Agricultural Systems 187 (2021) 102988

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

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

Yonas Berhanu [a,*], Ayana Angassa [b], Jens B. Aune [a]

[a] Department of International Environment and Development Studies (Noragric), Norwegian University of Life Sciences (NMBU), 1432 Ås, Norway
[b] Department of Range and Forest Resources, Botswana University of Agriculture and Natural Resources, Botswana

ARTICLE INFO

Keywords:
Low-cost technologies
Farm productivity
Economic returns
Conventional farm
Climate-smart agriculture
Greenhouse gas emissions

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 an approach to enhance the sustainability of maize-based mixed systems in southern Ethiopia. Planting multipurpose trees will give additional benefits in terms of fodder and carbon sequestration.

1. Introduction

Agriculture is the main productive sector of the Ethiopian economy. It accounts for 37% of the gross domestic product of the country, and is a source of livelihood for more than 70% of the country's population of approximately 103 million (FAO, 2018). Cereal-based mixed crop-livestock system predominate Ethiopian rain-fed agriculture. Crop production in Ethiopia is exposed to frequent dry spells, droughts (USGS, 2012) and declining soil fertility (Baye, 2017; Biazin and Sterk, 2013). In addition, poor management of soil fertility and continuous cropping exacerbate soil nutrient depletion and reduction of organic matter. These problems contribute to low and unpredictable crop yields and incomes, as well as food insecurity (USGS, 2012). Recent estimate show that about 67% of the smallholder farmers in Ethiopia live below the national poverty line (less than 1.90 USD person^{-1} day^{-1}) (FAO, 2018). Moreover, a large proportion of this farming population is considered highly vulnerable to production risks (e.g., crop failure or loss of outputs) (PARM, 2016), and these risks will be aggravated by climate variability and change.

In Ethiopia, increasing agricultural productivity of smallholder farms

---

* Corresponding author.
E-mail address: beryonas@gmail.com (Y. Berhanu).

https://doi.org/10.1016/j.agsy.2020.102988
Received 16 April 2020; Received in revised form 1 October 2020; Accepted 30 October 2020

is critical to enhance agricultural production and achieve food security in the face of rapid population growth (2.5% per year, FAO, 2018). This can be achieved, for example through improved land management practices and more effective use of existing and new technologies. However, in Ethiopia, not only is the use of improved technologies such as fertilizer is limited, but climate-smart agricultural (CSA) practices/technologies are not widely adopted (FAO, 2016; McIntosh et al., 2013). Estimates show that just over 50% of farmers use inorganic fertilizer, and application rates averages around 28 kg/ha (FAO, 2018), far below the recommended rates of 100 kg/ha. The low fertilizer use is due to agro-climatic conditions, farmers' cash constraints and limited access to credits (Alemu et al., 2014; McIntosh et al., 2013). The risk connected to fertilizer use also impede farmers from investing in fertilizer inputs.

Thus, given the abovementioned challenges, a range of CSA practices both existing and newly introduced, e.g., sustainable land management, conservation agriculture, agroforestry, crop residue management and traditional soil/water conservation have been widely promoted since the late 1990s in Ethiopia (FAO, 2016). However, the adoption is low due to limited access to input, capital constraints, perceived risks and low returns below expectations (FAO, 2016). Hence, it is imperative to develop technologies that address farmers needs and constraints.

This study investigates the short-term effects of alternative CSA technologies, such as micro-dosing, seed priming, mulching and intercropping with leguminous plants, and identify the best-fit technology that can increase maize yield, food security, feed production and income; enhance C stocks; and reduce GHG emissions at the farm level in southern Ethiopia.

2. Materials and methods

2.1. General approach

The study consisted of (i) farm surveys to characterize the farmers' current production practice (hereafter called conventional system); (ii) on-farm experiment to determine yield response of maize to CSA treatments; (iii) economic analysis to quantify profitability of the technologies.

