefs related to manure utilization and management.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Table S1: Manure production (ton) and total nutrient output (kg).

Author Contributions: YJ undertook the fieldwork, collected and processed the data, wrote and revised the manuscript; JA and AA provided commentary and a critical review of the manuscript.

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PAPER III

agriculture

MDPI

Article

Methane Emissions from Ruminant Livestock in Ethiopia: Promising Forage Species to Reduce CH_4 Emissions

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Abstract: This paper assesses the ability of fodder plants to reduce methane (CH_4) emissions while simultaneously improving animal productivity in Ethiopia. Enteric CH_4 emissions from ruminants in Ethiopia increased by 12% or ≈ 6197 Gg CO_2-eq. in 2017 compared to the year 2011. In this study, six tropical multipurpose forages (*Leucaena leucocephala* (Lam.) de Wit, *Moringa stenopetala* (Bak.f.) Cuf., *Sesbania sesban* (L.) Merr., *Cajanus cajan* (L.) Millsp., *Crotalaria juncea* L., and *Lablab purpureus* L.(Sweet)) and maize stover were characterized in terms of chemical composition, in vitro CH_4 production, and CH_4 concentration (%). The objective was to identify forages with low CH_4 production potential but with adequate forage quality. The forages differed significantly in chemical composition and in enteric CH_4 emission. The dry matter (DM), ash, crude protein (CP), neutral detergent fibre (NDF), acid detergent fibre (ADF), and acid detergent lignin (ADL) ranged between 89.4–95.4%, 6.08–12.5%, 3.3–30.7%, 20.4–76.0%, 10.8–44.8, and 2.9–14.1%, respectively. All forage plants, except maize stover, contained high CP content above a threshold value (i.e., 7%). *Cajanus c.* generates the lowest amount of CH_4 (32.83 mL/0.2 g DM incubated). CH_4 concentration (%) was used as a potential indicator to determine the capacity of a plant to lower CH_4 production. Among the studied species, *L. purpureus* showed the highest CH_4 reduction potential (16%) followed by *C. juncea* (23.45%), *M. stenopetala* (24.2%), and *L. leucocephala* (25.5%). *Moringa s.* was the most frequently preferred by the farmers followed by *C. juncea* and *L. leucocephala*. We concluded that *M. stenopetala*, *C. juncea*, and *L. leucocephala* can be promoted as valuable feed resources for ruminants while simultaneously reducing CH_4 emissions.

Keywords: ruminant livestock; methane emissions; methane reduction; promising forages; farmers' preferences; Ethiopia

1. Introduction

Ethiopia has a tremendous livestock resource, currently estimated at 60 million head of cattle and 61 million sheep and goats, in a variety of production systems ranging from pastoral to mixed crop–livestock systems with different levels of intensification [1]. For developing countries like Ethiopia—where the demand for animal products is expected to rise owing to a growing human population and economic changes [2]—this resource, if managed properly, has great potential to raise food outputs. However, despite the country's large livestock population, the production from livestock systems in Ethiopia is low, largely because of poor nutrition. The same is true in many tropical regions of the developing world, where a large proportion of the global ruminant population exists [3]. The productivity of ruminants is limited by the low nitrogen and high fibre content of native pastures and crop residues, which form the basis of the diet in these regions [4].

This low productivity not only results in high absolute CH_4 emissions, making developing countries responsible for 75% of global enteric CH_4 emissions but also in high emissions per unit of product [3]. These emissions are of worldwide concern, particularly in countries such as Ethiopia where large populations of ruminants are located (90% of ruminants in Ethiopia) [1] in mixed farming systems. These animals are mainly raised on the grazing of native pastures, aftermath and crop residues and, to a lesser extent, improved fields [5]. Ruminants fed on these types of forages produce more CH_4 (e.g., 1.6 kg CO_2-eq./kg of milk in Eastern and Western Europe) than ruminants fed on high quality forage diets (e.g., 9 kg CO_2-eq./kg of milk in sub Saharan Africa) [6]. Furthermore, CH_4 emissions represent a loss (up to 15%) of digestible energy to the animal as well as a threat to the environment [4].

Greenhouse gas emission in Ethiopia is estimated at 150 Mt CO_2-eq., and represented less than 0.3% of the global emissions in 2010 [7]. Estimates of CH_4 emission (data from The World Bank) indicate that agriculture, almost entirely through livestock, totalled 60.3 MT CO_2-eq. in 2008, which is approximately 71% of the national CH_4 emissions. Given the sizeable ruminant population in the country and the extensive nature of the production systems, the contribution of ruminants to GHG emissions is likely to be much greater than what is currently known. In any case, owing to the rising demand for livestock products, the population of domestic ruminants is likely to increase, which considerably accelerates the increase in GHG emissions [7,8]. Only limited documentation exists, however, regarding CH_4 emissions from the ruminant population in Ethiopia. As a result, limited mitigation efforts are directed toward this sector. It is therefore important to estimate CH_4 emissions to assess the gravity of this problem, and to study mitigation options. In contrast to developed countries, developing countries may be facing challenges that need to be addressed before the environmental burdens of GHG emissions become a priority in their national policies [9].

Ruminant production systems in the developing countries of the tropics are associated with lower feed efficiency and higher emission intensities as a consequence of low productivity, poor nutrition, and animals of low productive potential. In this regard, although mixed crop-livestock systems have low absolute emission per hectare, they produce high emissions per unit of output [3], which also represents an indirect economic loss for the farmers [10].

Given the growing human population and climate change, the principal challenge for developing countries such as Ethiopia is to enhance animal productivity while minimizing the environmental damage caused by livestock. A key to this is reducing CH_4 emissions from ruminants [4]. To this end, supplementing traditional feed resources with planted forages appears to be a simple solution to this problem. Cultivation of improved forage crops is relatively cheaper than purchasing concentrate supplements, more appropriate to the Ethiopian livestock production system, and is also environmentally friendly. Improved forage crops produce a significant amount of quality herbage that, when used in combination with crop residues, improves resource-use efficiency. These crops can also complement crop production by maintaining soil fertility by fixing nitrogen or when used as mulch. Improving the quantity and quality of forage produced will also improve animal feed efficiency, reduce CH_4 emissions per unit of animal product, and lead to production benefits for farmers. In this respect, the use of easily adapted multipurpose forages grown by small-scale farmers might be a potentially efficient way to increase ruminant productivity [11] sustainably.

In Ethiopia over the past five decades, several forage species and accessions have been evaluated in a wide range of agro-ecologies. So far, research on forage plants has been limited to adaptation, biomass, nutritive value, and in vitro digestibility [5]. Emphasis has also been placed on correcting the nutritional deficiencies of natural pastures [12] and crop residues [13,14]. The testing of forage plants, whether introduced or locally available for their potential to reduce CH_4 emissions, has received very little attention.

Therefore, we undertook this study (i) to estimate CH_4 production of some selected forage plants and (ii) to identify low CH_4 producing forages with adequate forage quality. The study focused on adapted forages recommended for use in the crop–livestock farming systems of southern Ethiopia and maize stover, a widely used feed for ruminants. In East Africa, especially in highland areas, maize yields although subject to a general lowering are likely to increase, providing more human food and animal feed [15]. This scenario presents an opportunity for greater emphasis on dual purpose food–feed crops such as maize to meet the future challenge of increasing ruminant productivity and sustainability of crop-livestock systems in the country. Although the value of maize residues as fodder is widely recognized, there is less understanding of its effect on enteric CH_4 production. We hypothesized that multipurpose forage species reduce CH_4 production while providing high quality feed to complement lower quality crop residues.

Such analysis will provide the opportunity to help design new management and feed strategies in Ethiopia. This study also quantifies the amount of enteric CH_4 produced from ruminant livestock in the country. Such emission data is essential to inform policy dialogue and avoid oversimplification.

2. Materials and Methods

2.1. Estimating Enteric CH_4 Emissions from Ruminant Livestock

In the current study, we employed a Tier 1 approach of the IPCC [16] for its ease of application (default values) to the Ethiopian context and for its input data requirement (population data for each specific animal category) to estimate enteric CH_4 emissions from the ruminant livestock. We calculated CH_4 emissions for each animal category by multiplying the animal population (number of head) by the average emission factors associated with the specific animal category (Equation (1)) and summed Equation (2). Results were expressed in gigagrams per year (Gg year^{-1}). Data for livestock population was obtained from the annual national livestock and livestock characteristics censuses conducted by the Central Statistical Authority of Ethiopia, which completes population inventories annualy in December, in the years 2010/2011 and 2016/2017. These surveys covered all the regions of the country except the nomadic pastoral areas (three zones of Afar and six zones of the Somali region) where livestock population is very low. The livestock population data covered 69 of 78 zones (i.e., 88%) for 2010/2011 and 66 of 75 zones (i.e., 88%) of the country for 2016/2017, respectively. The livestock categories included were dairy cattle, non-dairy cattle (beef cattle, breeding bull, calves, heifers and steers, and other matured cows), sheep, and goats. Almost all the cattle, sheep, and goat breeds kept by smallholders in Ethiopia are indigenous [1].

$$\text{Emissions } (CH_4)_{(T)} = EF_{(T)} \times N_{(T)}/10^6 \quad (1)$$

where:

Emissions $(CH_4)_{(T)}$ = enteric CH_4 emissions for a defined animal category T, Gg CH_4 year^{-1}
$EF_{(T)}$ = emission factor for each specific animal category T, kg CH_4 head^{-1}
$N_{(T)}$ = the number of heads for each specific animal category T in the country
T = category of animal

$$\text{Total } CH_{4\text{Enteric}} = \sum E_i \quad (2)$$

where:

Total $CH_{4\text{Enteric}}$ = total CH_4 emissions from Enteric Fermentation, Gg CH_4 year^{-1}
Ei = is the emissions for the ith animal categories

2.2. Assessment of Nutritive Value and CH_4 Emission Reduction Potential of Forages

2.2.1. Experimental Plants

Samples of seven forages—three tropical multipurpose trees (*Leucaena leucocephala*, *Moringa stenopetala*, and *Sesbania sesban*), one shrub (*Cajanus cajan*), two legumes (*Crotalaria juncea*, *Lablab purpureus*), and maize stover—that are being used for feeding ruminants in southern Ethiopia were analysed for chemical composition and in vitro CH_4 abatement. We chose all sample forages except maize stover based on (i) their broader use in the farming community, (ii) high biomass production potential, and (iii) adaptation to poor environmental conditions such as poor soils and ability to withstand drought conditions. Samples of palatable forage (i.e., fresh leaves, twigs, tender stems, and/or whole forage) were harvested from 3 individual plants (at a similar stage of physiological maturity at harvest) per each species selected at random. All tree species were planted on one geographical location in July 2014 while the rest of the studied forages were planted during the 2016/2017 growing season. The harvested samples were then pooled for each individual species to form representative samples. Here we have assumed that since samples are taken from individual plants of similar age and physiological status difference between individual plants of same species might be insignificant. Our main interest was to see the average effect of species on the parameters tested under the conditions provided and not on the effect of specific plant (from which we pooled the samples). Samples were oven-dried at 65 °C for 48 hours. Feed samples ground through a 1 mm sieve were used for chemical analyses and in vitro assays.

2.2.2. Chemical Analysis

Samples were analysed for dry matter (DM), ash, and crude protein (CP; N × 6.25) as described by AOAC [17]; neutral detergent fibre (NDF), acid detergent fibre (ADF), and acid detergent lignin (ADL) according to Van Soest et al. [18] using an ANKOM^{200} Fiber Analyzer (filter bag technique; ANKOM Technology Corp., Fairport, NY, USA). Both NDF and ADF were expressed exclusive of residual ash, and NDF analysis was without α-amylase and sodium sulfite. Residue from ADF determination was treated with 72% sulfuric acid for ADL estimation. Chemical analysis was in duplicate.

2.2.3. In Vitro Studies

The in vitro gas production technique employed to determine CH_4 production was developed by Menke et al. [19] and modified by Blummel and Ørskov [20] in that feeds are incubated in a thermostatically controlled water bath rather than a rotating incubator.

- Rumen Fluid Collection and Inoculum

Rumen fluid was obtained from two fistulated Adilo sheep (32.9 kg mean body weight) kept indoors and received a roughage-based diet containing mixed mostly grass (ad libitum) and supplemented with 400 g DM of concentrate per day offered in 2 portions. Ruminal fluid was collected before the morning feeding through a suction tube into a pre-warmed thermos flask (39 °C), previously filled with CO_2. The pooled ruminal fluid was strained through 8 layers of gauze, flushed with CO_2 [21], and then mixed with Menke's buffer (incubation medium) in a 1:2 ratio (v/v). The inoculum (rumen fluid + buffer) was prepared using the method described by Menke and Steingass [22].

