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Assessing the economic and mitigation benefits of climate-smart agriculture and its implications for political economy: a case study in Southern Africa

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List of Abbreviations

CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CSA	Climate-smart agriculture
FISP	Farmer Input Support Programme
GHG	Greenhouse gas
Ha	Hectares
IPCC	Intergovernmental panel on climate change
MACC	Marginal abatement cost curve
MSD	Minimum soil disturbance
NO	Nitric oxide
N_2O	Nitrous oxide
OLS	Ordinary least squares
PES	Payments for environmental services
tCO_{2e}	Tons of carbon dioxide equivalent
UNFCCC	United nations framework convention on climate change

1. Introduction

In Africa, above 250 million people are undernourished, corresponding to 19.1 percent of population (more than twice the world average). Such proportion is projected to rise to 25.7 percent by 2030, bringing Africa significantly off track to achieve the Zero Hunger target. Most undernourished are found in the sub-Saharan subregion, where 412 million people are projected to be food insecure by 2030, and where the current population is projected to double by 2050 (FAO et al., 2020). The region would need to increase crop production by 260% by 2050 in order to feed its projected population of nearly 2 billion people (UN, 2019a).

In recent years, a drop in crop yields due to climate variability and widespread droughts have contributed to the increase in food insecurity in several countries of the Eastern and Southern Africa subregions (FAO et al., 2020). Smallholders' productivity must therefore increase to enhance the supply of agriculture products and improve food and nutrition security (UN, 2019b). Climate change can further stress the natural resource base posing a serious risk to agriculture production, food security and economic growth of most vulnerable areas (IPCC, 2014). The food system needs to be transformed to respond to such challenges (CCAFS, 2020).

Climate-smart agriculture (CSA) represents an opportunity for Africa to scale-up cleaner production technologies that increase climate resilience of farming systems and enhance food security, encompassing diminished air emissions and soil fertility losses (Lipper et al. 2018). If African farmers substitute their current 'unclean' farming techniques with CSA practices, they will help to sustainably transform agriculture production systems (Mwalupaso et al., 2019) contributing both to the adaptation and mitigation pillars of CSA.

Technologies considered climate-smart vary considerably across regions, reflecting the context-specificity and the diversity of Africa's farming systems (WB and CIAT, 2018). CSA includes the principles of conservation agriculture, i.e. minimum soil disturbance (MSD), crop residue management, and crop rotation, particularly with legumes. Farmers may implement MSD either through planting basin or ripping; they do not plough or make planting ridges as is the case of conventional farmers. Crop residues that remain on the soil surface protect it from the physical impact of rain and wind and enhance soil ecology (Erenstein, 2003). Crop rotations interrupt the infection chain between subsequent crops and make full use of the physical and chemical interactions among plant species; they increase soil moisture, macro-fauna and carbon content (Thierfelder et al., 2013). Additionally, agroforestry and soil and water conservation practices are also included in CSA. Agroforestry (and improved fallow) consist of growing fertilizer (Nitrogen-fixing) trees through intercropping in maize systems (Akinnifesi et al., 2008) and using fast-growing trees to accelerate soil rehabilitation (WB, 2012). Soil and water conservation options include physical structures which can reduce soil loss and favour nutrients' holding (Wolka et al., 2018). Thus, CSA may lead to various improvements at farm and landscape scale: soil fertility, crop yields and food production, water storage and agriculture ecosystems resilience;

resource-use efficiency, residue valorisation and recycling; and mitigation in the form of reduced greenhouse gas (GHG) emissions and enhanced carbon storage in soils and biomass (Asfaw and Branca, 2018).

Several CSA technologies, tools, and approaches tailored to reducing climate-related risks have been developed in sub-Saharan Africa (Zougmorè et al., 2018). However, despite the evidence of successful CSA experiences in the region, small African farmers are constrained by various barriers to the implementation of CSA practices (Senyolo et al., 2018) Adoption will continue to be low if governments do not invest in policy incentives to scale-up CSA at local, national, regional levels and accelerate a transition towards eco-friendly agriculture (Makate, 2019).

Various CSA initiatives exist to scale-up CSA in Eastern and Southern Africa. The Comprehensive African Agriculture Development Programme launched in 2003 promoted the development of the public national agricultural investment plans for African countries. Preparation of CSA investment plans has been identified as the way to drive smart investments and making the case for financing (Branca et al. 2012) and is under development in the region (for example in Lesotho, Namibia, Zambia and Zimbabwe). Scale-up of such investment plans will be performed through climate finance funding options (WB, 2019c). The African Union Leaders "Malabo Declaration" in 2014 endorsed the inclusion of CSA in the New Partnership for African Development programme on agriculture and climate change, and set a goal of twenty-five million farming families practicing CSA by 2025 as a path for African agricultural development (Williams et al. 2015). It also requested the African Development Bank to provide support to African countries on investments in CSA through the Feed Africa strategy (GACSA, 2016). The Africa Climate Business Plan has been promoted by the World Bank to support the adoption of smart practices on three million hectares of farmland and improve CSA policy implementation capacity in at least twenty countries (WB, 2015). The Africa CSA Alliance supports the scaling-up of smart practices to at least six million farming households. The three Regional economic communities (Common Market for Eastern and Southern Africa, East African Community, and Southern Africa Development Community) support investments in national CSA programmes for at least 1.2 million small-scale farmers, addressing the linkages between agriculture, forestry and land use. Examples of such national-level initiatives include CSA framework programmes in Kenya, Uganda, Tanzania, Botswana and Namibia; the Adaptation of African Agriculture Initiative supporting smallholder farmers to adapt to climate change in Malawi, Mozambique, Tanzania, Zambia and Zimbabwe (Dinesh et al. 2017).

In this context, policymakers require succinct information on the costs-effectiveness of CSA and other measures capable to decrease GHG emissions (Eory et al., 2018). Biophysical benefits of specific climate-smart farm practices under various agro-climatic conditions in developing countries are published in the literature (Adegbeye et al., 2020). The objective of this paper is to analyse the on-farm impact of climate-smart practices on productivity and investment profitability jointly with their on-field potential to reduce GHG emissions and enhance carbon storage in a cost-effective way. There is lack of such empirical works which this paper will contribute to fill.

We apply an interdisciplinary economic and ecological approach to Malawi and Zambia case-studies. Using household survey data combined with information from global bio-physical databases for climate change mitigation impacts, we investigate the following objectives and research questions: i) What are the CSA packages mostly adopted by smallholders in different ecological settings and what is their profitability as compared to conventional farming? ii) What is the isolated effect of practices' adoption on crop yields after controlling for the impact of other variables? iii) What is the associated mitigation potential of the practices? iv) What are the interactions between mitigation and agricultural returns associated with the practices in the specific ecological contexts? The answers will provide information to develop conducive policies, investments and institutional actions needed for effective scaling-up and industrialization of CSA innovations in Africa.

2. Study area description

Malawi and Zambia are chosen as case-studies. In these countries, the decrease in crop productivity, due to land and soil degradation and poor farming methods, exacerbated by climate change, has created unfavourable economic and environmental conditions for most rural households which depend upon agriculture for their livelihoods. In their Nationally Declared Contribution to the UNFCCC 2015 Paris agreement, both countries have indicated agriculture as a potential source of mitigation, as well as a sector of concern and priority for adaptation (FAO, 2016). Policymakers consider CSA as a valid option to promote increases in smallholders' income while reducing their vulnerability.