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 1643 m, 1810 m and 1630 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). Rainfall is often unreliable, and drought spells are common (USGS, 2012). Cereal-based mixed crop-livestock (mostly cattle) farming system is the dominant economic activity in the study sites. Farmers cultivate maize (*Zea mays* L.), teff (*Eragrostis tef* (Zucc.)), wheat (*Triticum aestivum*. L.) and pulses such as haricot beans (*Phaseolus vulgaris* L.), mainly with one harvest per year. Maize is the major cereal crop and has a key role to ensure food security and provide fodder. Unfortunately, its production is constrained by low and declining soil fertility and moisture stress (Biazin and Sterk, 2013; Kassie et al., 2013). The problem is furthermore exacerbated by inadequate use of fertilizer. Fertilizer levels of 100 kg diammonium phosphate (DAP) ha^{-1} and 100 kg urea ha^{-1} has been recommended for maize production in Ethiopia. However, due to risks of failures, economic constraints and the lack of supply, most farmers in these areas are not able to apply these levels of mineral fertilizers. There is therefore a need to develop new fertilizer recommendations that are less expensive and less risky.

2.3. Farm survey

Socio-economic and farm characteristics were collected from the farmers who hosted the experiment. Data on land and livestock holdings, livestock activities including management and productivity levels, household size, cropping and feed practices, input use and accessibility were obtained based on a questionnaire and field observations. Maize grain and stover yields were estimated through field measurements (details are discussed below).

2.4. 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 (see Section 2.2 for details) of treatment (the control). The treatment that resulted in the greatest yield and economic return 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 (Aune et al., 2012; Camara et al., 2013; FAO, 2013; Sime and Aune, 2014).

The treatments were:

1. Control: 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. MD: Micro-dosing (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. SP + M: Seed priming (soaking seeds in water for 8 h prior to sowing), + 3 Mg/ha mulch, + recommended fertilizer levels (53,333 plants ha^{-1});
4. MD + SH: Micro-dosing + maize/sunnhemp intercropping (53,333 and 266,666 plants ha^{-1});
5. MD + LL: Micro-dosing + maize/lablab intercropping (53,333 and 66,666 plants $ha^{-1)}$;
6. SP + MD: Seed priming + micro-dosing (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 × 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 0.10 m. 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.

Maize yield on the conventional farm (i.e. representing the farmers' current system) was collected through field measurements. The conventional farm did not apply fertilizer, grew improved maize (BH-540) and used oxen for tillage. The grain and stover yields were compared with a model CSA farm developed at each site based on on-farm trials. To ensure similar biophysical conditions (soil type, climatic and topographic conditions), yield measurements on the conventional farm were taken from a farm section adjacent to the experimental plots. On each of the nine farms, the agronomic data was obtained from a 70 m^2 farm section (main plot). The maize was harvested in three 5.63 m^2 random sub-plots. The average of the three sub-plots was taken and used to

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).

compute the yield per ha for each farm.

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 and Ingram, 1993; van Reeuwijk, 2002). Soil characteristics of the study sites are given in Table 1.

2.5. *Economic analysis*

The economic feasibility of the 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.

2.6. *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 (Eq. (1)). We assumed that maize crop biomass contains 44% C. Thus, aboveground C biomass was calculated as:

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

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:

$$I_{maize-C} = 0.19 \times C_{biomass} \tag{2}$$

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:

$$\text{SOC}\left(\text{Mg C eq.ha}^{-1}\right) = I_{maize-C} \times 0.24 \tag{3}$$

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 Eq. (4) (Kuyah et al., 2012a) and the belowground biomass of the trees and/or saplings was estimated using Eq. (6), as recommended by (Kuyah et al., 2012b).

$$\text{AGB} = 0.0905{*}\text{DBH}^{2.4718} \tag{4}$$

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 Eq. (2) (MacDicken, 1997). Thus:

$$\begin{aligned}&\text{Aboveground carbon (AGC) or belowground carbon (BGC)}\\&\quad = \text{AGB or BGB}{*}0.5\end{aligned} \tag{5}$$

$$\text{BGB} = 0.490{*}\text{AGB}^{0.923} \tag{6}$$

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.