- ncubation to Determine Gas Production and Methane

About 200 mg of feed sample was incubated in triplicate in 100 mL of glass syringes in 2 separate runs/replications. In both runs, each sample was tested with 3 replications (using 3 syringes) plus 2 blanks (syringes incubated with the inoculum alone). The syringes containing feed samples, pre-warmed at 39 °C and their pistons lubricated with Vaseline to ease movement and prevent gas from escaping, were then inoculated with 30 mL inoculum (10 mL rumen + 20 mL buffer mixture) under continuous CO_2

flushing. They were incubated at 39 °C in a water bath for 48 hours and were shaken manually every hour for an initial 8 h (including 0 h) of incubation [23] and then at each recording time [24]. Gas production was recorded before incubation (0 h) and after 4, 8, 12, 24, and 48 h of incubation. Total gas values were corrected for blank incubation. However, due to the absence of reference standards with known gas values in Ethiopia, there was no correction for standard feed sample.

- Determination of Total Gas, CH_4 Production, and Other Parameters

Total gas production was measured by reading the position of the piston at each time point. Net gas production was calculated by subtracting mean blank values from the volume of gas produced from incubated feeds (Appendix A Annex 1). Methane production was measured at post-incubation period using the procedure described by Fievez et al. [25]. Accordingly, 4 mL of NaOH (10 M) was introduced into the incubated contents in each syringe via a connector (silicon tube) fitted between a syringe containing NaOH solution and the incubation syringe, thereby avoiding gas escape. Then, the incubation syringe was shaken, and the remaining gas volume was recorded. Mixing of the incubated contents with NaOH allowed absorption of CO_2, with the gas volume remaining in the syringe considered CH_4 (Demeyer et al., 1988, cited in Fievez et al. [25]. Test experiments prove that CH_4 volumes measured after absorption of CO_2 from in vitro incubations in syringes show consistent results with values in gas chromatography, which was shown for many feedstuffs [25]. The CH_4 concentration (percentage) was determined [26] as:

$$\text{Methane concentration (\%)} = (\text{Net CH}_4\text{ production/Net gas production} \times 100) \quad (3)$$

Using CP, ash contents and net gas production (GP) (corrected for blank) at 48 h incubation (GP, mL), in vitro organic matter digestibility (OMD %) and metabolizable energy (ME, MJ kg^{-1} DM) contents of the samples were calculated using equations of Menke and Steingass [22] as

$$\text{OMD (\%)} = 14.88 + 0.889\text{ GP} + 0.45\text{ CP} + 0.651\text{ ash} \quad (4)$$

$$\text{ME (MJ kg}^{-1}\text{ DM)} = 2.20 + 0.136\text{ GP} + 0.0057\text{ CP} \quad (5)$$

where GP is expressed in mL per 200 mg DM; CP and ash (% DM) respectively

2.3. Farmers' Preference Ranking of Test Forages

To understand the farmers' preferences, focused group discussions (with semi-structured questions), matrix ranking, and scoring were used. Initially, farmers' selection criteria were developed with a group of three farmers, each in three districts (Adamitulu-Judokombolcha, Halaba and Loka-Abaya) of southern Ethiopia, by asking them to list key attributes of forage plants of their choice. The criteria produced by the three groups were combined. Then, the common criteria for the preference of particular species over the other were used. The criteria included were: (i) palatability and animal preference (feed value), (ii) adaptability (able to grow in poor soil conditions and tolerant to drought), (iii) easy to establish and manage (including easy to harvest), (iv) multipurpose aspect (usefulness as a livestock feed and food), (v) compatibility with other crops, (vi) longevity (perennial nature and providing several harvests). Thereafter, nine farmers—three from each district—ranked forage plants individually (in decreasing importance) according to the predefined criteria. These farmers were involved in on-farm trials of the PhD project. The plants tested were widely grown by smallholders in Ethiopia and the famers engaged in the study were knowledgeable about the uses and management of the plants. We carried out initial assessment prior to planting the forages.

2.4. Statistical Analysis

Results were analysed using the general linear model procedure of SPSS [27]. Treatments were the seven forage plants. Prior to statistical analysis, gas production data from triplicate syringes for each sample per incubation run was averaged. Gas and methane production data was subjected to analysis of variance (ANOVA) with the plant sample as the treatment factor (fixed effects) and incubation run as a blocking factor, which was considered as random effects in a randomized complete block design based on the model:

$$Y_{ij} = \mu + \alpha_i + \beta_j + e_{ij} \quad (6)$$

where Y_{ij} = response variable (e.g., CH_4, GP); μ = the overall mean; α_i = the fixed treatment effect; β_j = effect of incubation run (random) and e_{ij} = the error term. Chemical composition data was analysed in a completely randomized design based on the model:

$$Y_{ij} = \mu + \alpha_i + e_{ij} \quad (7)$$

where Y_{ij} the dependent variable, μ = the overall mean; α_i = the fixed treatment effect and e_{ij} = the error term.

Means of chemical composition data were compared using the least square means procedure. Duncan's multiple range test was employed to compare means of CH_4 production, methane concentration, and total gas production. DM and CH_4 concentration data were log transformed. Means were considered significantly different at $p < 0.05$. Correlation analysis was conducted to quantify the relationship between CH_4 production and chemical composition. All statistical analyses were performed using SPSS statistical software version 25 [27].

2.5. Limitations of the Study

In the present study, the national CH_4 emissions from enteric fermentation were estimated using the IPCC Tier 1 methodology, which calculates CH_4 emissions for each animal category by multiplying the animal population by the average emissions factor associated with the specific animal category. Tier 1 factors are fixed values for each animal category in different regions of the world. Thus, this method of inventory does not account for differences in animals' physiological state, diet characteristics, or management in a given production environment [28]. Therefore, there might be some shortcomings in our national enteric CH_4 emissions data. As the emission factors for the Tier 1 method are not based on country-specific data rather are based on broad assumptions, they may not accurately represent the country's livestock characteristics and may be highly uncertain as a result to +50% [16]. However, except for the Tier 1 approach, most other prediction models require a large quantity of detailed information about animal and feed characteristics [16,29], which is difficult to gather in Ethiopia. Research is also unavailable to derive country-specific emission factors or other estimation parameters.

3. Results and Discussion

3.1. Methane Emission from Enteric Fermentation of Ethiopian Ruminant Livestock

It was estimated that total enteric CH_4 emissions from Ethiopian ruminant livestock in 2011 and 2017 were 50,201 Gg CO_2-eq. and 56,397.61 Gg CO_2-eq., respectively. Cattle (dairy and non-dairy) were the largest source of enteric CH_4 production in Ethiopia, contributing to 88% of emissions in 2011 and 87% in 2017. The total CH_4 emissions from enteric fermentation in ruminants increased by 12% in 2017 compared to the base year 2011 with an annual growth rate of nearly 2% (Table 1). The current trends in enteric CH_4 emissions are influenced by the increasing population size of goats, sheep, and non-dairy cattle population. This is caused by increases in the ruminant livestock populations, except dairy cattle. This growth in livestock population in the country is driven by the rapidly increasing demand for livestock products, this demand being driven by population growth, increasing incomes, and urbanization [7,8].

Table 1. Estimated enteric CH_4 emissions from ruminant livestock in Ethiopia, annual growth rate, and temporal variations over the period 2011–2017.

Animal Category	Number of Animals (Head) (1000)		CH_4 Emissions (CO_2-eq.) Gg Per Year [3]		AGR (%)
	2011 [1]	2017 [2]	2011	2017	
Dairy cattle	7447.24	7155.11	8564.32	8228.38	−0.67
Non-dairy cattle total	45,934.96	52,331.55	35,599.59	40,556.95	2.17
Beef cattle	463.92	477.27	359.54	369.88	0.47
Breeding bull	10,899.32	13,602.14	8446.98	10,541.66	3.69
<1 year (calves)	9617.04	10,738.38	7453.21	8322.24	1.84
1–3 years (heifers and steers)	8228.73	9963.21	6377.27	7721.49	3.19
Other matured cows	16,725.94	17,550.56	12,962.60	13,601.68	0.80
Sheep	25,509.00	30,697.94	3188.63	3837.24	3.09
Goat	22,786.95	30,200.23	2848.37	3775.03	4.69
Total[4]	101,678.15	120,384.84	50,200.91	56,397.61	1.94

[1] Population data [30]; [2] population data [1]; [3] emission values were converted to CO_2 equivalent (CO_2-eq.) using the factor [31] of 25 Gg; [4] population data reported are collected in December for each year; AGR: annual growth rate.

There are no recent estimates available on enteric CH_4 production from ruminant livestock with which to compare our data.

Nonetheless, the mean annual emissions growth rates recorded in the current study were slightly lower than the previous decade 2001–2011 for the Africa average (i.e., 2.4% per year) [32] and higher than the global average experienced in the earlier decades. According to the recent emissions report by Tubiello et al. [32], enteric CH_4 emission (from all ruminants) during the period 1961–2010 grew with an average annual growth rate of 0.95%. The mean yearly emissions growth rates currently recorded in Ethiopia calls for mitigation strategies to control the increasing CH_4 emissions. This effort may involve improving the quality of the fodder plants included in the ration of grazing ruminants [11,33]. In the following section, we discuss the nutritive value and CH_4 emission reduction potential of selected forage species.

3.2. Nutritive Value and Mitigation Potential of the Forages

3.2.1. Chemical Composition

The chemical composition of the forages was based on crude protein (CP), neutral detergent fibre (NDF), acid detergent fibre (ADF), and acid detergent lignin (ADL). The forages studied differed significantly ($p < 0.05$) in chemical composition (Table 2). Overall, the CP contents among the forages ranged from 3.26 to 30.68%. *S. sesban* had the highest and maize stover the lowest CP concentration. CP serves as a reliable measure of overall nutritional value. A threshold value for an adequate forage quality of 7% CP has been suggested, below which ruminal fermentation of forages may be limited and protein requirements of animals may not be met [34].

On the other hand, Waghorn and Clark [35] argue that forage CP concentrations must exceed 10% of DM for livestock maintenance requirements and about 19% for high-producing dairy cows or young growing stock. In this study, all test forages, except maize stover, had a higher CP content than the threshold level of 7%. However, the CP content of maize stover, *Crotalaria juncea* and *Lablab purpureus* was still below the critical level suggested by Waghorn and Clark [35]. *Sesbania sesban*, *Moringa stenopetala*, *Leucaena leucocephala*, and *Cajanus cajan* were the forages with the highest CP concentration. The high CP content of *S. sesban*, *M. stenopetala* and *L. leucocephala* in particular, suggest that these species can be used as a supplement for ruminants in the study area where native forages are CP-deficient. The utilization of such CP rich forages, in addition to their direct contribution to nutrient supply, may increase DM intake and increase the digestibility of poor quality feeds [36]. Although the CP content of maize stover is lower than the threshold level, with the expansion of cultivation and the resultant decline in grazing resources, crop residues will likely remain an important component of ruminant feeds in many parts of Ethiopia [37]. We also estimated the amount of maize stover produced in the country (discussed in Section 3.5).

The NDF and ADF contents are other commonly used measures to assess feed quality. An NDF content below 35.5% would be considered good quality, while above 46% would be considered poor [38]. In this study, an NDF value below the threshold was observed in *M. stenopetala*, *S. sesban*, and *L. leucocephala*. These forage species also had the lower concentration of ADF. A low ADF content can be seen as positive for forage quality because the lower ADF level means higher digestion [39]. Overall, the NDF and ADF contents were the lowest in *M. stenopetala* (21.1 and 10.9%, respectively) and highest in maize stover (75.9 and 44.7% respectively). The ADL content differed among forages ($p < 0.05$) with the lowest mean value measured in *M. stenopetala* (2.9%) and the highest in *C. cajan* (13.76%). Higher lignin was observed in *C. cajan*, *C. juncea*, and *L. leucocephala*, which are all legumes. Often, tropical forages are known for their higher lignin contents, a factor which can alter voluntary intake and digestibility of the forage [40] causing higher energy loss and resulting in an increase in CH_4 production per unit of product through a decrease in the efficiency of animal production [41]. Owing to the association with polysaccharide constituents, lignin forms a physical barrier and thus hinders the access of rumen microbes to fermentable cell wall components.

Consequently, the passage rate of feeds through the rumen is slowed down, thus limiting dry matter intake [40,42]. Lignin represents an undigested portion of the forage and is associated with fibre. Therefore, the greater the concentration of lignin in a plant, the lower the digestibly of the forage and the less dry matter an animal can consume [42].

In contrast, there are exceptions where lignin concentration and digestibility are not correlated [42] as seen in the current study where we found negative effects of lignin content on CH_4 production (discussed in Section 3.3). The chemical composition of studied forages is comparable with the range of values reported for similar forages for sub-Saharan Africa [43–45]. The chemical composition of the forages is reported in Table 2.