Malawi's economy is characterized by high dependence on small-scale agriculture which is responsible for 26 percent of national Gross Domestic Product, 72 percent of employment and 81 percent of export earnings (WB, 2019a). In Malawi, there are 2.67 million family farms, and the average holding size is 1 hectare (ha) of land (GOM, 2010). Smallholder farming is highly subsistent and produces root crops, cereals, and vegetables (WB, 2017). Maize is the most grown crop, accounting for about 93 percent of the land under cereal production (FAO, 2019). Calories from maize consumption amount to about 60 percent of daily calorie requirements of Malawi population (FAO, 2019). Similarly, in Zambia, agriculture accounts for 20 percent of national Gross Domestic Product, 54 percent of employment and 12 percent of export earnings (WB, 2019b) and mainly depends on smallholder rainfed production which uses simple technologies, with a minimal level of purchased inputs. In Zambia, there are 1.3 million farm households with a mean land size of 3.27 ha. Maize is the main crop, occupying 91 percent of the land under cereal production, and is the source of about 60 percent of daily calorie requirements of Zambians (FAO, 2019).

In both countries, crop yields are constrained by low soil fertility levels. In Zambia, major soil types include the black clays (vertisols) and sandy clays, while red clays, sand veldt and clay loam soils are common in plateau areas. In Malawi, lithosols can be found in most areas of the country while latosols (red-yellow soils) are found in the Lilongwe plain and some parts of the southern region (FAO, 2006).

3. Data

Primary data from an *ad hoc* household survey are used. The sample of interviewed households was built using a multi-stage stratified random sampling procedure, where each stratum is represented by the group of CSA adopters in the target areas[1]. The database contains information for: 1,433 fields cultivated by 505 households in Malawi; and 1,264 fields cultivated by 695 households in Zambia. Figure 1 shows the target areas in both countries, selected depending where the adoption of the climate-smart farming practices is recorded. For the climate change mitigation analysis, initial soil carbon stock levels are derived from the Harmonized World Soil Database (Hiederer and Kochy, 2012), while further averages data inputs derive from the household survey data[2].

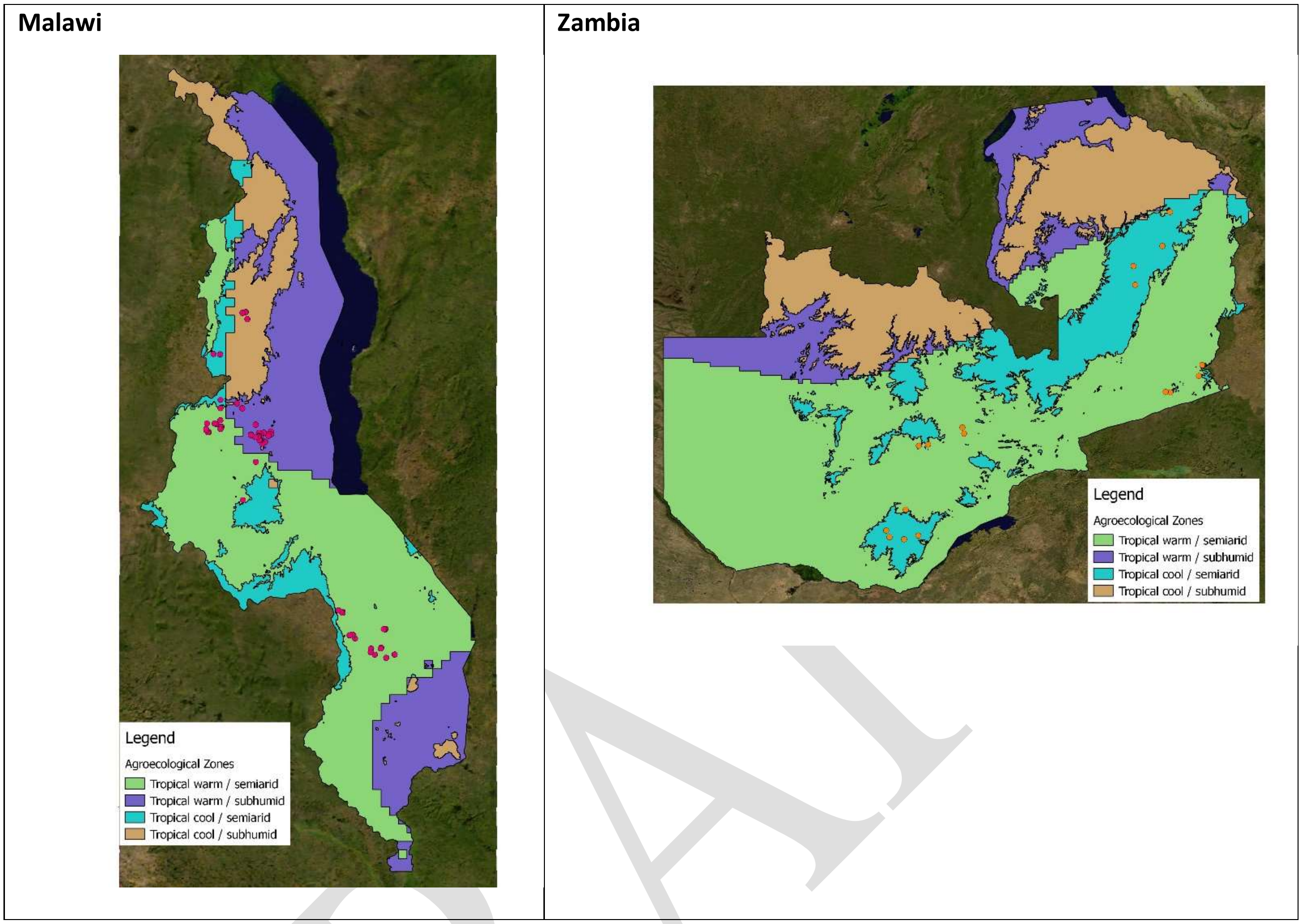
Sampled households adopt a wide range of cropping practices. They are listed in Table 1**.** Given the weight of maize in cropland production of Malawi and Zambia, we consider the impact of targeted practices on maize yields only.

Most sampled households adopt both conventional and different combinations of climate-smart farming practices. Thus, the outcomes of diverse practices does not depend on the households' socio-economic and structural characteristics, and farmers' organizational skills in optimizing the use of available resources. It is expected that only the specificities of target practices influence both the probability of adoption and impact on the outcomes analysed. This controls for the potential bias due to the different number of observations related to CSA adopters and farmers implementing conventional practices. We use the tillage practice implemented (i.e. MSD or tillage) as the discriminator between CSA (MSD-based) and conventional farming (tillage-based).

[1] The following equation was applied: $n_i = (N_i/N) * n$, where: n_i is the sample size for stratum i, N_i is the population size for stratum i, N is the size of population of sustainable farming adopters in the district, and n represents overall sample size.

[2] Given that the dataset used here is cross-sectional, our analysis cannot account for the dynamic changes that occur during the transition from one system to another. Agronomists suggest that converting conventional systems to MSD-based ones boosts crop yields after a few years of declining or stable yields. Unfortunately, due to lack of data these aspects are not taken sufficiently into consideration here.

Figure1: Areas targeted by the household survey in Malawi and Zambia.



Source: own elaboration.

Table1: Farming practices considered in the case-study.