2.7. *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. CO_2 emissions from the production of fertilizers were calculated using the emission factors of 0.91 kg C eq. kg^{-1} urea and 0.73 kg C eq. kg^{-1} DAP taken from New Zealand (Ledgard et al., 2011):

$$\text{Emissions}\left(\text{kg C eq.ha}^{-1}\right) = \text{Application rate in kg N ha}^{-1}{*}\text{EFsynthetic fertilizer} \tag{7}$$

where EFsynthetic fertilizer is an emission factor for fertilizer applied.

The fertilizers used in Ethiopia were sourced mainly from Europe and the Middle East and the GHG emissions associated with synthetic N manufacture were assumed to be similar for the case of New Zealand.

In addition, direct N_2O emissions arising from N fertilizer application were determined based on guidelines proposed by IPCC (IPCC, 2006) (Eq. (8)). According to the IPCC guideline, 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:

$$N_2O\ (\text{direct}) = \text{FSN} \times \text{EFN} \times 44/28 \times 265 \quad (8)$$

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 265 is the global warming potential (GWP) for N_2O over a 100-year horizon (IPCC, 2019).

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 265 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:

$$\begin{aligned}\text{Total GHG emissions (Mg C eq./farm)} &= CO_2 \text{ emissions from fertilizer production (Mg C eq./farm)}\\ &\quad + N_2O_{(\text{direct})} \text{ emissions from fertilizer application (Mg C eq./farm)}\end{aligned}$$

2.8. 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 and 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.

2.9. 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. 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. Characterisation of conventional farms

The conventional farm in Ziway has 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 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 2330 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 household size at this site 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 household size in the area is 1.3 AEU and the annual food energy requirement per family is 308 kg (237 kg per AEU).

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. Overall, the conventional farm has low crop yields resulting from poor soil fertility, moisture stress and no input use, among others (Kassie et al., 2013; Kassie et al., 2014). In all the study sites, the conventional livestock feeding system is based on natural pasture and maize residue. Other characteristics of the conventional farms are described in Table 2.

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 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).

Table 3

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

Treatments	Ziway		Halaba		Loka-Abaya		Overall	
	Maize grain	Stover	Maize grain	$Stover^{ns}$	Maize grain	$Stover^{ns}$	Maize grain	$Stover^{ns}$
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	5973	7810	4984	7526
$LSD_{5\%}$	774	1271	1564	4800	1180	3845	1611	3312

^{ns}Not significant. ^{a,ab,b,bc,c}Different letters indicate significant differences across treatments (Fisher's LSD test, $p < 0.05$).

[1] Control: Recommended fertilizer levels.

[2] MD: Micro-dosing.

[3] SP + M: Seed priming + 3 Mg/ha mulch + recommended fertilizer levels.

[4] MD + SH: Micro-dosing + maize/sunnhemp intercropping.

[5] MD + LL: Micro-dosing + maize/lablab intercropping.

[6] SP + MD: Seed priming + micro-dosing.

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
MD + SH	3.43 ± 1.12	7.39 ± 2.5	8.7 ± 3.43	6.5 ± 2.7
MD + LL	3.01 ± 1.63	3.31 ± 2.1	1.76 ± 0.7	2.70 ± 0.8

MD + SH: micro-dosing + maize/sunnhemp intercropping; MD + LL: micro-dosing + maize/lablab intercropping.