Table 2. Mean (%) chemical composition of the studied forages.

	DM	Ash	CP	NDF	ADF	ADL
Maize stover	92.19 (2.10)bd	7.90 (0.01)a	3.40 (0.20)	75.90 (0.21)	44.68 (0.11)	6.32 (0.11)
L. purpureus	92.90 (0.10)a	8.04 (0.01)a	15.01 (0.01)	44.04 (0.02)	24.22 (0.10)	8.31 (0.10)
C. juncea	94.11 (0.04)bd	7.60 (0.11)	14.50 (0.02)	53.10 (0.20)	44.02 (0.31)	13.70 (0.01)a
M. stenopetala	89.48 (0.06)	12.50 (0.03)	25.90 (0.13)b	20.74 (0.43)	10.86 (0.04)	2.90 (0.01)
S. sesban	94.92 (0.03)bcd	9.40 (0.05)	30.55 (0.20)	28.97 (0.10)	16.58 (0.24)	5.51 (0.21)
C. cajan	93.08 (0.06)a	6.20 (0.11)	19.69 (0.40)a	54.38 (0.01)	32.45 (0.60)	13.76 (0.44)a
L.leucocephala	95.35 (0.04)cd	11.20 (0.01)	25.60 (0.20)ab	34.00 (0.05)	22.22 (0.10)	10.95 (0.66)

Numbers in brackets are standard deviation. In each column, no or lower case lettering is used to show the significant differences between different types of treatments at $p < 0.05$ level.

3.2.2. Metabolizable Energy (ME) and Organic Matter Digestibility (IVOMD)

The nutritive value of a feed is determined by the concentration of its chemical components along with their rate and extent of digestion [46]. Feeds with high IVOMD are likely to have a high potential to supply the ME required to support animal production [47]. In this study, the calculated IVOMD and ME content varied among the forage species studied, ranging between 68 to 93% and 8.46 to 12.3 MJ kg^{-1} DM, respectively (Table 3). *Moringa stenopetala* and *L. purpureus* exhibited higher IVOMD and ME content (93, 11.28 and 92.4%, 12.3 MJ kg^{-1} DM, respectively). The ME values of the feeds were within the ranges of reported values for sub-Saharan Africa [45]. All the studied forages, except *C. cajan*, had OMD values above 70%, which suggests that these forages have high nutritional value for ruminants. Meissner et al. (2000), cited in Bezabih et al. [48] reported that forages having an OMD of 70% or more are considered to be of high quality. In line with this, Evitayani et al. [47] reported that the OMD of forages above 50% is a good indicator of their potential to supply ME.

Table 3. In Vitro Organic Matter Digestibility (IVOMD) and Metabolizable Energy (ME) of test forages.

Forage Type	IVOMD (%)	ME, MJ kg^{-1} DM
Maize stover	75.34 (6.60)	10.45 (1.00)a
L. purpureus	92.36 (10.04)a	12.31 (1.50)
C. juncea	82.33 (5.40)	10.85 (0.83)a
M. stenopetala	93.01 (5.80)a	11.28 (0.90)a
S. sesban	87.34 (7.62)b	10.42 (1.20)a
C. cajan	67.90 (4.60)	8.46 (0.73)
L. leucocephala	87.48 (6.90)b	10.58 (1.05)a

Numbers in brackets are standard deviation. In each column no or lower case lettering is used to show the significant differences between different types of treatments at $p < 0.05$ level.

3.2.3. Total Gas (mL), CH_4 Production (mL), CH_4 Concentration (%), and CH_4 Production Reduction Potential of the Studied Forages

Total gas and CH_4 production and the proportion of CH_4 in the total gas produced on the test samples are provided in Table 4.

Table 4. Means of total gas production (GP), CH_4 production and concentration (as a proportion (%) of total GP).

Treatments	GP, mL/0.2 g DM	CH_4, mL/0.2 g DM	CH_4 Concentration (%)
Maize stover	144.06 (37.60)b	44.33 (1.41)a	31.73 (7.30)a
L. purpureus	206.40 (54.12)	33.00 (4.71)b	16.25 (1.20)
C. juncea	155.71 (30.43)ab	35.67 (1.41)b	23.45 (5.50)c
M. stenopetala.	169.80 (33)a	40.50 (2.60)a	24.16 (3.17)c
S. sesban	137.20 (43.64)b	40.67 (1.41)a	31.06 (8.80)ab
C. cajan	67.40 (26.73)	32.83 (2.21)b	52.22 (17.60)
L. leucocephala	142.40 (37.6)b	35.17 (1.2)b	25.48 (5.90)bc

Numbers in bracket are standard deviation. In each column no or lower case lettering is used to show the significant differences between different types of treatments at $p < 0.05$ level.

Total gas, CH_4 production and percentage of CH_4 concentration varied significantly ($p < 0.05$) among the studied forages (Table 4). Gas volumes from the incubation of 0.2 g substrate ranged from 67.38 to 206.40 mL after 48 h incubation. The total GP was highest for *L. purpureus* and lowest for *C. cajan*. Maize stover generated the most substantial amount of CH_4 (44.33 mL/0.2 g DM incubated) and *C. cajan* and *L. purpureus* the lowest amount, with 32.83 and 33 mL/0.2 g DM, respectively. The difference observed in CH_4 production among the samples is mainly attributed to differences in the fibre contents (see Section 3.3.). The CH_4 concentration (as a proportion of total GP) of forage samples investigated showed high variability ($p < 0.05$), ranging from 16.25 for *L. purpureus* to 52.22 for *C. cajan.* Methane concentration was significantly lower for *L. purpureus* (16.3%) followed by *C. juncea* (23.5%) and *M. stenopetala* (24%) and was higher for *C. cajan* (52.22) than other species (Table 4). Methane as a proportion of total gas could be used as an indicator to determine the capacity of a plant to suppress CH_4 production in vitro [49,50]. Lower CH_4 to gas percentages indicate that a particular candidate would be better as a rumen modifier for CH_4 reduction than those yielding higher percentages. In the current study, *L. purpureus* had the highest CH_4 reduction potential. *Crotalaria juncea*, *M. stenopetala*, and *L. leucocephala* also showed a consistently lower CH_4 percentage, which makes them promising species to reduce CH_4 production in ruminants in the study area. It is also important to note that these species had relatively higher CP concentrations (Table 2), which make them an ideal source of protein supplement in ruminant feed. Most of the promising forages with high CH_4 reduction potentials were also leguminous, except *M. stenopetala*. Legumes which contain higher CP have been shown to be associated with lower CH_4 production. In vitro studies (see, for example, [26,51]) have shown that a large portion of the variability of CH_4 production in legumes can be associated with the presence of secondary metabolites in some legume species, which can inhibit CH_4 formation [52,53].

3.3. Relationship between Chemical Composition and CH_4 Production

In the current study, among the various chemical constituents, ADL contents of the forages studied had only a significant negative correlation (r = 0.66) with CH_4 production (Table 5). Here, CH_4 production consistently decreased as the ADL content increased. A possible explanation for this might be that lignin protects fibres from ruminal degradation and thus reduces methanogenesis [54] most likely due to a reduced nutrient availability for the rumen microbes involved in methanogenesis as reported by Hindrichsen et al. [55]. A negative correlation between ADL and CH_4 release observed in the present study is in close agreement with earlier findings of Singh et al. [56] and Hindrichsen et al. [55]. The weak relationship between CH_4 and ADL content of the forages observed in the present study, however, demands caution. The adverse effects of ADL on CH_4 production observed suggest a positive role of lignin in mitigating CH_4 emissions from ruminant production [39]. Despite this rare observation of positive effects of lignin, nutritionists usually suggest to minimize the lignin content of ruminant diets [42]. In the current study, despite considerable variation in the chemical composition of the forages investigated (Table 2), CH_4 production was not significantly correlated with most chemical parameters (Table 5). The presence of plant secondary metabolites (e.g., condensed tannins and saponins) or starch may be responsible for moderating methanogenis in the rumen and thus CH_4 production, although, their presence was not examined in the current study. For example, condensed tannins containing forage species are thought to reduce CH_4 production in vitro through direct inhibition of methanogens, as well as indirectly limiting methanogenesis through reduced availability of hydrogen [52,53], but they may also reduce animal performance mostly by reducing feed intake and digestibility [57]. In this regard, more detailed studies defining the type and concentration of plant secondary compounds of some of the tested forages (legumes in particular) and selecting effective ones, which could reduce CH_4 production without negatively effecting protein supply, are needed. Additionally, high starch content favours the production of propionate and reduces ruminal pH, thus inhibiting methanogen growth [58]. The correlations between CH_4 production, CH_4 concentration, and chemical composition of forages are presented in Table 5.

Table 5. Correlations coefficients between CH_4 production, CH_4 concentration and forages chemical composition (n = 14).

	DM	Ash	CP	NDF	ADF	ADL
CH_4 production (mL/0.2 g DM)	−0.32	0.30	−0.20	0.11	0.02	−0.66 *
CH_4 concentration (%)	0.10	−0.41	0.03	0.27	0.18	0.30

Level of significance: * $p < 0.05$.

3.4. Farmers' Preferences and Ranking of the Studied Forage Species

Moringa stenopetala was found to be a highly preferred species for its palatability and animal preference, easy propagation, adaptability, easy establishment and management, multipurpose nature, and its compatibility with other crops (Table 6). *Moringa stenopetala* constitutes a vital component of the mixed farming systems found in parts of southern Ethiopia. The plant is mainly grown on farm boundaries and in the homestead. This is a fast-growing tree that is tolerant of drought and poor soil conditions and can survive for many years [59]. All these features might have contributed to the farmers' choice of this tree among the studied forage plants. Next to *M. stenopetala*, farmers in the study area had a high preference for *C. juncea* and *L. leucocephala*, both of which showed promising performance in terms of their values to farmers (Table 6). Although *Sesbania sesban* is widely cultivated in the study areas, farmers had shown low level of preference for this multipurpose tree. This could be a consequence of its poor agronomic performance in terms of adaptability, establishment, and biomass production in these areas, in particular in Ziway and Halaba (first author's personal observation and informal discussion with farmers).

Table 6. Farmers' preference and ranking of the forages.

Forages Criterion	*Maize Stover* [a]	*L. purpureus*	*C. juncea*	*M. stenopetala*	*S. sesban*	*C. cajan*	*L. leucocephala*
Palatability and animal preference	0.04	0.19	0.20	0.24	0.11	0.08	0.14
Adaptability	0.11	0.17	0.25	0.25	0.10	0.00	0.12
Easy to establish and manage	0.08	0.15	0.23	0.22	0.11	0.12	0.10
Multipurpose	0.21	0.08	0.07	0.25	0.11	0.15	0.13
Compatibility with other crops	0.07	0.09	0.22	0.24	0.12	0.14	0.12
Longevity	0.03	0.06	0.09	0.21	0.21	0.18	0.21
Sum of weighted scores [1]	0.55	0.74	1.06	1.40	0.76	0.67	0.81
Rank [b]	7	5	2	1	4	6	3

[a] Maize stover was evaluated only with respect to livestock use. [b] 1 = Most preferred; 7 = Least preferred; [1] Sum of weighted scores was developed to obtain the final ranking of the studied forages and calculated as: weighted sum = sum of [(7 × number of responses for 1st rank + 6 × number of responses for 2nd rank . . . ..+ 1 × number of responses for 7th)] divided by (7 × total responses for 1st rank + 6 × total responses for 2nd rank . . . .+ 1 × total responses for 7th rank).

3.5. Production of Crop Residue and the Potential of the Studied Forages to Intensify Ruminant Farming in Ethiopia Sustainably

In Ethiopia, most of the available feed energy and protein supplies for ruminants originate from rangelands and crop residues. Communal or private natural grazing and browsing, cut-and-carry system combined with tethering of animals, are the commonly practiced feeding systems in the country. Crop residues are estimated to cover up to 50% of the feed supply in mixed systems, whereas grassland resources cover up to 90% of livestock feed in pastoral systems [5]. Reports from the highland areas of East Africa show that maize yields, although subject to a general lowering, are likely to increase, providing more human food and animal feed [15]. Concentrates are expensive and seldom used in the country (see, for example, Assaminew and Ashenafi [60]). Above all, with the expansion of cultivation and shrinkage of the traditional grazing areas, crop residues are becoming an increasingly important component of ruminant feeds in many parts of Ethiopia [37,61]. We estimated the amount of crop residue produced from one of the major crops (i.e., maize) produced in the country [62]. Owing to the scarcity of data, dry matter obtainable from natural pastures and other land use categories such as forests was not estimated in this study. Using the recommended conversion factor [63] and based on national crop production data [64], we estimated that nearly 16 million tons of maize stover was produced in 2016/2017 in Ethiopia (Appendix A Table A1). In light of the various uses of maize stover on-farm (fodder, mulch, fuel) in the country, our intention here is to give an indication of dry matter quantity of the stover produced, not the quantity offered to livestock or potentially available to animals. Inadequate feed quality, typified by high NDF and low protein contents, and inadequate amount of feed impede improved animal production in Ethiopia. In the present analysis, maize stover exhibited the lowest CP concentration (3.40%) and a higher concentration of NDF (75.90%) and ADF (44.68%).