Practice group	Practice name
Tillage	Ridging Ploughing (by oxen or tractor) Contour ploughing
Minimum soil disturbance (MSD)	Planting basins Ripping (by hand, oxen or tractor)
Agronomy	Crop rotations
	Intercropping (mixed cropping) Cover cropping
Residue retention	Incorporating in soils Mulching
Agroforestry/Improved fallow	Fertilizer trees/Fast-growing trees for soil rehabilitation
Soil and water conservation	Bunds (earth, stone) Grass barriers and embankments Terraces

Source: own elaboration.

4. Methodology

The interdisciplinary methodology used to conduct the present analysis consists of four analytical steps. We look at: (i) on-farm costs and revenues of various climate-smart farm practices and their profitability as opposed to conventional farming used as the counterfactual, through a marginal analysis; (ii) potential of CSA to improve crop yields controlling for other determinants, through an econometric model; (iii) expected GHG reduction and carbon sequestration benefits of CSA practices, through a mitigation option model; and (iv) social cost-effectiveness of such practices in mitigating climate change, by building marginal abatement cost curves (MACCs) which visualize the policy agenda for climate-smart agriculture scaling-up.

4.1 Marginal analysis

The first methodological step aims at assessing the comparative profitability of climate-smart agriculture technologies with respect to conventional management, used as the counterfactual. We compute production costs and revenues by crop and technology over 1-year production cycle and for 1 hectare of land. We build the following profitability indicators commonly used in farm management (Kay et al., 2020): gross margins (revenues minus variable costs), returns to cash capital (variable costs to revenues ratio), returns to family labour (amount of family labour employed on-farm to revenues ratio), labour productivity (yield to amount of family labour employed on-farm ratio) and capital intensity (cash input costs to labour ratio, where cash input costs are chosen as a proxy of the capital invested by farmers).

4.2 Econometric analysis

The marginal analysis provides useful information about the on-farm costs and revenues of crop production, which contribute to overall household's income but it does not allow to determine whether any changes observed in crop productivity is a direct effect of the adoption of the CSA practices. Therefore, we perform a second methodological step conducting an econometric analysis to isolate the impact of the specific farming practices on crop yields. Following research previously conducted in the same area (Kamanga et al., 2000) and with analogies in terms of variables included (De-Graft and Kweku, 2012), we estimate a log-linear Cobb-Douglas production function, using ordinary least squares (OLS) regression, in the following form (Murthy, 2020):

$$ln(Y) = \alpha_0 + \sum_{k=1}^{K} \beta_k \, lnX_k + \gamma_1 Z + \gamma_2 D + \gamma_3 M + \varepsilon \qquad [1]$$

where Y is crop yields expressed in kg per hectare; X is a vector of k inputs namely, field size in hectares, total man days of labour per hectare, quantity of fertilizer used expressed in kg per hectare, a dummy variables for the use of improved seeds; Z is a vector of socio-demographic characteristics of the household such as household size, age of the household head, average education of household members, and household wealth; D is a dummy variable for the adoption of climate-smart farming practices; and M includes variables controlling for weather events in the agricultural season and/or agro-ecological conditions. The coefficient of interest is γ_2 that is, the marginal effect of adoption of practice D on crop productivity.

We consider the same set of explanatory variables in both the Malawi and Zambia OLS regressions, including inputs used in the production process, household size and heads' age, household members' average education and wealth levels[3]. We also examine weather-related variables: in Zambia, we look at the total rainfall during the cropping season and the average maximum temperature recorded during the growing season[4]; in Malawi, we account for the potential differences in relevant climatic conditions that could affect maize production across the sample by controlling for agro-ecological zones (semi-arid versus sub-humid)[5]. Descriptive statistics are in Tables 2 and 3.

Table 2. Sampled households in Malawi, descriptive statistics

Variable	Number of observations	Mean	Standard Deviation	Min	Max
Maize yield (kg/ha)	564	2,081.57	1,738.33	92.593	10,000
MSD (1=yes)	564	0.337	0.473	0.000	1.000
Residue retention (1=yes)	564	0.651	0.477	0.000	1.000
Crop rotation with legumes (1=yes)	564	0.378	0.485	0.000	1.000
Cover crop (1=yes)	564	0.083	0.277	0.000	1.000
MSD*Residue retention	564	0.257	0.437	0.000	1.000
MSD*Crop rotation with legumes	564	0.105	0.306	0.000	1.000
MSD*Cover crop	564	0.025	0.156	0.000	1.000
Log crop area (ha)	564	0.481	0.358	0.010	3.240
Log family labour (man-days)	564	94.082	85.677	0.000	671.605
Log fertilizer (kg)	564	240.467	182.175	0.000	1,235
Improved seeds (1=yes)	564	0.741	0.438	0.000	1.000
Semiarid Agroecological Zone (1=yes)	564	0.569	0.496	0.000	1.000
Household size (No.)	564	6.360	2.236	1.000	16.000
Age of household head (years)	564	49.103	13.600	16.000	85.000
Avg. education of household members (years)	564	6.989	2.400	0.000	12.000
Assets index	564	0.038	1.062	-0.792	6.061

Source: own elaboration

[3] Using Principal Component Analysis an index of durable assets owned by the household is computed and used as proxy of wealth.
[4] Rainfall data have been obtained from the African Rainfall Climatology Version 2. Temperature data have been retrieved from the European Centre for Medium-Range Weather Forecasts.
[5] Due to data limitations, it was not possible to match administrative sample units with geo-referenced weather variables and to use the same weather variables as in Zambia.

Table 3. Sampled households in Zambia, descriptive statistics

Variable	Number of observations	Mean	Standard Deviation	Min	Max
Maize yield (kg/ha)	573	2,093.53	1,693.11	115.0	9,583
MSD (1=yes)	573	0.733	0.443	0.0	1.000
Residue retention (1=yes)	573	0.691	0.462	0.0	1.000
Crop rotation with legumes (1=yes)	573	0.047	0.212	0.0	1.000
Cover crop (1=yes)	573	0.026	0.160	0.0	1.000
MSD*Residue retention	573	0.555	0.497	0.0	1.000
MSD*Crop rotation with legumes	573	0.044	0.204	0.0	1.000
MSD*Cover crop	573	0.014	0.117	0.0	1.000
Log crop area (ha)	573	1.431	1.219	0.203	7.000
Log family labour (man-days)	573	4.414	0.875	0.681	6.853
Log fertilizer (kg)	573	4.522	1.983	0.115	6.908
Improved seeds (1=yes)	573	0.904	0.295	0.000	1.000
Total rainfall during cropping season (mm)	573	8.709	0.711	7.860	9.800
Avg. of decadal max temp during growing season (C)	573	26.763	0.513	25.576	27.784
Household size (No.)	573	7.791	3.069	2.000	20.000
Age of household head	573	45.445	12.320	20.000	82.000
Avg. education of household members (years)	573	7.206	1.984	0.000	12.250
Assets index	573	0.234	1.077	-0.814	6.242