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, seed priming 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, which were significantly higher than the control. At this site, SP + MD and SP + M increased maize grain yields by 2147 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 (8296 kg ha^{-1}). No significant differences were observed in average stover yields among treatments at Halaba and Loka-Abaya. At both these sites, however, seed priming combined with micro-dosing (SP + MD) recorded slightly higher 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

Table 5

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[1]	MD[2]	SP+M[3]	MD+SH[4]	MD+LL[5]	SP+MD[6]
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	27	27	27	27	27
Legume seed	5.24	–	–	–	52	89	–
DAP	0.64	64	17	64	17	17	17
Urea	0.50	50	13	50	13	13	13
Total input costs		141	57	141	110	146	57
Total variable costs (TVC)*		215 ± 5^{b}	131 ± 5^{a}	215 ± 5^{b}	184 ± 5	220 ± 5^{b}	131 ± 5^{a}
Returns (USD/ha)							
Gross margin (TR-TVC)		2732 ± 796^{a}	3319 ± 538^{ab}	3468 ± 772^{ab}	4615 ± 945^{b}	3865 ± 859^{ab}	4127 ± 942^{b}

^{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.

[*] Labour costs not shown in the table.

[1] Control: Recommended fertilizer levels.

[2] MD: micro-dosing.

[3] SP + M: seed priming + mulch + recommended fertilizer levels.

[4] MD + SH: micro-dosing + maize/sunnhemp intercropping.

[5] MD + LL: micro-dosing + maize/lablab intercropping.

[6] SP + MD: seed priming +micro-dosing.

Table 6
Productivity, food and feed self-sufficiency, and economic contributions of the conventional farm and the CSA farm at the three study sites.

Output	Ziway		Halaba		Loka-Abaya	
	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[a]	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

[a] calculated by multiplying stover yield per ha with the average cultivated area.

Table 7
Summary of potential contributions of the conventional farm and the CSA farm at the three sites.

Output	Overall	
	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[a]	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

[a] calculated by multiplying stover yield per ha with the average cultivated area.

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, seed priming 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 where seed priming combined with micro-dosing of fertilizer substantially increased pearl millet grain yields by up to 106% over the control (Aune et al., 2012). Another experiment in the central Rift Valley region of Ethiopia has shown that the combined use of micro-dosing and seed priming increased maize grain yields by 33 to 75% compared to the unfertilized treatment without seed priming (Sime and Aune, 2020). 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 seed 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 and 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-dosing) 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.

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*

Separate profitability analyses for the sites are presented in Tables A1 to A3 (in Appendix), while results of the combined profitability analysis are presented in Table 5. 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 A1). In Halaba, the highest benefits were obtained when 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 5684 versus USD 2815 ha^{-1}) (Table A2). 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 A3).

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 5). 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 (4615 USD ha^{-1}), followed by SP + MD (4126 USD ha^{-1}) and MD + LL (3865 USD ha^{-1}). Increased net benefits in MD + SH and MD + LL were the result of additional forage legume biomass yields. 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 5). 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).

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

As shown in Tables 6 and 7, the CSA treatment tested (i.e. seed priming combined with micro-dosing) 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. seed priming combined with micro-dosing (SP + MD) (based on farm trial data). The CSA farm 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 7). This result indicates that it could be feasible to intensify maize production using such low-cost technologies in Ethiopia. In previous MD + SP research, yield increases of up to 75% over the farmers' common practice of without fertilizer application and seed priming is reported (Sime and Aune, 2020).

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 2281 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 7, 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 and 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 7, 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 slightly higher 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).

Table 8
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	0.10
Total GHG emissions from fertilizer production and application, Mg C eq./farm	0	0.16
Farm-GHG balance (difference between C gains (SOC retention) and losses/emissions), Mg C eq./farm	−0.12	−0.24

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 farm developed using seed priming in combination with micro-dosing contributed to higher gross margins (by 218%) compared with conventional system (Table 7), because a high yield was obtained at a low cost (Table 5). 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 5). 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 part of the 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. An earlier study from Mali showed that the use of micro-dosing in combination with seed priming created a surplus in cereal production (Aune et al., 2012). This same study showed benefits of this low-cost, low-risk technology on food security, improved feed supply and household economy due to enhanced grain and stover yields. The results from the study in Mali corroborates the result from the present study.

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 8 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. Overall, the CSA farm exhibited slightly greater storage of SOC than the conventional farm. 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 contributed to a net sequestration of 0.24 Mg C per year.