Furthermore, maize stover had the lowest emission reduction potential (Table 4) and was the least preferred by the farmers (see Section 3.4). However, given the expected long-term reliance on crop residues, replacing or reducing maize stover use would be difficult, or even impossible. Animals feeding on these resources will, therefore, require additional protein. Some of the forage plants tested here have the potential to provide adequate protein at a minimum cost. To this end, the value of *S. sesban* (CP: 30.55%), *M. stenopetala* (CP: 25.9%), *L. leucocephala* (CP: 25.6%) and *C. cajan* (CP: 19.7%) needs due acknowledged as they have the highest CP concentrations (Table 2). The use of these forage species could clearly help to rectify some of the problems associated with low feed quality and partly address the major problems of long-term sustainability of crop-livestock systems in southern Ethiopia. There is a possibility of integrating these species in farmland along the farm border or around homesteads. This strategy could allow farmers to use their land simultaneously for the cultivation of crop, forage, and trees, where products can have multiple uses [5]. The current promotion of sustainable intensification of crop–livestock systems at the national level [7,65] is a good opportunity for scaling out these promising forage species in mixed farming systems in Ethiopia, thereby contributing to improved utilization of maize stover, reduced environmental damage, and improved livestock productivity.

4. Conclusions

Total enteric CH_4 emission from ruminant livestock in Ethiopia increased by 12% or ≈ 6197 Gg CO2-eq. in 2017 compared to the year 2011. The analysis leads to the conclusion that CH_4 emissions from ruminant livestock in Ethiopia amounted to an annual growth rate of nearly 2%, which is higher than the global average experienced between 1961 and 2010 (0.95%). As we discussed earlier, promising forage plants with high feeding quality and low CH_4 production potential were identified. Nonetheless, *L. purpureus*, *C. juncea*, *M. stenopetala*, and *L. leucocephala* were found to have such desirable qualities. Overall, with the exception of maize stover, all the forages species evaluated in this study were of high CP concentration. The high CH_4 reduction potential and high levels of CP content of these forages could be used for CH_4 mitigation while simultaneously enhancing protein supply in ruminant's forage diets in southern Ethiopia. We have shown that multipurpose forage species such as *C. juncea*, *M. stenopetala*, and *L. leucocephala* greatly reduced CH_4 emissions, had high CP contents, and were preferred by the farmers', which would provide an exciting pathway for intensifying the mixed farming system in southern Ethiopia. The current promotion of sustainable intensification of crop–livestock systems in Ethiopia is a good opportunity for scaling out these promising forages in the country. Nevertheless, there is a need for screening the species using larger datasets to identify where and how to best promote these multipurpose forage species for wider adoption in the country. We suggest that future research should consider optimum level of inclusion of maize stover with the identified promising forage species through feeding experiment to improve livestock production in southern Ethiopia and beyond.

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Appendix A

Table A1. National estimates of maize stover produced per annum in the 2016/2017 production year in Ethiopia.

Residue	Grain Production (10^6 ton)	Conversion Factor	Estimated Maize Stover Production (10^6 ton) **
Maize *	7.85	2	15.69

* Crop residue production was estimated by multiplying the amount of grain produced with established conversion factor for the crop [63]. ** Does not include stover produced by commercial large-scale farms. Source: CSA report [64].

Annex 1 Equation employed to calculate gas production

$$GPt = [(SVt - SVo) - (BVt - BVo) \times 0.2\ g]/ACW$$

GPt = volume of gas produced at time "t"
SVt = syring reading for the sample at time "t"
SVo = syring reading for the sample at the beginning of the incubation

BVt = mean of the three replicates blank readings at time "t".
BVo = mean of the three replicates blank readings at the beginning of the incubation.
ACWs = actual weight of the sample incubated on dry matter basis

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PAPER IV

The contribution of frankincense to the agro-pastoral household economy and its potential for commercialization - a case from Borana, southern Ethiopia

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ABSTRACT

Frankincense, gum arabic and myrrh are among the most valuable commercial non-timber forest products in the drylands of eastern Africa. This study examines the frankincense value chain and its contribution to the household economy in southern Ethiopia. The study applied a combination of sustainable livelihood and value chain frameworks to assess the values and the contribution of frankincense to household economies. Data originate from a household survey, focus group discussions, key informant interviews and field observations. On average, the annual cash income generated from the harvest and sale of frankincense was estimated to be 60 USD per adult equivalent unit (AEU) and this income was estimated to contribute 35% of the total household's annual cash income. Our analyses reveal that income from frankincense constitutes the second largest share of the total average household cash income after livestock, which accounted for 60% of total household income. The poorer households (44% of sample) have a relatively higher reliance on frankincense income (49.8%), almost as much as from livestock production and non-farm revenues combined. Frankincense production and trading functions as a safety net and supplementary source of income for the herders. Nevertheless, despite the abundance of the resource and a growing domestic market demand, the marketed quantities are low, extraction practices are primitive and both local and national markets are poorly developed. The value chain analysis showed that the prices increase from nearly 1 USD per kg at the harvest sites to 5.5 USD per kg at the retail level. Recommendations include improving harvesting and processing skills through training, introducing harvesting and post-harvest technologies, improving market access, providing credit services, and training gatherers and local traders on value adding processing and marketing skills. These measures could improve the economic returns from frankincense extraction and sale and contribute to increased incomes and more sustainable livelihoods.

Key words*:* Frankincense, value chain, frankincense income, household economy, southern Ethiopia, sustainable livelihood

1. Introduction

Millions of rural dwellers throughout the world depend on non-timber forest products (NTFPs) for household subsistence and cash incomes (FAO, 1996; Kar and Jacobson, 2012; Shackleton, 2011; Sunderlin et al., 2005). Some of these products have important commercial markets and generate substantial revenues (Jensen, 2009; Kusters and Belcher, 2004; Marshall et al., 2006). Collection and marketing of NTFPs offer an easy entry into the market economy for the forest-dependent poor population (Kar and Jacobson, 2012; Shackleton, 2011; Vedeld et al., 2007; Vedeld et al., 2004). Extraction and trade of NTFPs also provide an economic safety net in times of dire need (Angelsen and Wunder, 2003; Sunderlin et al., 2005). Despite this, research and development activities on NTFPs has fluctuated over the past decades.

Even though commercial performance of NTFPs and development linkages have been widely discussed in the literature for more than thirty years (Belcher and Schreckenberg, 2007; Neumann and Hirsch, 2000; Pérez and Arnold, 1996), no generally agreed-upon approach to generalize results has evolved yet (Angelsen et al., 2014; Wunder et al., 2014). Consequently, no clear paradigm shift to promote commercialization of NTFPs has occurred in national development approaches in developing countries (Lemenih and Kassa, 2011a; Wunder et al., 2014).

In recent years, however, the desire to promote the adoption of locally specific development options, along with global concerns over rural poverty and the negative effects of climate change have led to renewed interests in commercial extraction of NTFPs. In the drylands of Africa, NTFP commercialization has been increasingly promoted as a strategy for improving rural livelihoods and an approach to foster resilience (De Leeuw et al., 2014; Lemenih and Kassa, 2011a; Wagner et al., 2013). It is argued (Belcher and Schreckenberg, 2007; Jensen and Meilby, 2008; Neumann and Hirsch, 2000) that improved market access and NTFP commercialization, i.e. increasing the value of NTFP in trade, and the integration of gatherers/harvesters into markets can increase rural incomes and employment opportunities. Under the right conditions and, if managed well, commercialization may also provide incentives for environmental conservation, particularly of valuable tree species (Belcher and Schreckenberg, 2007; Jensen and Meilby, 2008). Earlier reports further note that commercial extraction of NTFPs may be a viable (both ecologically and economically) activity to areas where population densities are low (Homma, 1992).

Frankincense, gum arabic and myrrh are the most economically valuable NTFPs in the dryland areas of Ethiopia. Among these, frankincense is a widely used and traded product, and constitutes an essential part of the livelihoods of rural communities (Lemenih et al., 2003b; Lemenih and Kassa, 2011a) Yet, despite its potential to stimulate local development in parts of Ethiopia (Lemenih and Kassa, 2011a) and elsewhere in Africa (Abtew et al., 2012), frankincense remains an underutilised resource in southern Ethiopia.

The present study was conducted to quantify the contribution of frankincense to the agropastoral household economy and assess its value chain in southern Ethiopia. The results of this study may contribute to the growing national and global initiatives aimed at supporting the design of context-specific livelihood interventions in the drylands (De Leeuw et al., 2014).

2. Conceptual framework and analytical approach

In this study, a combination of the sustainable livelihood approach (SLA) (Scoones, 1998) and the value chain framework was employed (Gereffi et al., 2001; Kanji et al., 2005; Ribot, 1998). The value chain analysis (VCA), combined with SLA, is widely used in examining the role of NTFPs in generating local livelihoods (Ingram, 2014; Kar, 2010; Neilson and Shonk, 2014).

The SLA approach analyses the role of the household's resources or assets as determinants of activities, and highlights the link between access to assets, choice of livelihood activities, and the resultant cash and subsistence incomes. The SLA is also often used to assess aspects of households' vulnerabilities and adaptation options. It is further used to examine how institutions, policies and other factors external to direct household control impact households' willingness and capability to produce various livelihood outcomes (Scoones, 1998). In our case, SLA was used to study frankincense and show how it contributes to a household's livelihoods and economic wellbeing. At the core of the framework are the livelihood capitals or assets that households combine to form livelihood strategies and diversification patterns with particular livelihood outcomes (Challies and Murray, 2014; Scoones, 1998). This scenario permits a study of the total economic production (i.e. per household) as well as the distributional effects or patterns of production.

Frankincense is a freely accessed wild-harvest product and frequently used by agro-pastoralists in southern Ethiopia as a form of natural, additional capital. Thus, in the context of SLA, frankincense gathering is a livelihood strategy. Hence, knowledge on how this natural resource can contribute to livelihoods is essential to be able to understand the links between various elements of household income and dependence on the product. While the SLA provides sufficient framework for analysing livelihood outcomes of frankincense gathering, it does not sufficiently explain the role of markets and market linkages (Dorward et al., 2003; Kanji et al., 2005). A value chain analysis is therefore used as a complementary framework to better assess linkages between production and the market for frankincense.

The value chain analysis is both a descriptive and an analytical tool to analyse the activities and processes involved at specific geographical scales from conception of production, through production to harvest, transformation to end users and the final disposal after use (Hoermann et al., 2010; Ingram, 2014; Jensen, 2009; te Velde et al., 2006). The value chain analysis can be used to understand the functioning of a value chain and to identify strategies for functional upgrading (Stein and Barron, 2017). It can also be used to assess potentials to support pro-poor economic development (UNIDO, 2011; Webber and Labaste, 2006). However, applying the VCA framework has often been found to place too much emphasis on the structure and dynamism of marketing networks and the distributional gains along the chain (Lowitt et al., 2015; Rich et al., 2011). Furthermore, the VCA tends to focus on examining the incomes and assets associated with the relevant chain and product, while ignoring other income generating activities of the same households (Bolwig et al., 2010). Rural households in the developing world typically depend on multiple income sources for their survival and livelihood. The VCA also focuses more on economic efficiency and optimization of value chains and less on unequal power and redistribution of costs and benefits along the value chain. A livelihood analysis goes beyond costs and prices, income and consumption to provide complementary information by which to assess (rather than measure) the choices that people make in particular contexts. Apart from its focus on increased incomes, it recognises other livelihood outcomes – for example, improved food security or a more sustainable use of natural resources (Kanji et al., 2005). More specifically, it organizes and identifies constraints and opportunities associated with improving household income and displays how they are interlinked.

Combining the two approaches thus yields a more comprehensive understanding of both the market related-aspects of frankincense and the way in which markets for frankincense relate to livelihood strategies (Challies and Murray, 2014; Kanji et al., 2005; Kar, 2010). A key component of such analysis is looking at the relative importance of different activities and income sources at the household level (e.g., the relative contribution of frankincense income to household economy compared to other livelihood sources (Trædal and Vedeld, 2018). The present study is focused on the upstream/productive end of the supply chain i.e. the small-scale frankincense extractors (hereafter referred to as gatherers) in southern Ethiopia. Further links and functions were investigated by moving up the chain as suggested by Marshal et al. (2006).