Source: own elaboration

4.3 Mitigation option model

In the third methodological step, we apply the mitigation option model developed by Vetter et al. (2014) to estimate the climate change mitigation potential of CSA practices in the form of reduced GHG emissions and enhanced carbon storage in soils and biomass. The model considers all major GHG emission processes, including: (i) variations in soil organic carbon on cropped soils due to changes in management practices; (ii) changes in soil organic carbon stocks and carbon stored in biomass due to the introduction of agroforestry; (iii) direct field emissions of N_2O and NO from fertilizers and crop residues; (iv) indirect N_2O emissions from volatilization of ammonia as well as nitrogen runoff and leaching; (v) N_2O and CH_4 emissions from crop residues burning or composting; and (vi) GHG emissions from production and application of fertilizers and other agrochemicals. We apply a mix of Tier-1, Tier-2 and simple Tier-3 methods to estimate GHG emissions, which implies that a certain level of management-, crop-, and location-specificity of GHG emission estimates is realized, while using comparably robust methods that are less data-intensive and sensitive than process-based, bio-physical modelling (Del Grosso et al., 2002). We use data inputs to compute average fertilizer intensities for the mitigation estimations and assess spatial-specificity with initial soil carbon stock estimates and further soil input variables at a resolution of 30 arc-seconds from the Harmonized World Soil Database (Vetter et al., 2014). GHG emission estimation in the mitigation option model is based on the methodology for field related nitrous oxide emissions from Stehfest and Bouwman (2006), an adapted application of IPCC

(2006a) and further complementing methodologies. Table 4 lists the specific estimation approaches and an indication of the level of practice-, location- and crop-specificity.

Table 4. Methodologies used for estimating GHG emissions and carbon sequestration processes

Process/practices	GHG emissions	Methodology	Sensitivity to agricultural management practices	Sensitivity to agro-ecological variables	Crop specificity
Fertilized cropland	Direct N_2O & NO emissions	Stehfest and Bouwman (2006)	Amount of Nitrogen applied	Soil carbon, soil pH, soil texture & climate (temp, subtropical, tropical)	Cereals, Legume, Grass, W-Rice, Other
	Volatilization of ammonia (Indirect N_2O emissions)	Bouwman et al. (2002)	Type of fertilizer application, type of fertilizer	Soil ph, soil Cation-exchange capacity, climate (temp vs trop)	Upland corps, flooded crops, grass
	N leaching/runoff (Indirect N_2O emissions)	IPCC (2006a)	Amount of N applied	Drylands (no leaching) versus humid regions (default factor)	Amount of Nitrogen added to soil through crop residues
Fertilizer production	CO_2, N_2O	IFA (2009)	Type of fertilizer, fertilizer amount	Not applicable	Not applicable
Residue management (removed; left untreated in heaps and pits)	N_2O, CH_4	IPCC (2006b)	Residue amount	None	Crop type
Residue management (left on field; incorporated)	N_2O	IPCC (2006a)	Residue amount	None	Crop type
Residue management (burned)	N_2O, CH_4	IPCC (2006a)	Residue amount	None	Crop type
Pesticide (production, application)	CO_2	Audsley (1997)	Applied pesticide amount	Not applicable	Not applicable
Agroforestry	Soil organic carbon	Vetter et al. (2014)	Type of agroforestry system	None	Agri silvicultural, alley cropping, home garden, improved fallow, multi-storey systems, woodlots
	Above-ground biomass	Vetter et al. (2014)	Type of agroforestry system	None	Agri silvicultural, alley cropping, home garden, improved fallow, multi-storey systems, woodlots
Land preparation (crop residue, tillage, fertilization practice)	Soil organic carbon	IPCC (2006a)	Intensity of carbon inputs, tillage practice	Soil organic carbon, moisture regime (dry, moist, wet), climate (tropical, temperate, boreal)	Limited: increased crop residues operationalized as more carbon input

Source: own elaboration

4.4 Cost-effectiveness analysis

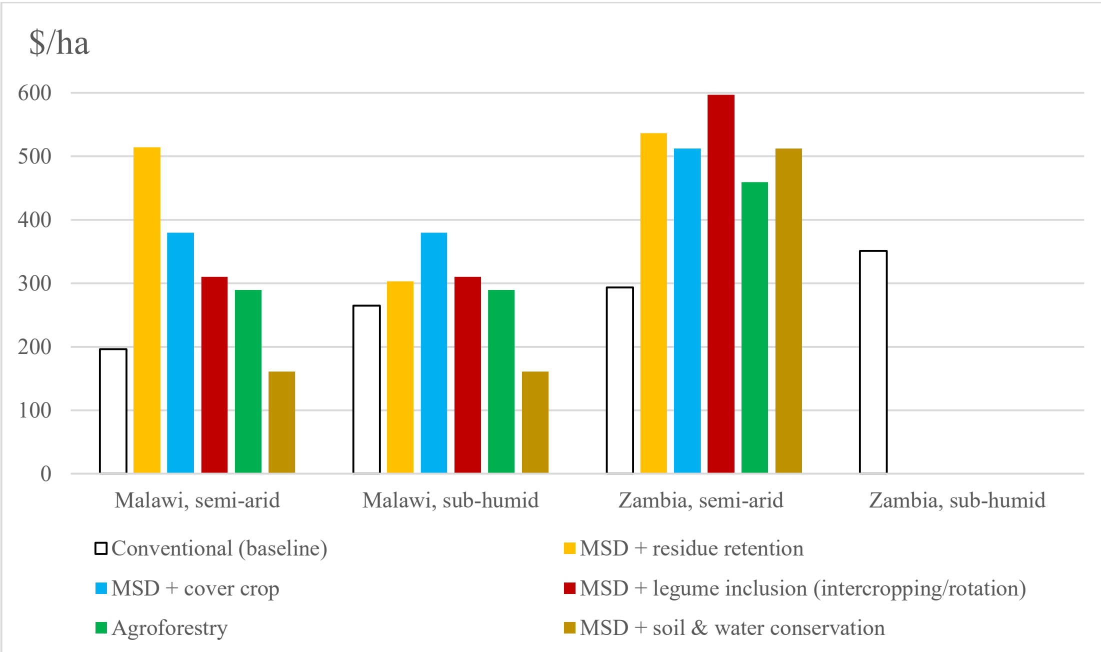
The fourth step estimates CSA cost-effectiveness in generating mitigation benefits. With reference to earlier research about marginal abatement cost curves (Jiang et al., 2020) we apply MACCs to quantify emission abatement costs of each CSA practice (Huang et al., 2016). We compute the unitary mitigation potential in terms of $ per ton of carbon dioxide equivalents (CO_2e) abated and compare it with conventional farming (counterfactual). We use here the ‘bottom-up’ approach to deal with the heterogeneity of agricultural technologies (Branca et al., 2015). For each farming practice, we link the gross margins (step one of the methodology) with the mitigation potential resulting from the mitigation option model (step three). The private MACCs are built by plotting the gross margins of various farm management measures (per unit of CO_2e mitigated) on the vertical axis, and the volume of emissions saved (total units of CO_2e mitigated over a 20-year period) on the horizontal axis. Positive gross margins indicate negative abatement costs (and vice versa). This means that the adoption of such practices is expected to increase on-farm economic returns and, at the same time, generate mitigation benefits. The curve is upward-sloping. Farming practices are ordered by increasing abatement costs and volumes of CO_2e abated. Since marginal abatement costs rise with the mitigation increments, moving along the curve from left to right worsens the mitigation profitability of farming practices, as each ton of CO_2e mitigated becomes more costly; indicating the management options that should progressively be implemented to seek cost-effective climate change mitigation.