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

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) (Fig. A1).

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.

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.

Declaration of Competing Interest

The authors declare no conflicts of interest. Moreover, the authors state that there is no financial/personal interest that could affect their objectivity.

Acknowledgments

This study was supported by the project “Research and Capacity Building in Climate Smart Agriculture in the Horn of Africa” (Grant number: ETH-13/0016), funded by the Norwegian Agency for Development Cooperation (Norad). We sincerely acknowledge Norad for supporting the research project. The authors are grateful to Alemayehu Chala (PhD) for his unreserved support during the entire period of fieldwork. We also thank all farmers who took part in the field experiments.

Appendix A. Appendix

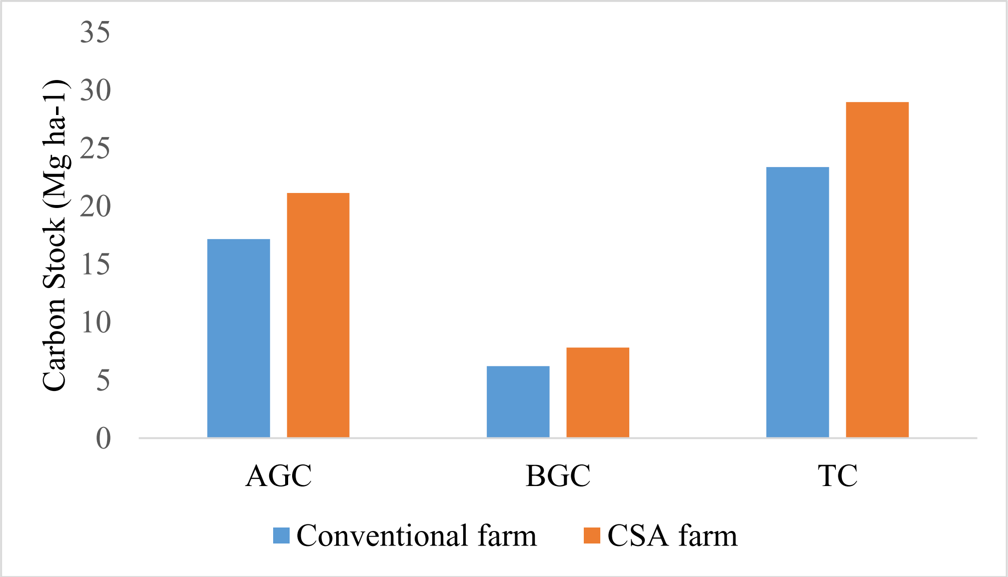

Fig. A1. Average farm-level carbon stock in multipurpose trees growing under conventional and CSA farms in Ziway, four years after establishment (2018).

Table A1
Costs and benefits analysis for CSA practices and the control at Ziway.

Gross income (USD)	Price per unit (USD)	Treatment					
		Control[1]	MD[2]	SP+M[3]	MD+SH[4]	MD+LL[5]	SP+MD[6]
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	27	27	27	27	27
Legume seed	5.24	–	–	–	52	89	–
DAP	0.64	64	17	64	17	17	17
Urea	0.50	50	13	50	13	13	13
Total input costs		141	57	141	110	146	57
Total variable costs (TVC)*		219 ± 6^{b}	136 ± 6^{a}	$219 \pm 6.^{b}$	188 ± 6	225 ± 6^{b}	136 ± 6^{a}
Returns (USD/ha)							
Gross margin (TR-TVC)		2128 ± 365^{a}	3116 ± 107^{bc}	2713 ± 390^{ab}	3825 ± 567^{c}	3563 ± 549^{c}	3699 ± 289^{c}

^{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.

[*] Labour costs not shown in the table.

[1] Control: Recommended fertilizer levels.

[2] MD: micro-dosing.

[3] SP + M: seed priming + mulch+ recommended fertilizer levels.

[4] MD + SH: micro-dosing + maize/sunnhemp intercropping.

[5] MD + LL: micro-dosing + maize/lablab intercropping.