3. The study area and description of frankincense

The study was conducted in Borana, southern Ethiopia. The study area is characterized by a semi-arid climate and a bimodal rainfall pattern. Diminishing rainfall and climate variability (Niang et al., 2014; USGS, 2012) are the most important physical constraints to agricultural production in Borana. The area is the home of the Borana agro-pastoralists whose livelihood is based on herding and cropping on small plots as well as forest resource utilization. The area is known for its abundant and diverse species of gum and resin-yielding trees principally in the genus *Acacia, Boswellia* and *Commiphora* from which local communities actively collect frankincense, gum and myrrh (Worku, 2006).

This study focuses on frankincense (also called olibanum); a widely traded aromatic, congealed, resinous exudate derived from species of the genus *Boswellia* (FAO, 1995). Three types of frankincense are Ethiopian: the Tigray, the Ogaden and the Borana type. The Borana type, the focus of this paper, is produced from *Boswellia neglecta* S. Moore and originates in the drylands of Borana (Deffar, 1998; Lemenih et al., 2003b; Tadesse et al., 2007). In Borana, frankincense is harvested from natural stands through natural exudation. The Borana type frankincense is a black-coloured, fragrant resin exudate that oozes out in small droplets from the trunks and branches of the trees.

Frankincense has been used in embalming, cosmetics and as incense in rituals and religious ceremonies in ancient Egypt, Greece, Rome and China for thousands of years (Tucker, 1986). In Ethiopia, frankincense is used as a fragrance in the home, and in many religious and social rituals such as the coffee ceremonies. The product is also used as a raw material in food, adhesives, cosmetics, paints and pharmaceutical industries in the developed world (FAO, 1995; Tucker, 1986). Frankincense reportedly has health benefits and is even today used in various traditional medicines in Asia and Africa (Yaniv and Dudai, 2014). The product is believed to have the oldest global supply chain in the world, and Ethiopia is claimed to be one of the main sources of frankincense of antiquity (since the Aksumite period) (Munro-Hay, 1991; Tucker, 1986). The country is also one of the major producers and exporters of frankincense in the world (FAO, 1995; Lemenih and Teketay, 2003a).

This study was conducted in two districts (Yabello and Arero) where frankincense is actively collected and marketed (Worku, 2006). These districts are amongst the poorest in Ethiopia. Due to recurrent droughts and erratic rainfall, these areas have experienced severe food insecurity problems, and increasing temperatures and declining spring rainfalls are projected to be major future challenges to agro-pastoralists in these areas (Niang et al., 2014), supporting the importance of alternative cash income generating options.

4. Materials and methods

4.1 Research approach and sampling

The present study was conducted as a case study (Yin, 1994). Due to the semi-nomadic nature of the pastoral populations, it is difficult to find a reasonable sampling frame in terms of a list of population members from which a relevant sample can be drawn and it is uncertain and difficult to assert and correctly identify and locate gatherers using conventional household-based sampling strategies. Moreover, frankincense gathering is not a fulltime activity as households collect the product while herding their animals and executing other income generating activities. In addition, no prior data were available on the number of gatherers in the study areas and along the chain. For such hard-to-reach populations then, constructing the sampling frame using methods such as household surveys is not easily feasible (in terms of time and cost) since the population is dispersed in time and space and is very mobile (Heckathorn, 2011). It was thus difficult to assess the total number of households and household members engaged in frankincense gathering and trade during the period of data collection.

We therefore employed a respondent-driven sampling (RDS) approach to manage these difficulties and access gatherers and other hard-to-reach actors and stakeholders. Respondent-driven sampling is a network-based method designed to study hard-to-reach populations, in which respondents refer the researcher to other respondents. The method provides a study sample through referrals (i.e. one interviewee providing information about the next points in the chain) made among people who share or know of others who possess some characteristics that are of research interest (Heckathorn, 1997; Wejnert and Heckathorn, 2008). In this study, the participants were encouraged to identify and access a sample of respondents who were as representative as possible. To minimize the risk of not reaching certain subgroups via this insider method (i.e. RDS) (Biernacki and Waldor, 1981), we supplemented with both purposive and more random sampling strategies. Accordingly, frankincense gatherers (n=34) were selected using a combination of RDS and purposive sampling methods whereas RDS was employed to select mobile traders (n=5), collectors (n=6), and microenterprises (n=2). In addition, petty traders at the village level (n=7), and urban petty traders (n=7) were selected using purposive sampling techniques. The state-owned Natural Gum Processing and Marketing Enterprise (hereafter called the state-owned enterprise (SOE)) was selected using purposive sampling. For the RDS and purposive sample, respondents were selected because they were known to be currently involved in frankincense extraction and trading.

4.2 Methods of data collection

The study was further conducted through a combination of qualitative and quantitative methods, comprising a questionnaire survey; key informant interviews (KII), focus group discussions (FGD) and also seeking various secondary data sources. Secondary data were collected from the state-owned enterprise that dominates the frankincense processing and export market in the country. Semi-structured interviews with the above-mentioned actors and stakeholders (N=61) involved in the gathering, collection, and trading constituted the primary source of information. Gatherer data were drawn from the household survey; all other participant data come from the value chain survey using KII, FGDs, and direct market observations.

4.2.1 Harvest estimation

The key variables were collected based on respondent's recall of average quantity of frankincense sold daily, harvesting days per week and length of harvest season, instead of the preferred but more time consuming and costly method of direct measurement. In order to avoid recall problems and minimize inaccuracies, data were collected during one of the two production seasons and at harvest sites. They were also cross-checked with *in situ* observations. Moreover, focus group discussions were held (a day after the interviews) in the villages to triangulate data and to clarify points raised in interviews.

Annual production is calculated as average sale per day of unprocessed frankincense multiplied by the average number of harvest days per week multiplied by the average number of harvest months in the year 2015/16 (two seasons) as recalled by the respondents. For average harvest quantity, respondents were asked to provide estimates of the maximum (high harvest) and minimum (low harvest) harvest data the average of which was used to calculate production per gatherer per day.

4.2.2 Income calculation

An important general principle in measuring the real contribution of any particular activity to overall economic wellbeing is the use of gross and net income (Cavendish, 2002). In our case study, income sources of the households were disaggregated into livestock production (live animal, milk and butter sales), frankincense extraction and non-farm activities (income from safety net programme (MoRAD, 2010)). Incomes obtained from crop production and chicken were not included in the present computation. Crops were grown on small plots for subsistence use. As they could not produce enough food to cover their basic requirements, most households in our sampled villages depend heavily on buying grains. Due to semi-nomadic nature of the populations in the area, most households do not keep chicken (ref. FGD and observation). Therefore, we excluded crop and chicken data from the income computation. For each economic activity, net income was calculated as gross value minus the total costs of all inputs (except family labour). In the net income calculations, the family labour was still not deducted from gross income. In the study area, the households used their own labour in all production activities. Calculating the net income from livestock involved multiplying the quantities of products and number of animals sold by the actual price at village markets and deducting the other annual costs incurred. In Ethiopia, the poorer pastoral households without options (i.e. in areas where access to income is rare or absent), critically depend on gifts and remittances from their kin or from wealthier neighbours as the source of cash income (MoRAD, 2010). These households would often sell these animals to purchase food grain and other basic products. Thus, we have included gifts in our livestock income computation. The total net income from livestock production is thus the sum of the net income from sales of live animals, animals received as gifts, milk and butter sales over a year as a production period. Furthermore, only the cash income values (excluding household consumption) are included in this calculation. The cash income obtained from non-farm activities is based on the amount earned during the study year. Income analysis, in the present study, aimed at elucidating total household cash income (i.e. the sum of livestock, frankincense and non-farm income), per capita income, and the respective shares of frankincense incomes.

4.2.2.1 Income from frankincense

The households in the study area were harvesting frankincense along with herding their animals and the labour invested in frankincense collection was their own family labour. Wage labour is virtually absent. The opportunity costs for their own time involved in frankincense gathering is thus marginal or negligible and labour cost is thus not considered here. This is often a major problem in quantifying livelihood cost and benefits in rural Africa (Ingram, 2014). Additionally, unlike other parts of the country (Woldeamanuel, 2011), gatherers in the study area do not use frankincense for home consumption. Thus, no in-kind incomes were included in the present computation. The analyses did not include any access costs as frankincense is harvested from open woodlands. Gatherers often obtain sacks from collectors. Moreover, frankincense (i.e. naturally exuded) is manually picked from trunks and branches of the trees. Gatherers thus incur no costs. Annual net income (Wollenberg and Ingles, 1998) from frankincense sale were thus calculated as the quantity traded multiplied by the village market prices.

4.3 Data analysis

Both quantitative and qualitative analyses methods were employed to analyse and present the data. The main statistical analysis applied are descriptive statistics, analysis of variance (ANOVA) and regression. The regression is employed to analyse relationships between the relative frankincense income and households' total income. Descriptive statistics were used to describe the demographic profile of gatherers and levels of income, quantities and values of frankincense marketed in the study area. Data from the gatherers from the two villages (one from each district) were pooled (therefore, n =34) because the sample size was too small to analyse each village individually once disaggregated into wealth categories. The villages where data were collected are relatively similar in terms of natural habitats, a heavy reliance on the natural resource base, rather open access to forest resources, similar production systems and ethnicity characteristics (both villages are Borana agro-pastoralists). Household wealth in this dryland (in Borana) area is closely connected to livestock and, since it reflects common access to livelihood capital, we categorized households into three wealth groups based on the size of cattle holdings: poor (0−14 tropical livestock units, TLUs), medium (14–21 TLUs) and better-off (above 21 TLUs). As observed in many NTFP studies (Godoy and Bawa 1993; Kar and

Jacobson, 2012; Quang and Anh, 2006), we also expect a negative relationship between dependence on frankincense income and household wealth. Our interest in this paper is not only to examine the relationship between livestock holdings and frankincense income, but also to examine to what extent households differ in their reliance on frankincense income. The evidence of different groups may provide suggestive insights about the degree of dependence of different groups of the population on the studied product, which may be of relevance for policies aimed at improving the livelihoods of vulnerable groups in the area.

For inter-household comparisons, we do not use the total cash income per household, but we adjust it according to the size of the household. The adult equivalent unit (AEU) scales the consumption level of household members of different ages to the equivalent consumption level of an adult (Deaton, 2003). Adults (above 18) were given a weight of 1 while children (below 18) were given a weight of 0.3 as suggested in (Deaton, 2003). A one-way ANOVA was carried out to test the differences in the relative frankincense income and mean income per AEU among the wealth groups. The means were separated using the least significant difference (LSD) test. A probability level of 0.05 was used in both the tests. Information collected using KII, FGDs, and observations were summarized and narrated. All income figures are reported in purchasing power parity (PPP) adjusted 2016 USD using a conversion figure of 21.94 Ethiopian birr (ETB) per 1 USD. In this study, we included only households engaged in frankincense extraction so as to enable us to compare and contrast incomes obtained from different household economic activities.

4.4 Value chain analysis and mapping

Data from actors and stakeholders through interviews with gatherers, traders, and retailers were supplemented with market reports from the SOE and used to conduct the frankincense VCA. This included the following analyses:

Value chain mapping, i.e. mapping and description of the chain via graphic presentation of the stages in the chain and the different actors and stakeholders involved in the chain and their function in the value chain (McCormick and Schmitz, 2001)

Quantifying the volume of product that moves through the different paths of the chain, and the distribution of (net income) profits along the chain.

4.4.1 Profits along the chain and the commercialization margin

Quantitative data on the cost and revenues, value added, and profit distribution were calculated as described in (Marshall et al., 2006).

Profit margin at each stage was calculated to evaluate the benefits along the product value chain as:

$$\text{Profit margin} = Revenue - total\ cost$$

where Revenue = sale volume x unit price

$$\text{Profit margin \%} = \frac{(\text{Revenue} - \text{total cost})}{\text{Revenue}} \text{x}100$$

The costs include transportation, labour, material (sacks) and taxes.

Furthermore, a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis was used for analysing internal and external factors that influence production and marketing of frankincense. Focus group discussions were the basis of identifying these factors, which were later verified through literature searching and expert consultation.

5. Results

5.1 The frankincense value chain

The frankincense value chain analysis for southern Ethiopia broke activities down into four functional segments: extraction and collection (product assembly); handling and processing (storage, transportation and processing); commercialization, which involves price establishment, marketing and facilitating functions such as regulatory support. Fig. 2 describes the value chain map (a conceptual model) of frankincense representing the situation in southern Ethiopia. The arrows in the market maps represent transitions of the product between actors and stakeholders in different segments of the value chain. The chart shows the structure of the frankincense value chain from harvest to end users and the role that the different actors and stakeholders play at the different stages. The bold lines show the most important channel of the product flow.