5. Results

5.1 Marginal analysis

Looking at the comparative profitability of climate-smart agriculture technologies with respect to conventional management, we find that in both country-cases, maize cropped under MSD-based systems earns higher margins than under tillage-based farming, in the same agroecology (Figure 2). Yields increase due to CSA implementation determines an increase in the total value of production (computed as the product between yields and the farm-gate price) which more than counterbalances the higher costs of production of the CSA practices, leading therefore to rising margins. Differences are more significant in semi-arid areas, indicating potentials to enhance resilience and adaptation to extreme weather events. Soil conservation practices provide ecological benefits in terms of increased soil moisture, which are mostly beneficial to yields where water is a limiting factor (Wolka et al., 2018). Gross margins are somehow lower for more costly and labour-intensive practices such as soil and water conservation structures and agroforestry.

Figure 2: Gross margins of maize cropping in different agro-ecological zones of Malawi and Zambia.



Source: own elaboration

Positive economic results of the CSA practices may come at higher intensity of labour and herbicide use. Maize production costs are higher in CSA systems than in conventional ones, independently of the agroecological zone (Table 5): (i) cash input costs are higher because CSA requires better inputs (improved seeds, fertilizers and herbicides for weed control) than conventional farming; (ii) labour costs are higher since labour requirements for weeding are higher in MSD-based systems (the full tillage conventional systems help to kill weeds before sowing that reduces weed intensity) and planting basins (MSD-based technique) are more time-consuming than ridging (conventional technique). In both agroecological zones, CSA shows higher labour productivity (yield to labour ratio) than conventional management since the increase in crop yield, consequent to CSA implementation, more than offsets the higher labour requirements. Likewise, CSA also generates returns to labour (labour to revenues ratio) higher than the opportunity cost of labour (minimum rural wage rate). Nevertheless, these upfront cash inputs and labour costs represent a barrier to the adoption of MSD-based systems which might make conventional systems preferred for the smallholders.

Relevant variables used to derive such results are compared using t-test at 1 and 5% α-level of statistical significance. We find that for the key variables which determine the profitability of CSA practices (i.e. yields, fertilizers and labour) a statistically significant difference among the averages for CSA and conventional management exist (see table A in the supplementary material). We investigate about the statistical relationship among such variables in the econometric analysis section 5.2.

Table 5: Capital- and labour-related indicators of maize cropping by agro-ecological zone

Indicator	Unit of measure	Semi-arid areas		Sub-humid areas	
		Conventional	CSA	Conventional	CSA
A) Malawi					
Cash inputs	$/ha	310.30	347.16	302.10	346.96
Labour costs	$/ha	85.60	110.60	85.60	103.79
Returns to cash capital	$/$	2.13	2.78	2.40	2.17
Return to family labour	$/person day	3.29	5.95	4.10	4.92
Labour productivity	Kg/person day	13.2	19.7	14.9	15.4
Capital intensity		3.6	3.1	3.5	3.3
B) Zambia					
Cash inputs	$/ha	409.5	444.6	382.8	-
Labour costs	$/ha	78.8	108.7	139.9	-
Returns to cash capital	$/$	0.9	1.0	1.9	-
Return to family labour	$/person day	0.3	1.2	2.6	-
Labour productivity	Kg/person day	18.8	22.4	25.6	-
Capital intensity		5.2	4.1	2.7	-

Source: own elaboration

5.2. Econometric Analysis

Regression coefficients are the rate of growth of maize yields associated with a unit change in the explanatory variable (Tables 6 and 7). We consider four model specifications: dummies for the adoption of four CSA practices (i.e. MSD, residue retention, crop rotation with legumes and the use of cover crops) are included (columns 1a, 1b); interactions of MSD with the other practices to assess to what extent farmers gain additional benefits from combining single CSA practices, as per Conservation agriculture principles, are explored (columns 2a, 2b). The main difference between specifications labelled as (a) and (b) is that in the latter we include an interaction term between MSD dummy and inorganic fertilizer quantity to assess whether any observed yields change due to MSD adoption is moderated by fertilizer use intensity. We find positive and significant coefficients of MSD dummy in both countries, indicating that the implementation of MSD and all its combination with other smart techniques increases maize yields compared to conventional farming. We then look at both MSD- and interaction term coefficients to assess if such increase is the combined effect of various CSA practices adopted simultaneously through a MSD-based package, or results from the implementation of a single CSA practice (residue retention, crop rotation with legumes or cover crops): we find that since the coefficient for MSD variable is significant but the interaction is not, the combined effect of multiple MSD-based practices is key to increase yields. Although acknowledging the limitations of our cross-sectional analysis which makes challenging to claim causation[6], such results provide robust evidence on the direction and magnitude of changes in productivity associated with CSA adoption.

Table 6: Malawi, OLS estimation results for maize production function

	Yields (Kg/ha)			
	(1a)	(1b)	(2a)	(2b)
MSD (1=yes)	0.147**	0.792**	0.274**	0.955**
	(0.063)	(0.345)	(0.088)	(0.360)
Residue retention (1=yes)	0.083	0.08	0.125*	0.127*
	(0.060)	(0.060)	(0.061)	(0.059)
Crop rotation with legumes (1=yes)	0.024	0.025	0.008	0.008
	(0.0 57)	(0.056)	(0.075)	(0.075)
Cover crop (1=yes)	0.146	0.127	0.222*	0.201
	(0.095)	(0.081)	(0.121)	(0.111)
Log crop area (ha)	-0.374***	-0.369***	- 0.370***	-0.364***
	(0.043)	(0.045)	(0.043)	(0.046)
Log family labour (man days /ha)	0.035	0.035	0.035	0.035
	(0.038)	(0.035)	(0.038)	(0.035)
Log fertilizer (kg/ha)	0.197***	0.234***	0.195***	0.234***
	(0.037)	(0.049)	(0.037)	(0.049)
Improved seeds (1=yes)	0.091**	0.090**	0.098**	0.097**
	(0.037)	(0.035)	(0.038)	(0.037)
Semiarid agro ecological zone (1=yes)	-0.057	-0.037	-0.056	-0.036
	(0.054)	(0.052)	(0.054)	(0.051)
Household size	0.005	0.005	0.005	0.005
	(0.011)	(0.012)	(0.011)	(0.011)
Age of household head	-0.002	-0.001	-0.002	-0.001
	(0.002)	(0.002)	(0.002)	(0.002)
Average education of household members (years)	0.039***	0.037***	0.038***	0.035***
	(0.009)	(0.010)	(0.009)	(0.010)
Assets index	0.130***	0.134***	0.129***	0.132***
	(0.028)	(0.026)	(0.026)	(0.023)
MSD*Fertilizer		-0.123*		- 0.128*
		(0.062)		(0.065)
MSD*Residue retention			-0.174	-0.192
			(0.114)	(0.123)
MSD*Crop rotation with legumes			0.063	0.063
			(0.101)	(0.097)
MSD*Cover crop			-0.256	-0.255
			(0.170)	(0.183)
Constant	5.422***	5.230***	5.409***	5.208***
	(0.168)	(0.235)	(0.171)	(0.243)

[6] These limitations point towards potential endogeneity of the adoption decision and selection due to both observable and unobservable characteristics. While we try to control for several important observable household characteristics that may also partly capture some unobservable dimensions, such as managerial capability or experience, it is important to note that a substantial number of households in our sample cultivate maize fields under both conventional and climate-smart systems. This is particularly true in the case of Malawi where 71 per cent of the households have plots under both systems, whereas in Zambia this share amounts only to 28 per cent. Given these figures, selection on adoption is should not be an issue in the results for Malawi, while results for Zambia should be interpreted with more caution.