[6] SP + MD: seed priming + micro-dosing.

Table A2
Costs and benefits analysis for CSA practices and the control at Halaba.

Gross income (USD)	Price per unit (USD)	Treatment					
		Control[1]	MD[2]	SP+M[3]	MD+SH[4]	MD+LL[5]	SP+MD[6]
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	1251^{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	27	27	27	27	27
Legume seed	5.24	–	–	–	52	89	–
DAP	0.64	64	17.00	64	17	17	17
Urea	0.50	50	13	50	13	13	13
Total input costs		141	57	141	110	146	57
Total variable costs (TVC)*		213 ± 4^{b}	129 ± 4^{a}	213 ± 4^{b}	182 ± 4	218 ± 4^{b}	129 ± 4^{a}
Returns (USD/ha)							
Gross margin (TR-TVC)		2815 ± 697^{a}	3243 ± 705^{ab}	3658 ± 890^{ab}	5684 ± 452^{c}	4543 ± 929^{bc}	4028 ± 1284^{ab}

^{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.

[*] Labour costs not shown in the table.

[1] Control: Recommended fertilizer levels.

[2] MD: micro-dosing.

[3] SP + M: seed priming + mulch+ recommended fertilizer levels.

[4] MD + SH: micro-dosing + maize/sunnhemp intercropping.

[5] MD + LL: micro-dosing + maize/lablab intercropping.

[6] SP + MD: seed priming + micro-dosing.

Table A3

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

Gross income (USD)	Price per unit (USD)	Treatment					
		Control[1]	MD[2]	SP+M[3]	MD+SH[4]	MD+LL[5]	SP+MD[6]
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	89	–
DAP	0.64	64	17	64	17	17	17
Urea	0.50	50	13	50	13	13	13
Total input costs		141	57	141	110	146	57
Total variable costs (TVC)*		213 ± 4[b]	129 ± 4[a]	213 ± 4[b]	182 ± 4	218 ± 4[b]	129 ± 4[a]
Returns (USD/ha)							
Gross margin (TR-TVC)		3253 ± 976	3599 ± 679	4035 ± 220	4337 ± 529	3489 ± 868	4653 ± 1054[ns]

[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.

[*] Labour costs not shown in the table.

[1] Control: Recommended fertilizer levels.

[2] MD: micro-dosing.

[3] SP + M: seed priming + mulch+ recommended fertilizer levels.

[4] MD + SH: micro-dosing + maize/sunnhemp intercropping.

[5] MD + LL: micro-dosing + maize/lablab.

[6] SP + MD: seed priming + micro-dosing.

References

Alemu, D., Yirga, C., Bekele, A., 2014. Situation and Outlook of Maize in Ethiopia. Ethiopian Institute of Agricultural Research, Addis Ababa, Ethiopia.

Anderson, J.M., Ingram, J.S., 1993. Tropical Soil Biology and Fertility: A Handbook of Methods. C·A·B International, Wallingford, Oxon OX10 8DE, UK.

Assaminew, S., Ashenafi, M., 2015. Assessment of feed formulation and feeding level of urban and periurban dairy cows nexus with economic viability in central highland of Ethiopia. Livest. Res. Rural. Dev. 27 (7).

Aune, J.B., Coulibaly, A., 2015. Microdosing of mineral fertilizer and conservation agriculture for sustainable agricultural intensification in sub-Saharan Africa. In: Lal, R., Singh, B.R., Mwaseba, D.L., Kraybill, D., Hansen, D.O., Eik, L.O. (Eds.), Sustainable Intensication to Advance Food Security and Enhance Climate Resilience in Africa. Springer, New York, Dordrecht, London, p. 657.

Aune, J.B., Traoré, C.O., Mamadou, S., 2012. Low-cost technologies for improved productivity of dryland farming in Mali. Outlook Agric. 41 (2), 103–108.