The transfer of frankincense from the production area to end users is carried out by a set of specialized economic actors and stakeholders, and the commodity is traded through formal and informal markets at harvest sites, village, urban and central (national) markets. The major actors and stakeholders are gatherers, collectors and microenterprises, retailers, the state-owned enterprise, wholesalers and private exporters and consumers (Fig. 2).

Formal regulatory, supporting, and/or controlling stakeholders are largely absent in the studied frankincense production sites. In this study, no formal interviews were made with private exporters, consumers and support institutions. Thus, results are presented based on observations, key informant interviews at the state-owned enterprise and informal discussions with various government officials. The current frankincense value chain and major actors (such as gatherers, collectors and retailers) and stakeholders (such as wholesalers and exporters) involved are mapped out in Fig. 2 and their functions are further discussed below.

5.2 Chain actors, stakeholders and activities

5.2.1 Socioeconomic characteristics and functions of the gatherers

We start with an overview of the households' socioeconomic characteristics and income levels before turning to a description of gatherers as the first actors in the market value chain.

All surveyed households were engaged in a diversified set of livelihood activities. On average, the households in the study area earned an annual cash net income of 213 USD per AEU. The livestock incomes provide, on average, close to 60% and frankincense close to 35% of the total income (see Table 1). Incomes from non-farm sources, which was mainly from remittances and cash-for-work schemes, represented 5% of the total income. The average household size (adult equivalent) was 4 while the average age of the respondents was 33 years old. All surveyed households reported that they keep livestock. Cattle are the most valued animals in the area. The average cattle holding, measured in TLU, was 17.8, ranging from 5.6 to 70 per household. Based on the wealth categories as defined in the methodology section, 44% of the households were poor while 32% and 24% were in the medium and better-off categories, respectively. Of the studied households, only 14.7% had some form of formal education and none had received any form of agricultural extension and/or NTFPs production training. Socioeconomic characteristics of households engaged in frankincense gathering are shown in Table 1.

Table 1 Socioeconomic characteristics of households engaged in frankincense gathering in Borana, southern Ethiopia, 2016.

Attributes		Better-off (n=8)[a]	Medium (n=11)	Poor (n=15)	Sample mean (n=34)
Age (in years)[b]		39.8 (11.2)	33.82 (7.5)	29.53 (4.41)	33.32 (8.26)
HH size (AEU)		5.2 (2.44)	3.97 (1.91)	3.45 (1.01)	4.03 (1.81)
Resident status (%)	Local villagers	8.82	20.56	29.4	58.8
	Non-residents (migrants)	14.71	11.8	14.71	41.2
	None	17.7	23.53	14.71	55.9
Education hh head (%)	Read and write	5.9	8.82	14.71	29.4
	Primary school	0	0	14.71	14.7
Cattle TLU		35.53 (16)	17.69 (2.15)	8.49 (2.2)	17.83 (13.2)
Cattle per AEU		7.16 (3.63)	4.23 (2.2)	3.75 (2.44)	4.71 (2.95)
Livestock income in USD		223 (160)	194.54 (138)	69.4 (51.64)	146 (131.2)
Frankincense income in USD		34.48 (17.9)	57.62 (30)	74.70 (29.1)	59.7 (31)
Non-farm income in USD		4.5 (4.9)	4 (3.75)	12.55 (11.74)	7.9 (9.3)
TI per AEU in USD		262.04 (162.11)	256.14 (147.5)	156.62 (69.73)	213.62 (129.9)

[a]Households were categorized based on level of cattle holdings; [b]age of the household head; HH: household; AEU: adult equivalent unit; TLU: tropical livestock unit; TI: total income (i.e. the sum of livestock, frankincense and non-farm incomes). Standard deviations in parenthesis.

There is a long tradition of frankincense harvesting and trade in Borana and other parts of Ethiopia. Gatherers are the first actors in the chain. All sampled households and members involved in frankincense gathering were male. Some 59% of them were local villagers who lived and harvested the product in their home village (village of origin). Key informants reported that frankincense harvesting was mainly a dry-season activity coinciding with pastoral mobility during the low cropping season and low levels of milk production. Frankincense gathering was mainly done by male herders (supported by young boys), largely as a supplement to herding. Tapping is not a common practice in the study area. All frankincense which is collected comes from gathering natural exudates. The average amount of frankincense collected by a gatherer was 5 kg per day and the average number days engaged in gathering were about 3 days per week. The average annual production was an estimated 219±74 kg per household (Table 2). It was stated (ref. KII) that the gatherers often delivered frankincense to the market immediately after collection (fresh, unsorted and uncleaned). Depending on the quantity of frankincense collected per day, the gatherers deliver the product either to camps set up by the collectors at the harvest sites (often close to water points) or to microenterprises at village markets, or to village level petty traders (Fig. 2). This was mainly the case when they had small quantities - often less than 1 kg. Transactions in the village were done largely in exchange for money, but occasionally for commodities (exchanging with frankincense equivalent) for daily consumption. Gatherers earned, on average, 205 USD annually (ETB 4489) from frankincense gathering and sales (see Table 3). Selected variables pertaining to frankincense harvest by the gatherers are presented in Table 2.

Table 2 Frankincense harvest and sales prices, Borana, southern Ethiopia, 2016.

Variables	Mean	Std.dev.	Min	Max
Harvest trips per week	2.71	0.76	1	4
Harvest quantity per day (in kg)	5.12	1.25	2.5	8.5
Quantity produced per year (in kg)	218.59	74.39	80	408
Price per kg - formal market (USD)	0.9	-	-	-
Price per kg - informal market (USD)[a]	1.05	-	1	1.1

[a]Markets operating fully outside of government regulation and observation. Traders in such markets participate in the illegal import and export of frankincense across the border (through border towns such as Moyale) to Kenya.

5.2.2 Collectors and microenterprises

Collectors and microenterprises are involved in buying, storing and supplying frankincense largely to the SOE. Both actors largely vend unprocessed products. Collectors are mainly local operators living in frankincense-producing villages. They sell the frankincense in weekly rural markets adjacent to the production sites. They are commonly organized at a central place in the village or in the district centre. Collectors have established trading relationships with the SOE and sometimes receive advances from the company. These actors also trade basic commodities (sugar, tea, tobacco, maize flour, etc.) as well. They bring goods to the harvest sites, exchanging them with gatherers for cash or frankincense equivalent.

Microenterprises are small-scale cooperatives established by youth groups and are mainly local actors at the district or village level. These actors collect and assemble frankincense from producers and, to a lesser extent, from collectors in village markets. They largely sell the item (partially dried and cleaned frankincense) to the SOE and occasionally to mobile traders (often less than 0.1 tonne per transaction) as well as directly to consumers. They usually had collection sites and their own smaller storage houses where they may store for a while. Microenterprises process (dry, clean and sort) and pack part of the product in smaller quantities (often 250 g) for sale to mobile traders and consumers (Fig. 1, right). The microenterprises were found to be weak in terms of operating and fixed capital. They lack processing equipment, buildings for drying and storage and they do not have transport means. Their trade with the gatherers was limited.

5.2.3 State-owned processing and trading enterprise

The state-owned enterprise is the dominant market operator in the frankincense value chain in Ethiopia (35% of the export trade volume) (Kassa et al., 2011) and also in the study area. Processing, marketing (domestic and export) and facilitation are the major functions of the company. The company functions through its branch offices established in towns such as Jabillo near the producing areas. The company sets prices and sometimes pre-finances the collectors through contractual agreements. The company works in rural weekly markets and offer free transport services to the collectors as an incentive. To this end, the company's pick-ups transport goods to the collection points (harvest sites/village markets) and transport frankincense on their return. The company procures frankincense in bulk from microenterprises and transports the unprocessed frankincense to the main depot located at Adama (Nazreth) town where the processing unit is located. Following this, it delivers the product to the exporters and domestic wholesalers. The company has storage facilities in towns close to the production sites. The company also processes and sorts the product into different grades according to size, colour and state of cleanliness before packing it for export or for the domestic market. Processing activities consist of drying, cleaning, sorting and grading. These activities were performed manually by hired female labourers.

Fig. 1. Left: village based petty trader. Right: Partly processed (dried, cleaned and sorted) frankincense packed for sale by a microenterprise (top) and woman selling packed frankincense (bottom) (at Yabello town). (Photo by the first author).

5.2.4 Private exporters and wholesalers

Apart from the state-owned enterprise, there are also private companies involved in frankincense export from Ethiopia. Exporters procure processed frankincense from the state-owned enterprise. They also wholesale frankincense of low grade for local use to other wholesalers and urban-based retailers. Wholesalers source frankincense largely from the state-owned enterprise, and also occasionally from other wholesalers and exporters. These stakeholders often supply larger urban markets and sell to other domestic wholesalers or urban-based retailers in the towns. Both private exporters and wholesalers are located in Addis Ababa. There are no exporters or wholesalers in smaller villages/towns.

5.2.5 Retailers

In the present study, two types of retailers were recognized: mobile traders and small-scale retailers; hereafter called petty traders. The mobile traders purchase either directly from microenterprises or from village petty traders and resell to their customers in major towns such as Hawassa and Shashemene. They do not have a permanent station but are street vendors along roadsides and involved in door-to-door sale directly to urban petty traders (described below) and end users such as street coffee venders, individual households and cultural restaurants. The amount sold per transaction was typically more than 0.5 kg. The second group of retailers (i.e. petty traders) sell small quantities of frankincense (up to 5 kg per sale (market observation)) to mobile traders and less than 0.5 kg per transaction to consumers. They could be sub-categorized into village level petty traders and urban petty traders. The former categories are small shop owners operating nearest to frankincense producing villages and often buy one plastic bag (equivalent to 0.55 kg) per transaction from gatherers (see Fig. 1, left). They largely sell to consumers and, to a lesser degree, to mobile traders. These were characterized by non-specialized activities engaged in trading of diverse commodities as well.

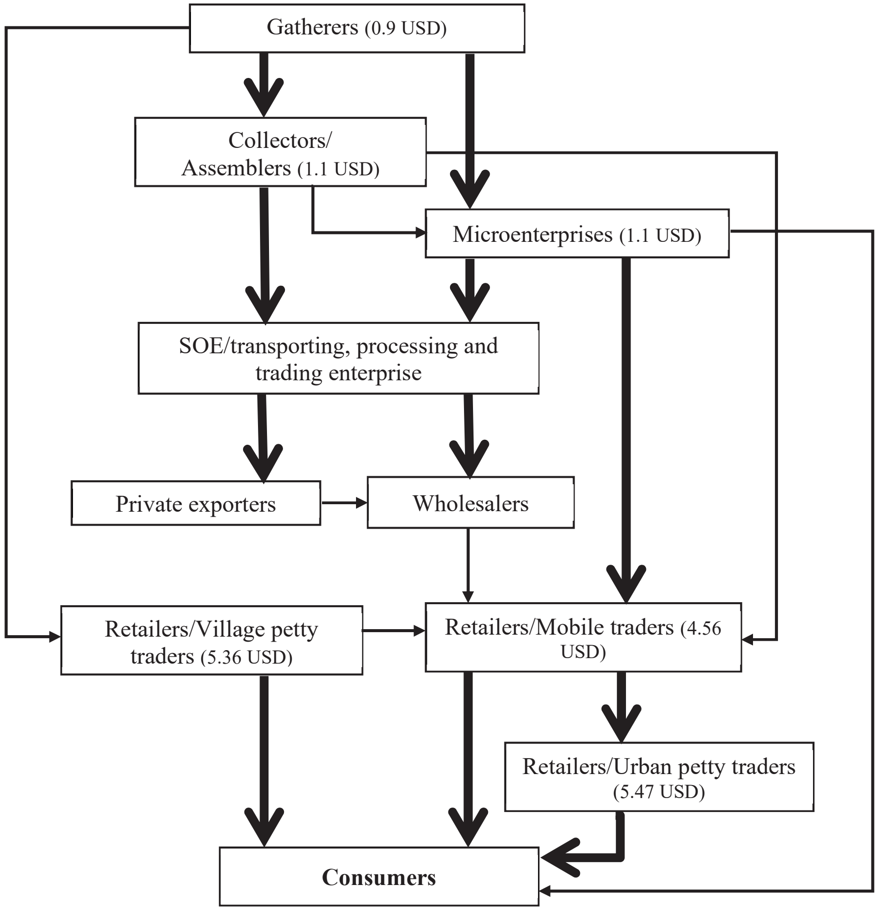
Urban petty traders are street venders selling on roadsides, and on daily markets called *gulit*. *Gulit* is a small trading centre found on the streets or in village centres, where different vegetables and other consumer goods are sold. Markets of this kind are open every day for a few hours per day on a regular basis. Village-level petty traders normally perform pre-sale activities limited to drying and cleaning. Although it is required to hold a license, retailers in our case study do not have retail license and thus paid no fees related to frankincense trading. All retailers were female vendors.