Observations	564	564	564	564
R-squared	0.386	0.393	0.39	0.398
Robust standard errors in parenthesis, *** p<0.01, ** p<0.05, * p<0.1				

Source: own elaboration

Table 7: Zambia (only semiarid agroecological zone), OLS estimation results for maize production function

	Yields (Kg/ha)			
	(1a)	(1b)	(2a)	(2b)
MSD (1=yes)	0.238***	0.270*	0.345**	0.437*
	(0.070)	(0.143)	(0.131)	(0.234)
Residue retention (1=yes)	0.107	0.108	0.253	0.263
	(0.084)	(0.085)	(0.170)	(0.180)
Crop rotation with legumes (1=yes)	0.280*	0.280*	-0.702	-0.717*
	(0.154)	(0.155)	(0.399)	(0.394)
Cover crop (1=yes)	0	0.003	-0.089	-0.079
	(0.132)	(0.130)	(0.225)	(0.229)
Log crop area (ha)	-0.319***	-0.319***	-0.314***	-0.315***
	(0.046)	(0.046)	(0.049)	(0.049)
Log family labour (man days/ha)	0.094	0.093	0.094	0.092
	(0.056)	(0.055)	(0.055)	(0.054)
Log fertilizer (kg/ha)	0.153***	0.158***	0.153***	0.167***
	(0.022)	(0.027)	(0.022)	(0.030)
Improved seeds (1=yes)	-0.128	-0.128	-0.138	-0.138
	(0.109)	(0.109)	(0.103)	(0.104)
Total rainfall during cropping season (mm)	0.145	0.146	0.141	0.144
	(0.103)	(0.104)	(0.102)	(0.104)
Average decadal max temperature during growing season (°C)	-0.094	-0.094	-0.095	-0.096
	(0.147)	(0.147)	(0.151)	(0.151)
Household size	0.006	0.006	0.004	0.004
	(0.015)	(0.015)	(0.014)	(0.014)
Age of household head	-0.011***	-0.011***	-0.011***	-0.011***
	(0.003)	(0.003)	(0.003)	(0.003)
Average education of household members (years)	-0.026	-0.026	-0.025	-0.025
	(0.024)	(0.024)	(0.024)	(0.024)
Assets index	0.132*	0.132*	0.137**	0.137**
	(0.061)	(0.061)	(0.060)	(0.061)
MSD*Fertilizer		-0.007		-0.019
		(0.027)		(0.031)
MSD*Residue retention			-0.215	-0.228
			(0.160)	(0.171)
MSD*Crop rotation with legumes			1.060**	1.077**
			(0.413)	(0.405)
MSD*Cover crop			0.076	0.063
			(0.276)	(0.288)
Constant	7.948*	7.926*	7.960*	7.910*
	(3.728)	(3.747)	(3.816)	(3.836)
Observations	573	573	573	573
R-squared	0.319	0.319	0.326	0.326
Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1				

November 2020

Source: own elaboration

5.3 GHG mitigation analysis

Focusing here on the results for maize production systems with medium-fertilizer intensity[7], GHG mitigation impacts vary strongly across different agricultural management practices (Table 8): the median annual GHG mitigation benefits for the CSA practices considered range between 0.1-1.6 tCO_2e per hectare, excluding agroforestry which leads to more sizeable annual mitigation benefits[8]. Specifically: (i) the application of legume inclusion and residue retention lead to low annual mitigation benefits, below 0.4 tCO_2e per hectare; (ii) the isolated application of cover crops, as well as the combined application of reduced tillage and residue retention, or reduced tillage and legume inclusion can generate bigger mitigation benefits up to 0.8 tCO_2e per hectare; (iii) the combined application of either reduced tillage and cover crops, no-till and residue retention, no-till and legume inclusion or no-till and cover crops, lead to higher GHG mitigation benefits, up to 1.6 tCO_2e per hectare. Such coefficients are aligned with those reported in the literature, as shown in WB (2012) which summarizes the results of a meta-analysis of soil carbon sequestration rates in Africa for several land management practices. Also, the estimated impacts vary depending on the agro-ecological zone: for each CSA practice, in sub-humid areas the carbon sequestration levels are higher than those recorded in semi-arid areas. This is in line with the literature findings showing that the mitigation effects of sustainable land management adoption are higher in areas of higher rainfall (Branca et al., 2013). The spatial variability of GHG mitigation impacts across the study area and agroecological zones is shown in the Figures A and B in the supplementary material.

Table 8: Median annual climate change mitigation benefits from adopting CSA practices in maize production across Malawi and Zambia.

Practices adopted by farmers	Malawi	Zambia
	(tCO_2e/ha)	
No tillage	0.62	0.63
Minimum soil disturbance	0.13	0.29
Legume inclusion (intercropping/rotation)	0.33	0.35
Residue retention	0.24	0.26
Cover crop	0.59	0.77
Legume inclusion + residue retention	0.24	0.26
MSD + residue retention	0.37	0.54
No tillage + residue retention	0.90	0.93
MSD + legume inclusion	0.46	0.63

[7] Based on the household survey data in Malawi, a medium intensity of fertilizer use has been defined as applying: 20 kg/ha of urea (46.7%N); 4.8 kg/ha of ammonium nitrate (35%N); 6.3 kg/ha of triple super phosphate (48%P_2O_5); 0.18 kg/ha of diammonium phosphate (18% N; 46% P_2O_5); and 0.87 kg/ha of Calcium ammonium nitrate (27% N).

[8] GHG mitigation benefits from agroforestry systems have been evaluated based on a review of mitigation estimates reported throughout the literature. Due to differences in planting density and tree species, the estimated GHG impacts vary strongly by type of agroforestry system, such as agri-silviculture, alley cropping, or improved fallow systems. No country specific estimates for Malawi and Zambia could be developed. GHG mitigation estimates refer to generic tropical conditions across Sub-Saharan Africa.

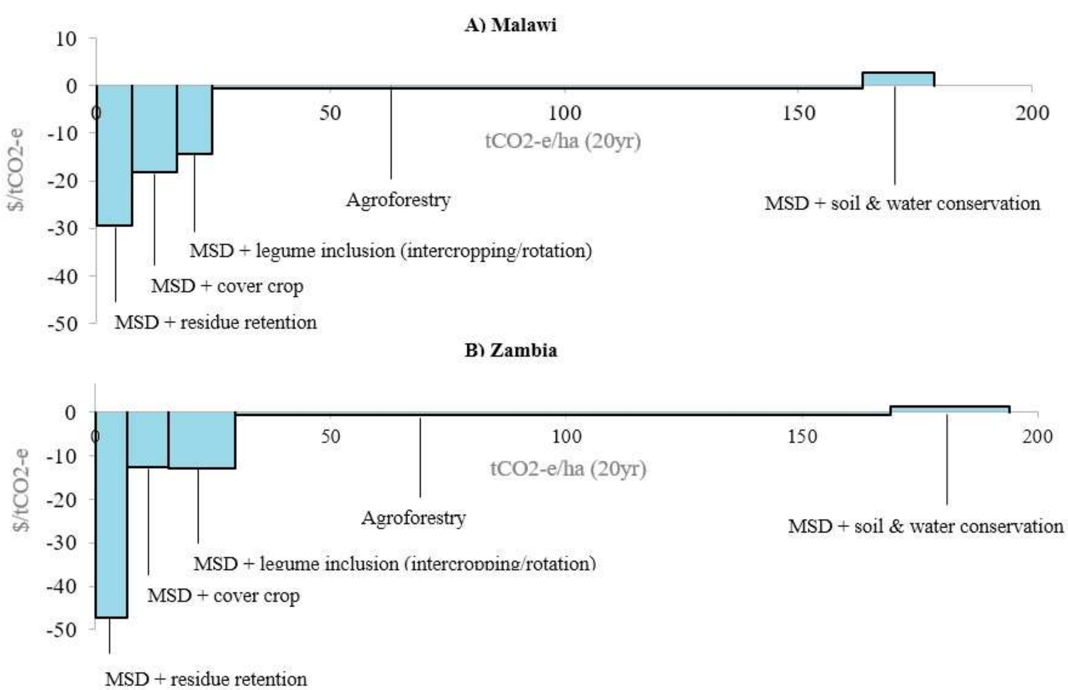
No tillage + legume inclusion	0.99	1.02
MSD + cover crop	0.73	1.11
No tillage + cover crop	1.28	1.58
MSD + soil & water conservation	1.27	1.43
Agroforestry	6.95	6.95