Aune, J.B., Coulibaly, A., Giller, K.E., 2017. Precision farming for increased land and labour productivity in semi-arid West Africa: a review. Agron. Sustain. Dev. 37 (16), 1–10.

Baye, T.G., 2017. Poverty, peasantry and agriculture in Ethiopia. Ann. Agrar. Sci. 15, 420–430.

Berhanu, Y., Olav, L., Nurfeta, A., Angassa, A., Aune, J.B., 2019. Methane emissions from ruminant livestock in Ethiopia: promising forage species to reduce CH4 emissions. Agriculture 9 (130), 1–16.

Biazin, B., Sterk, G., 2013. Drought vulnerability drives land-use and land cover changes in the Rift Valley dry lands of Ethiopia. Agric. Ecosyst. Environ. 164, 100–113.

Brookfield, H., Stocking, M., Brookfield, M., 2002. Guidelines on agrodiversity assessment. In: Brookfield, H., Padoch, C., Parsons, H., Stocking, M. (Eds.), Understanding, Analysing and Using Agricultural Diversity. ITDG Publishing, Southampton Row, London, WC1B 4HL, pp. 103–105.

Camara, B.S., Camara, F., Berthe, A., Oswald, A., 2013. Micro-dosing of fertilizer – a technology for farmers' needs and resources. Int. J. AgriSci. 3 (5), 387–399.

CIMMYT, 1988. From Agronomic Data to Farmer Recommendations: An Economics Training Manual. The International Maize and Wheat Improvement Center (CIMMYT), Mexico. D.F.

Deaton, A., 2003. Household surveys, consumption, and the measurement of poverty. Econ. Syst. Res. 15 (2).

Duncana, A.J., Bachewe, F., Mekonnena, K., Valbuenaa, D., Rachierd, G., Lulee, D., Bahtaf, M., Erenstein, O., 2016. Crop residue allocation to livestock feed, soil improvement and other uses along a productivity gradient in Eastern Africa. Agriculture. Agriculture. Ecosyst. Environ. 228, 101–110.

Eagle, A.J., Olander, L.P., Henry, L.R., Haugen-Kozyra, K., Millar, N., Robertson, G.P., 2012. In: REPORT, T. W. G. o. A. S. o. t. L. n. A. G. G. T.-A (Ed.), Greenhouse gas mitigation potential of agricultural land management in the united states: a synthesis of the literature. Nicholas Institute for Environmental Policy Solutions, Duke University, Durham, NC.

FAO, 2013. Climate-smart Agriculture: Sourcebook. FAO, Rome.

FAO. (2016). Eastern Africa Climate-smart Agriculture Scoping Study: Ethiopia, Kenya and Uganda. Njeru, E., Grey, S. and Kilawe, E. (Addis Ababa, Ethiopia).

FAO, 2018. Small Family Farms Country Factsheet: Ethiopia.

Giller, K.E., Witter, E., Corbeels, M., Tittonell, P., 2009. Conservation agriculture and smallholder farming in Africa: the heretics' view. Field Crop Res. 114, 23–34.

Giller, K.E., Corbeels, M., Nyamangara, J., Triomphe, B., Affholder, F., Scopel, E., Tittonell, P., 2011. A research agenda to explore the role of conservation agriculture in African smallholder farming systems. Field Crop Res. 124, 468–472.

Harris, D., 2006. Development and testing of "On-Farm" seed Priming. Adv. Agron. 90, 129–178.

Henry, M., Tittonell, P., Manlay, R.J., Bernoux, M., Albrecht, A., Vanlauwe, B., 2009. Biodiversity, carbon stocks and sequestration potential in aboveground biomass in smallholder farming systems of western Kenya. Agric. Ecosyst. Environ. 129, 238–252.

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use. Intergovernmental Panel on Climate Change.

IPCC, 2019. Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems (Approved Draft).

Kassie, B.T., Hengsdijk, H., Rötter, R., Kahiluoto, H., Asseng, S., Van Ittersum, M., 2013. Adapting to climate variability and change: experiences from cereal-based farming in the Central Rift and Kobo Valleys, Ethiopia. Environ. Manag. 52, 1115–1131.