5.2.6 Consumers

Street coffee venders, individual households, religious institutions, particularly the Ethiopian Orthodox Church, and cultural restaurants are the main consumers of frankincense in Ethiopia. Frankincense in Ethiopia is used as fragrance in the homes, and in many religious and social rituals such as coffee ceremonies. Research indicates that large volumes of frankincense produced in the country are consumed locally (Lemenih and Kassa, 2011a).

5.2.7 Support institutions

Support stakeholders include government institutions such as the district revenue office, the district cooperative agency and district office of climate change, forestry and environment, and NGOs and transporters. Support institutions are outside the major value chain in the study area. Their role and functions are to facilitate and influence activities of the core value chain actors and stakeholders in the marketing chain. The government institutions issue production and marketing permits, establish cooperatives at the local level, collect taxes, commission and fees including royalty fees from traders at the local, regional (sub-national) and national levels. NGOs are mandated to facilitate and support establishment of cooperatives. However, among the main value chain stakeholders there was no mention of banks and micro-financial institutions providing financial support to the sector. Moreover, stakeholders providing development, technical harvesting, or processing support were not observed.



(Numbers in brackets are approximate mean prices per kg received by various types of actors and stakeholders. Data on price received by SOE, exporters and wholesalers not available.)

Fig. 2. Market actors, stakeholders and their relationships in the frankincense value chain, Borana, southern Ethiopia, 2016.

5.3 Price, quantities and value of marketed frankincense

The state-owned enterprise, wholesalers and private exporters were involved in multiple commodity trading; thus, it was difficult to obtain data on quantities and values from these participants. This in turn made it problematic to analyse the benefits to these participants. Thus, the present analysis merely considers their roles in physical functions and commercialization of the commodity. Based on the interviews with the key-informants, the results of estimated quantities of frankincense traded and price realized by the different actors are shown in Table 3.

Table 3 Mean annual frankincense quantities turned over along different value chain actors, Borana, southern Ethiopia, 2016.

Category	Gatherers (n=34)	Collectors (n=6)	ME (n=2)	MR (n=5)	VPT (n=7)	UPT (n=7)
Quantity gathered/bought (tonne)	0.22	5.33	10.5	0.54	0.04	0.19
Purchase price (USD/kg)	0	0.9	0.9	2.07	1.0	4.56
Quantity sold (tonne)	0.22	5.30	10.4	0.53	0.038	0.18
Sale price (USD/kg)	0.93	1.1	1.1	4.56	5.36	5.47
Total cost per year	0	4913	9966.4	1138.9	42.20	857.86
Total revenue[a]	204.59	5775.75	11371.01	2406.56	174.64	1015.76
Profit (Revenue less total cost)	204.59	862.70	1404.63	1267.7	132.45	157.90
Profit margin (%)		14.58	12.39	52.68	73.47	15.44
Added value		0.2	0.2	2.49	4.36	0.91

ME: Microenterprises; MR: Mobile retailers; VPT: Village petty traders; UPT: Urban petty traders; [a]Price*Average production

The prices obtained at the different stages for gatherers, collectors/microenterprise, mobile traders, village and urban retailers were 0.9 USD, 1.1 USD, 4.56 USD, 5.36 USD and 5.47 USD kg^{-1}, respectively (Table 3). The price differences stem from costs and value added including the transfer or relocation benefits of the product.

The price is usually fixed by the state-owned enterprise at the beginning of each collection season, and fixed prices remain unchanged for the rest of the year. The SOE fixes the price at the head office, and branch offices would undertake the purchases. Subsequently the traders set a price at which they buy from gatherers (ref. KII). However, the traders in the informal markets offer higher prices that ranged in this study from 1 to 1.1 USD (22–24 ETB) per kg (Table 2). Due to their strong market linkages with the traders, the limited capacity of the traders in the informal markets and the lack of alternative marketing outlets, the gatherers still prefer to sell through the formal markets.

5.4 Profit margins and distribution along the value chain

The analysis centred on four groups of actors along the frankincense value chain (gatherers, collectors, microenterprises and retailers). The average price, costs, incomes and profit distribution of the actors are presented in Table 3.

5.4.1 Producers

The average annual production was estimated at 218.59±74.39 kg per household. As mentioned in the methodology section, there is no cash cost incurred at this stage. The net average income of the gatherer in this study was found to be 205 USD per year.

5.4.2 Profit gained at different levels

The main costs for collectors, microenterprises and mobile retailers were transportation costs, purchasing the product and various material costs. The average annual net income of collectors, microenterprises, mobile retailers, village level and urban level petty traders was estimated to be 863, 1405, 1268, 132 and 158 USD, respectively. The profit margins made were 15, 12, 53, 73 and 15% for the collectors, mobile traders, microenterprises, mobile retailers, village level and urban level petty traders, respectively. The results clearly demonstrate that benefits are unevenly distributed among the value chain actors.

5.5 The contribution of frankincense production to the household economy: a case of gatherers in Borana, southern Ethiopia

Frankincense extraction was the second most important livelihood activity among the studied households (i.e. the gatherers) in the study area (Table 4). The income of agro-pastoralists derived from livestock and the sale of livestock products contributes 60% of the average total household cash incomes. All the wealth groups acquired substantial frankincense incomes. The average annual income generated from frankincense sale was estimated to be 59 USD per AEU. The income was estimated to contribute, on average, to 35.22%, ranging from 4.2% to 77.1% of the total household annual income. The high frankincense income shares reflect opportunities to further enhance returns from the product. However, as can be seen in Table 5, the contribution of frankincense to household income (per AEU by wealth group) varied from 16% to 50%, which was significant ($P < 0.05$). Income from non-farm sources, which were mainly from remittances and cash-for-work schemes, represented by comparison some 5% of the total income. This type of non-farm income is common in most chronically food insecure districts of the country.

Table 4 Reported annual cash income (in USD) per household and per AEU by source, Borana, Ethiopia, 2016.

Income source	Average income per HH[a] per year		Average income per AEU per year		Income shares (%)	
	Mean income	Max (min) values	Mean income	Max (min) values	Mean	Max (min) values
Livestock income	505.48	1640.84 (30.08)	146.05	565.81 (7.01)	59.37	94.49 (9.42)
Non-farm income[b]	29.40	101.19 (0)	7.87	31.62 (0)	5.40	22.11 (0)
Frankincense income	204.59	371.92 (72.93)	59.70	143.05 (10.81)	35.22	76.1 (4.2)

Total income	739.47	1736.55 (291.02)	213.62	598.81 (42.79)	

[a]HH=household; [b]includes incomes from remittance and cash-for-work.

5.6 The contribution of frankincense income by wealth groups

As shown earlier, frankincense contributes more than one-third of households' annual cash income. However, the poorest households obtained a significantly larger amount of frankincense income compared to the medium and better-off wealth groups ($P < 0.05$) (Table 5). We found no significant difference in mean annual frankincense income (per AEU) between medium and better-off groups. The mean annual income (per AEU) the better-off, medium and resource-poor households earned from frankincense was 34, 58 and 75 USD, respectively. The frankincense harvest was thus found to be particularly important for the poorer households. The income from frankincense is almost as important as livestock production and non-farm income combined among the poor households, amounting to half (49.81%) of their mean annual income (Table 5). Better-off households had lower income from frankincense extraction. No significant difference was observed in the share of frankincense income between better-off and medium groups ($P > 0.05$) (Table 5). However, the medium group still obtained a higher share of their income from frankincense than the better-off did.

Table 5 Mean total and relative annual frankincense income per AEU by wealth groups, Borana, Ethiopia, 2016.

Variable	Better-off (n=8)	Medium (n=11)	Poor (n=15)	Sample mean (n=34)
TI (USD/AEU/year)	262.04 (43.51)	256.14 (37.12)	156.62 (31.78)	213.62 (22.3)
FI (USD/AEU/year)	34.48 (9.65)[a]	57.62 (8.23)[ab]	74.70 (7.04)[b]	59.70 (5.3)
FIS (%)	16.16 (3.14)[a]	29.20 (5.62)[a]	49.81 (3.13)	35.22 (3.35)

TI: total income; FI: income from frankincense; FIS=Frankincense income share (as share of total income). Standard errors in parenthesis; [a,ab,b]Groups with different or no letters are significantly different from each other (Fisher's LSD test, $P < 0.05$).

An ordinary least square linear regression was carried out to investigate the relationship between the relative frankincense income and households' total income. We found that the relative frankincense income was negatively correlated with the total household income ($R^2 = 0.398$; $P<0.001$; $n=34$) (Fig. 3). This indicates that frankincense income decreases with increasing household total income. This regression analysis also confirms that the poorer households generate a larger share of their total income from frankincense income compared to the medium and better-off households.

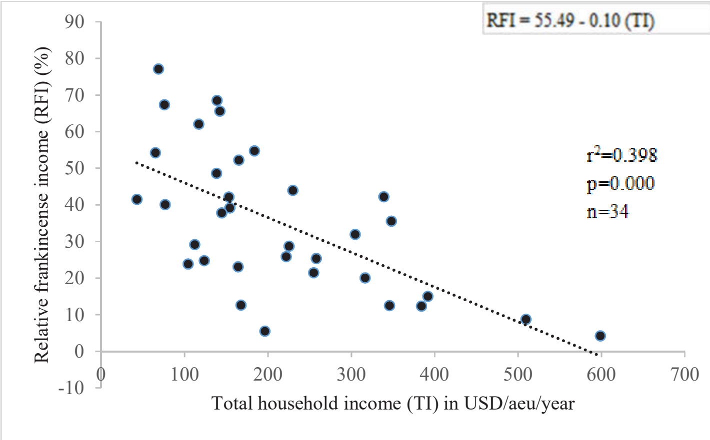


Fig. 3. Relationship of relative frankincense income to total annual household income, Borana, Ethiopia, 2016.

5.7 Analysis of factors influencing frankincense production and commercialization (SWOT analysis)

The possible **strengths** of the frankincense value chain that came out of the SWOT analysis were abundance of the resource, accessibility, good domestic markets and availability during the dry seasons. The resource is found abundantly in forests and is freely accessible to the agro-pastoralists for gathering, without any restrictions. Other possible strength of frankincense gathering is that the collection is non-destructive with only minor damage to the forest resource. The **opportunities** that were identified are favourable marketing locations, absence of substitutes, increased domestic markets and possibilities for expansion into the export market. Moreover, there were no restricted regulations regarding frankincense harvesting and selling in the study area. These could be positive factors to support the commercialization of the product. Furthermore, the frankincense production can be integrated with livestock husbandry. However, the production and marketing of frankincense in the study area is under **threats** such as underdeveloped markets, high dependence on a single company, lack of government support and low unpredictable prices. If introduced, improper tapping methods such as intensive tapping regime may also be an additional threat. The **weaknesses** found were lack of marketing skills and extension services, lack of knowledge of harvesting techniques and post-harvest handling, lack of associations of gatherers and collectors, labour competition with herding and inadequate research and development on processing technologies and value creation. Another important weakness of the frankincense value chain is that gatherers and local traders have limited access to cash or credit and thus capital. Table 6 summarizes the results of the SWOT analysis.

Table 6 SWOT analysis of the Frankincense market chain in Borana, southern Ethiopia.

Strength	**Weakness**

• Resource endowments • Free access/available nearby the village • Good demand in the domestic/national market • Available in the dry seasons • Extraction is non-destructive	• Lack of knowledge of harvesting techniques and post-harvest handling • Lack of access to credits/financial support • Absence of production and marketing facilities • Lack of marketing skills and marketing extension services • Inadequate research and development on processing technologies and value addition • Lack of associations of gatherers and collectors • Labour competition with herding
Opportunities	**Threats**
• Growing domestic markets • Export potential • Absence of substitutes • Favourable location of marketing sites to the gatherers • No regulations exist regarding the quantity of produce harvested and sold	• Lack of government support • Underdeveloped market: lack of buyers/market outlets • Higher dependence on a single company • Low unpredictable prices to gatherers and collectors/microenterprises • Damage to the trees if improper tapping method is introduced

6. Discussion

Despite the abundance of the resource and the age-old traditions of trading, in-depth field studies in southern Ethiopia are rare, and to our knowledge, this study is the first of its kind to characterize the frankincense value chain including the prices and income generated at the different levels in the value chain. The paper also examined the product's contribution to the household's economy among small-scale agro-pastoralists in southern Ethiopia.