Source: own elaboration

5.4 Cost-effectiveness analysis

Private marginal abatement costs curves derived from the analysis are shown in Figure 3. The curve for Malawi considers average value of semi-arid and sub-humid zones. The curve for Zambia refers to semi-arid areas only. Each bar corresponds to a specific practice implemented on 1 hectare of land. The height displays the on-farm unit mitigation cost, estimated in $ per ton of CO_2e measured on the y axis. The width indicates the mitigation potential, expressed in ton of CO_2e measured on the y axis. The area displays the on-farm abatement cost (in $). Marginal abatement costs are negative for all MSD-based options but soil and water conservation, indicating that the adoption of the practice determines positive margins (i.e. cost savings). They are slightly negative also for agroforestry, which shows a much bigger mitigation potential with respect to the alternative practices.

Figure 3: marginal abatement cost curves for maize production in Malawi and Zambia



Source: own elaboration

6. Discussion

CSA is a cleaner production approach which sustainably increases crop productivity (Hens et al., 2018). It is a suitable strategy to enhance the resilience of smallholder farming systems in Africa (Partey et al., 2018) and specifically in the study area object of this study (Cacho et al., 2018).Our results confirm that the adoption of MSD-based options significantly increases crop productivity and on-farm economic returns to smallholders, directly enhancing physical and economic resilience, as well as land use efficiency, particularly in semi-arid areas.

Farmers face multiple climate-related risks and the adoption of CSA packages may help to simultaneously tackle such risks and exploit all possible adaptation benefits of the technology, reducing cropping systems' vulnerability both in Malawi (Maguza-Tembo et al., 2017) and Zambia (Khonje et al., 2018). Indeed, we observe that the productivity increase recorded among sampled farmers is determined by a combination of CSA practices, which are intended to be synergic, rather than by single practices.

CSA diminishes soil fertility losses, improving residue re-use and enhancing soil nutrient properties (Steenwerth et al., 2014), therefore improving systems' physical resilience. The following econometric findings indicate that CSA can substitute chemical fertilization: (i) the interaction of MSD variable with chemical fertilisers is not significant in Zambia and is even negative (and significant) in Malawi; (ii) the interaction of MSD with crop rotation with legumes in Zambia is positive and significant, demonstrating the fertilization effect of Nitrogen-fixing leguminous which may substitute for chemical fertilization; (iii) the coefficient for fertilizer use is significant and positive confirming that fertilization increases yields.

CSA reduces air emissions and increases soil carbon sequestration (Nyasimi et al., 2014). We find that the practice surveyed increase soil organic matter inputs and soil carbon levels, while not leading to excessive increases in nitrous oxide emissions. However, for specific field-level conditions, emission levels may strongly vary from such average statements. Also, the estimated effectiveness of reduced- and no-tillage in increasing soil carbon levels is disputed in the literature and needs further research (Powlson et al., 2016). Anyhow, across all GHG mitigation estimates, it is important to consider that soil carbon sequestration has a limit when a new equilibrium soil carbon level is reached (about 20 years). The mitigation impacts vary depending on the agro-ecological zone: for each CSA practice, in sub-humid areas the carbon sequestration levels are higher than those recorded in semi-arid areas. This is in line with the literature findings showing that the mitigation effects of sustainable land management adoption are higher in areas of higher rainfall (Branca et al., 2013).

However, through the marginal analysis we demonstrate that the CSA options considered are more labour-intensive and incur higher production costs than conventional agriculture, which can be an adoption barrier for the smallholders. Also, the regressions' results indicate that: (i) labour availability may limit the adoption of labour-intensive CSA practices (indeed, the size of cropped area is negative and significant, indicating that to wide farm size corresponds low CSA adoption); (ii) capital availability can increase yields due to enhanced access to inputs and technology knowledge (assets level is positive and significant); (iii) younger and more educated farmers perform better than others (households' members education level is positive and significant in Malawi and households' head age is significant and negatively related to yield in Zambia). Similar findings are reported in the literature: Ngoma (2018) discovers that CSA practices require more labour for weeding and land preparation; Sims and Kienzle (2016) notice that labour availability may be a limiting factor in low-mechanized production systems; capital availability can increase yields due to enhanced access to inputs and technology knowledge (Matshe, 2009); education complements capital (Meijer et al., 2015). Overall adoption and diffusion of CSA technology in Africa has been slow because farmers are constrained by technological, socio-economic and institutional barriers, ineffective policies and absence of proper incentives (Branca and Perelli, 2020).

In our study we quantify the (private) costs of CSA implementation born by farmers to generate (public) benefits in the form of GHG mitigation. This is visualized through the on-farm MACCs. The negative marginal abatement costs estimated for most MSD-based practices indicate a double win situation since they are likely to be attractive to farmers for the increase in agricultural returns they can generate, while also generating public benefits. Other studies have built MACCs for a similar set of CSA practices. In a recent report by McKinsey & Company (2020), cost savings of about \$41/tCO_2e for the low- or no- tillage practice are indicated. Such value is in line with the size of most MSD-based packages discussed here. Also, in a previous research from the World Bank (WB, 2012), costs savings are associated to CSA practices, even if they are generally bigger (in absolute terms) than those found in our study (with the exception of improved fallow for which abatement costs are similar). However, results are comparable in relative terms, since practices such as reduced tillage, residue management, intercropping, use of cover crops, and crop rotations are found to be more cost-saving than agroforestry (improved fallow) or soil and water conservation interventions. In any case, the comparison is difficult because: (i) different practices are considered in cited studies; (ii) data reported in the literature are global or regional weighted averages which do not account for the national differences considered in the present work; (iii) in the gross margins computations we use on-farm prices which are lower than market prices commonly used in other studies, and lead to lower margins and, consequently, smaller cost savings associated with the respective abatement options.

The MACCs inform sectoral decision makers in designing evidence-based policies supporting CSA uptake and in advocating for more informed political-economic changes of agriculture production systems towards climate-resilient pathways. This is particularly important in view of the recent reports indicating the key role of agriculture in mitigation (WRI, 2019) and building GHG national inventories (IPCC, 2019).