Kassie, B.T., Van Ittersum, M.K., Hengsdijk, H., Asseng, S., Wolf, J., Rötter, R.P., 2014. Climate-induced yield variability and yield gaps of maize (*Zea mays* L.) in the Central Rift Valley of Ethiopia. Field Crop Res. 160, 41–53.

Khatri-Chhetri, A., Aggarwal, P.K., Joshi, P.K., Vyas, S., 2017. Farmers' prioritization of climate-smart agriculture (CSA) technologies. Agric. Syst. 151, 184–191.

Kuyah, S., Dietz, J., Muthuri, C., Jamnadass, R., Mwangi, P., Coe, R., Neufeldt, H., 2012a. Allometric equations for estimating biomass in agricultural landscapes: I. Aboveground biomass. Agriculture. Ecosyst. Environ. 158, 216–224.

Kuyah, S., Dietz, J., Muthuri, C., Jamnadass, R., Mwangi, P., Coe, R., Neufeldt, H., 2012b. Allometric equations for estimating biomass in agricultural landscapes: II. Belowground biomass. Agriculture. Ecosyst. Environ. 158, 225–234.

Latham, M.C., 1979. Human nutrition in tropical Africa: a textbook for health workers: with special reference to community health problems in East Africa. In: Food and Nutrition Series, 2nd ed. FAO.

Le Houerou, H.N., Hoste, C.H., 1977. Rangeland production and annual rainfall relations in the Mediterranean basin and in the African Sahelo-Sudanian zone. J. Range Manag. 30 (3), 181–189.

Ledgard, S.F., Boyes, M.A., Brentrup, F., 2011. Life Cycle Assessment of Local and Imported Fertilisers Used on New Zealand Farms.

MacDicken, K.G., 1997. A Guide to Monitoring Carbon Storage in Forestry and Agroforestry Projects. Winrock Internationl Institute for Agricultural Development.

McIntosh, C., Sarris, A., Papadopoulos, F., 2013. Productivity, credit, risk, and the demand for weather index insurance in smallholder agriculture in Ethiopia. Agric. Econ. 44, 399–417.

Mengistu, A., 2006. Country Pasture/Forage Resource Profiles.

PARM, 2016. Ethiopia: Agricultural Risk Profile Factsheet.

Pearson, T., Walker, S., Brown, S., 2005. Sourcebook for Land Use, Land-use Change and Forestry Projects.

Reynolds, T.W., Waddington, S.R., Anderson, C.L., Chew, A., True, Z., Cullen, A., 2015. Environmental impacts and constraints associated with the production of major food crops in Sub-Saharan Africa and South Asia. Food Sec. 7, 795–822.

Sime, G., Aune, J.B., 2014. Maize response to fertilizer dosing at three sites in the central rift valley of Ethiopia. Agronomy 4, 436–451.

Sime, G., Aune, J.B., 2020. On-farm seed priming and fertilizer micro-dosing: Agronomic and economic responses of maize in semi-arid Ethiopia. Food Energy Secur. 9 (190), 1–13.

Stonehouse, D.P., 1997. Socio-economics of alternative tillage systems. Soil Tillage Res. 43, 109–130.

UN-DESA, 2017. Household Size and Composition Around the World 2017– Data Booklet (ST/ESA/SER.A/405).

USGS, 2012. A climate trend analysis of Ethiopia: famine early warning systems network—informing climate change adaptation series. In: Fact Sheet, pp. 2012–3053.

van Reeuwijk, L.P. (Ed.), 2002. Procedure for Soil Analysis, 6th ed. International Soil Reference and Infromation Center, Wageningen.

Zhang, W., Liu, K., Wang, J., Shao, X., Xu, M., Li, J., Wang, X., Murphy, D.V., 2015. Relative contribution of maize and external manure amendment to soil carbon sequestration in a long-term intensive maize cropping system. Sci. Rep. 5 (10791).