6.1 Frankincense production and the value chain

Currently the present value chain is entirely dependent on naturally exuding trees unlike the northern parts of Ethiopia (Lemenih and Kassa, 2011b) and other parts of Africa (Abtew et al., 2012) where tapping of trees is commonly practised to harvest frankincense. It is easier to harvest from naturally exuding trees because it is less labour intensive and there is less of a need for control and monitoring of land and tree resources. This may also be because gatherers do not have the knowledge and skills about tapping techniques and post-harvest handling. In the northern areas, there are more sedentary farmers and fewer agro-pastoralists. The low marketed quantities in our case study may also be due to smaller harvest volume/production quantities (Table 3). However, the resource is considered to be abundant by most authors

(Lemenih and Kassa, 2011a; Worku, 2006). More income from harvesting frankincense could likely be generated by increasing the number of harvesting days, but there might be trade-offs between harvesting frankincense and herding. Improved collection techniques such as tapping could still most likely increase quantities collected per day, but it comes at a cost of higher labour input for households. As observed in northern parts of Ethiopia (Eshete et al., 2012), without well enforced management regimes and adequate support, intensive tapping may also cause damages to the resource base. From our market observations and the key informant interviews, marketing took place at production sites, in the village and in other rural markets, rural and urban retail markets and wholesale markets. The mapping of value chains in actor networks: from gatherers to actors in retail, and in the stages from extraction to retail and consumer, we find results comparable with general descriptions of NTFP trade features found in the literature (Abtew et al., 2012; De Caluwé, 2011; Jensen, 2009). It characterizes key routes of frankincense trade, value actors, profits, activities and relations associated with production, exchange and distribution of the commodity.

6.2 Value added and profit margins

As stated earlier, gatherers constitute the base of the frankincense value chain. They deliver fresh and unprocessed frankincense to the market. As expected, these actors received the lowest price in the chain (Sec 5.3). The gatherers are disadvantaged by their weak bargaining power, and typically accept low prices for their product.

In general, the value share of an agent or actor will depend on the role, position or function in the value chain. The upgrading potential of an agent or actor will also depend on their ability to acquire new and more remunerative functions in the value chain (Mitchell and Coles, 2011). Rather than selling the raw frankincense, for example, gatherers could acquire new functions such as drying, cleaning, sorting and packaging before selling to increase the farm-gate value of frankincense. Gatherers could also establish cooperative marketing groups to increase their share of the market prices as marketing groups can increase bargaining power and their marketing performance (Aoudji et al., 2012; Devaux et al., 2009; Mitchell et al., 2009).

Collectors and microenterprises are the second group of actors, who achieve higher than farm gate prices, but still lower than retail prices. This is in part because they are often tied to monopsonic relationships with the state-owned enterprise. Poor market access often makes it difficult for this group of traders to bargain for better prices with the state-owned enterprise, which normally provides transport, and sometimes gives advance to these traders. Our analysis reveals that the value-added tend to be the highest for village petty traders and mobile traders. However, value addition was limited to the transfer of frankincense to the retail outlet; no transformation of the raw material occurred apart from minor processing limited to drying and cleaning i.e. the removal of bark and tree debris. However, frankincense destined for export or wholesale market is cleaned and sorted into different grades. This takes place in processing plants owned by the state-owned enterprise.

The distribution of profits of actors in the chain is often used as the primary indicator of income shares in VCA (Gereffi et al., 2001; te Velde et al., 2006). The study revealed that frankincense production and trade is profitable for many actors, a finding that is in line with other NTFP literature (Abtew et al., 2012; Ingram, 2014; Jensen, 2009). Gatherers do report a higher profit margin than other actors along the value chain because they incur no cash cost and the alternative value of family labour is arguably often extremely low (Table 3). Opportunities of wage labour or salaried employment, even temporary, are virtually absent in the study area. Moreover, gatherers sell the produce directly to collectors and microenterprises at harvest sites, thus they have less expenditures, and they make considerable returns. The group with the second highest profit margin (73.5%) was village petty traders. This group obtained increased profits in part because they add value to the product through primary processing thereby selling at higher prices. However, the quantity and value of frankincense traded by these actors is very small (Table 3).

There exists a rather stable domestic market for frankincense in Ethiopia (Lemenih and Kassa, 2011a). Moreover, owing to both population and economic growth, the demand for frankincense is likely to grow in the country, providing an incentive for increased production. Therefore, there is a possibility for increased incomes along the value chain.

Policy recommendations to develop the sector include improved harvesting and processing skills through training, developing or introducing harvesting and processing equipment, improving market access for gatherers, providing credit service, training and skills development in trade, especially in quality grading for gatherers and local traders. As reported earlier, gatherers have no access to credit, nor is there any government support for frankincense production and trade in the area (Table 6). Farmers in other parts of the country, particularly in the highland regions, often receive credit in cash or as inputs direct from a credit unit, which they repay in cash after the harvest. Such service is not common in the agro-pastoralist areas of southern Ethiopia. Facilitating access to credit is an essential requirement for successful NTFPs commercialization (Marshall et al., 2006). Provision of credit in equipment could enable gatherers to improve their frankincense income through increased volume of production and trading. However, significant scaling up of production through introduction of improper tapping method may cause damage to frankincense producing trees. Development of community-based organizations and/or strengthening customary resource management institutions could effectively minimize or eliminate unsustainable extraction of the resource (Ingram, 2014).

The SWOT analysis suggests that there is a possibility to enhance commercialization of frankincense in southern Ethiopia. However, frankincense production and marketing in the study area is characterized by an absence of and/or lack of proper equipment for harvesting and post-harvest processing, weak integration, lack of associations/organization, little value adding activities, whereas gatherers and traders (notably at the local level) have underdeveloped harvesting and marketing skills, lack of access to credit and extension services. In addition, although there exists a number of studies on the abundance of Boswellia neglecta from which the product is derived (Lemenih and Kassa, 2011a; Worku, 2006), research on value addition processes and on developing technologies is virtually absent. Moreover, unlike northern Ethiopia (Lemenih and Kassa, 2011a), research on regeneration status/tree recruitment rate and domestication potential of the tree species is limited. The major threats influencing frankincense production and trade in the area are higher dependence on a single company and lack of government support such as providing market facilities and financial services.

To increase production and profitability of the frankincense it is essential to mitigate the above-mentioned threats/weakness. This can be achieved by the following interventions:

- Advocacy that encourage policy makers and government institutions to recognize the economic contribution and commercialization potential of frankincense
- Training gatherers (small-scale agropastoral households) on improved tapping and handling techniques to increase production and produce higher quality products
- Developing or introducing better tapping techniques to improve production and avoid damages to the forest resource
- Training gatherers on value adding processes and marketing skills to upgrade their function in the value chain
- Supporting gatherers and collectors to organize and collaborate, thus strengthen their access to resources and market. It is widely acknowledged that collective action plays a key role in creating market access for gatherers/producers, strengthening their bargaining power and visibility in the chain, improving their access to credits, technical support and market information (De Caluwé, 2011; Ingram, 2014; Marshall et al., 2006; Seville et al., 2011)
- Create business linkages between gatherers and local traders (collectors and microenterprises)
- Strengthening market institutions and establish marketing facilities
- Establishing community-based organizations and/or strengthening existing customary resources management institutions, with proper support and regulations. This could enable to minimize or mitigate the likely degradation of the tree species caused by unsustainable extraction. Besides, research and development on regeneration capacity of the frankincense producing trees and options for domestication could have a positive impact in maintaining the resource base, product sustainability and continued trade.

6.3 The economic contribution of frankincense production in Borana: implications for agro-pastoralists adaptation and resource sustainability

The harvest of wild NTFPs represent an important source of income to millions of people worldwide (Shackleton, 2011). Vedeld et al. (2007), estimate in a meta-study that as much as 20–25% of rural households' income derives from forest environmental resources. In Northern Benin for instance, income from NTFPs accounted for about 39% of the total household income (Heubach et al., 2011). In Sudan, gum and resins were found to contribute 14–21% of the household income (Abtew et al., 2014). In this study, frankincense alone was an important income source for agro-pastoral households, representing from 4.2 to 77.1% of the total household cash income. The annual income from frankincense extraction and sale averages 59 USD per AEU in our sample and this income was estimated, on average, to contribute 35 percent of the total household's annual income. The result supports the notion that many rural populations are highly dependent upon forest resources for their livelihoods.

Frankincense production and sales diversify the economic activities and reduce the risks associated with frequent crop and pasture failures in the drylands of Ethiopia (Lemenih et al., 2003b; Wagner et al., 2013); hence, the trade increases the adaptive capacity of the agro-pastoralist communities. Due to their low adaptive capacity and risk-prone production environments, these communities are vulnerable to the effects of drought and climate variability and are severely exposed to food and feed insecurity. Crop failure in such areas can lead to a 'price scissors', where livestock values plummet just as cereal costs surge, leading to a large shift in the terms of trade (IUCN, 2011). One advantage for the gatherers is that the income from frankincense is obtained during the dry season when there are few other income generating opportunities (Lemenih et al., 2003b). In addition, the seasonality of frankincense harvesting and selling make the activity compatible with pastoral mobility and with farming in the rainy season.

In this study, the share of frankincense income is 35% of total reported household cash income. Cash income from frankincense is generally small (see Table 5). With the existing patterns of production, there is little evidence to suggest that frankincense income has a substantial role as a pathway out of poverty or poverty mitigation for any group of households in this sample. Overall annual income of gatherers is still low, i.e. USD 213/AEU. These households are among the poorest in the country with an average income of less than 1 USD per capita per day, which reflects a high incidence of poverty in the study area. Frankincense income therefore functions as an economic *safety ne*t in difficult times for the households. However, since the resource is abundant and freely accessed combined with the lack of wage job opportunities, frankincense production could be used to create alternative jobs and more incomes. Above all, if the gatherers increased the volume of production through tapping and acquiring new functions such as basic processing and packaging, this could enable them to increase their incomes and gradually improve their livelihoods. A combined implementation of these options, by raising incomes, could possibly play a positive role for reducing poverty in the study area. More importantly, the forest resource is vital; even for the medium wealth groups, relative frankincense income reaches nearly 30%, well above the previous high forest (timber and NTFPs) income shares (22%) found for all groups in an early synthesis of 51 case studies from developing countries (Vedeld et al., 2007), an indication of the important role that frankincense played in the majority of households' economic activity in the study area.

Besides its economic contribution, the use of dry woodlands for extraction of frankincense could have ecological significance in the study area. Drylands are inherently vulnerable and land degradation is easily irreversible (Bainbridge, 2007). Conservation of the vegetation cover is thus seen as an appropriate strategy to ensure long-term viability of dryland areas (Cortina et al., 2011) such as in Borana. The non-destructive extraction of frankincense (Sec. 5.2.1), therefore, adds a conservation benefit for the dryland ecosystems and for the sustainable use of the frankincense tree species in the study area if threats mentioned above do not endanger the resource base. Frankincense producing trees are abundant and widespread in the drylands of southern Ethiopia (Lemenih et al., 2003b; Worku, 2006). More efficient governance of the value chains and better organization among the gatherers can lead to more efficient frankincense production and ensure better returns for the actors upstream along the value chain (te Velde et al., 2006). NTFPs collected from communal lands such as in the study area may best be managed by using community organizations to ensure that overexploitation does not occur. Abundance of the resource, homogeneity of the gatherers (i.e. gatherers involved are the Borana agro-pastoralists), low human population density and compatibility of frankincense harvesting with livestock production might provide an opportunity to ensure sustainable utilization of the resource and hence improve livelihood outcomes.

7. Limitations and recommendations for future research

In this study, we measured, through a case study from southern Ethiopia, the value of frankincense at the upstream end of the supply chain. As the wholesalers and exporters engaged in multiple products marketing, it was difficult to obtain data on volumes and incomes from these stakeholders. Another limitation in this study is that the data were collected from a limited number of gatherers and market actors. The data presented should thus be considered as a pilot case study in obtaining insights in the commercialization of frankincense that originates from the southern Ethiopia and therefore cannot be generalizable to other parts of Ethiopia. Future research on frankincense resources (including the regeneration capacity and domestication potential of frankincense yielding trees) and analysis of overall livelihoods of the agro-pastoral population would allow for a more complete and accurate assessment of the product and its values (economic, environmental and social), and thus increase the external validity of the results. In addition, value chain analysis that considers the national harvest and trade, and international markets could enhance the wider validity of conclusions.

8. Conclusion

This article has estimated the contribution of frankincense to involved households' economy and the product's value chain in southern Ethiopia. The annual income generated from frankincense harvest and sale was estimated to be 60 USD per AEU contributing to 35% of the total household's annual income and almost 50% for the poorest people. Frankincense is thus shown to be of particular importance for poorer households.

While frankincense harvest is only one activity within a diversified household livelihood strategy, the cash it generates can play an important role as an economic safety net, in sustaining and improving households' economy in the study area. The value chain analysis further revealed that frankincense production and trade is profitable for many actors. Nevertheless, despite the resource's abundance and a growing domestic market demand, the marketed quantities are low, extractions practices are primitive and both local and national markets are poorly developed. The SWOT analysis suggests that there is great potential in commercialization of frankincense in southern Ethiopia, bearing in mind to mitigate weaknesses and threats to production and marketing of the product.

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