Important policy implications exist. To enhance CSA diffusion in the country, policies should: (i) prioritize the implementation of MSD-based systems in semi-arid areas, where the benefits of CSA are higher; (ii) support research and extension to develop, test and coherently promote CSA technology packages (given their potential to reduce cropping systems' vulnerability to multiple risks) and encourage crop diversification, e.g. the insertion of legumes in the rotations to reduce the need for chemical fertilizers, especially where access to production inputs is limited; (iii) enhance smallholders' access to seed varieties suitable for varied agroecological zones, make fertilizers and herbicides more affordable to farmers since such inputs can exploit the CSA potential, and reduce transactions costs throughout the value chain via real-time market information; (iv) support the development of markets for mechanization to deal with labour scarcity which can reduce the implementation of labour-intense MSD-based systems; (v) finance capacity building and training programs to strengthen farmers' knowledge about improved farm practices and strategically target younger farmers, which are found to be more prone to CSA implementation; (vi) be differentiated considering values of land, capital and labour productivity associated to MD-based technology uptake in different agroclimatic zones and related higher competition with conventional tillage-based systems.

Public support for agriculture in Malawi and Zambia is principally in the form of subsidies aimed at improving food security and reducing poverty. It is implemented through the Food Reserve Agency (FRA) and the Farmer Input Support Programme (FISP) that in 2019 accounted for 51% of agricultural spending in Zambia (IAPRI, 2019) and 27% in Malawi (GOM, 2019). In the short-run, CSA policies could be made actionable through the alignment of such subsidy programs with climate resilience, for example by: (i) improving targeting capacity of the subsidy programs, e.g. prioritizing areas vulnerable to climate change, selecting farmers who can use fertilizer profitably but are not already using it, or developing detailed farm registries that include geo-spatial information which could also help to delivery support services such as weather insurance to farmers (Jayne et al., 2018); (ii) facilitating delivery at the agro-dealer level of improved seed varieties other than staple cereal crops, e.g. legume seed varieties targeted to the different agroecological zones, more resilient to weather variations, more efficient in water and nutrient utilization and more productive (Gee et al., 2016); (iii) decoupling FISP from social protection goals and subordinating subsidy access to the effective on-farm adoption of suitable CSA practices (Nkhoma, 2018); and (iv) using extension services and information and communications technologies to show farmers how the application of fertilizer obtained through FISP can become more profitable when complementary CSA practices are adopted (Jayne et al., 2018).

Subsidy programs, however, are promoted at the expense of other important agriculture development areas, such as research, extension and infrastructure investments which are generally under-funded. Therefore, in the longer period, policies to promote CSA uptake should include some of the following elements: (i) enhance research programs to develop CSA packages of practices suitable for enhancing the resilience of smallholder farming systems in different agroecological zones; (ii) strengthen advice and monitoring capacity of agriculture extension programs, including access to climate- and weather-related information; (iii) invest in strategic rural infrastructure and logistics in areas more vulnerable to climate change, e.g. smallholder irrigation systems in semi-arid areas, cooling and storage facilities to reduce post-harvest losses due to heat waves or floods; (iv) improve customary land security through registration or land certification to encourage CSA adoption since farmers are more motivated to undertake investments in the plots they can guarantee will remain under their control (WB, 2019d).

Based on secondary data available about the costs of CSA implementation through different delivery mechanisms (from farmer field schools and participatory extension approaches to outgrower and weather insurance schemes) in Zambia (WB, 2019d) and Malawi (WB and CIAT, 2018), it is possible to indicatively estimate that about $400 million and $100 million are needed every year for nationwide CSA scaling-up in Zambia and Malawi, respectively. Considering that an average CSA investment project lasts six years (WB, 2019d) this translates in finance requirements of about $2.4 billion in Zambia e $0.6 billion in Malawi. Since most MSD-based options generate positive margins it is plausible to expect that such external financial resources will be only needed upfront to overcome the adoption barriers and that investing in CSA will be sustainable in the long-run. Globally, climate finance available in 2017/8 amounted at $579 billion (both from public and private actors), of which only $19 billion went to Sub-Saharan Africa (CPI, 2019). Unfortunately, public funds supporting climate action and those supporting agriculture remain largely separate. CSA enhances adaptation and mitigates emissions and could be targeted by both adaptation and mitigation funds. Also, in the national agriculture investment plans CSA does not represent a separate category. Thus, it is not easy to clearly identify the resources spent on CSA. For example, in Zambia, based on interviews with major donors and project implementers, it is estimated that $118 million were spent in 2017 on 38 different CSA-related projects financed, among other sources, by the Global Environment Facility and the Green Climate Fund (WB, 2019d).

Funding mechanisms and models that could smartly blend adaptation and mitigation financing sources, and flexibly support multi-objective climate-smart agriculture initiatives are needed (Shames et al., 2012). In this respect, payments for environmental benefits[9] could be an option to incentivize CSA adoption if tailored appropriately. According to the MACCs' results, policies should promote the adoption of MSD-based technology options first, in order to mitigate climate change in a cost-effective way, gain social efficiency and

[9] Over the past 20 years, payments for ecosystem services (PES) has become a well-known mechanism to promote environmentally sustainable land-use practices (Wegner, 2016). PES programs can provide incentives to land managers to adopt practices that generate various environmental services (e.g., carbon sequestration, water quality or flows, biodiversity). The effectiveness of this instrument will depend on various factors including capacity to aggregate suppliers and level of transaction costs to be borne to implement the program, and the beneficiaries' willingness to pay for the environmental services (Branca et al., 2011).

optimize the use of climate finance. However, even if most MSD-based options are cost savings and the relative marginal abatement costs are negative, it is not likely that instituting payments for the environmental benefits would be enough to induce adoption given the amount of mitigation benefits they generate (Thierfelder et al., 2017). For such practices, the key issue is whether they generate positive net returns to the farmer and the capital and labour requirements can be met. Similarly, measures that involve soil and water conservation structures generate a negative gross margin to producers – as well as relatively low levels of mitigation benefits – and would not be a valid option for such payments. In contrast, the agroforestry (improved fallow) option generates much greater levels of mitigation, but relatively lower agricultural returns. For example, in Malawi, agroforestry marginal abatement cost amounts to -0.63$/t CO_2-e (costs almost offset the benefits). Indeed, while costs to build infrastructures and planting trees are borne in the first years, the benefits are gained in the long-term, generating a negative flux of net benefits in the short-term. Agroforestry scaling-up would require incentives as payments for the mitigation benefits. Given the discussion above on barriers to CSA adoption, one potential role of such payments would therefore be to bridge the up-front financing gap associated with agroforestry implementation. Based on the evidence from the literature on results-based carbon finance in the study area, establishing international and multi-stakeholder partnerships, building social capital and adopting participatory learning approaches can increase inclusive participation to payments for mitigation programs for CSA, expand their impacts at local scale and feed good practices into national policy development (Stringer et al., 2012).

Carbon payments could therefore be supportive of agriculture, forestry and other land use sector policies aimed to enable a balance between the direct benefits on GHG emission and carbon sinks, and the trade-offs and cost barriers associated with the implementation of land management options with high mitigation potential (Bustamante et al., 2014). Such payments could play a role in ensuring both human wellbeing of smallholders and the success of proposed climate change mitigation programs in Sub-Saharan Africa (Palm et al., 2010). Indeed, significant trade-offs between increased productivity and mitigation occur from the CSA-related land management change. To this extent, the analytical results discussed here could be used by policymakers to minimize such trade-offs, to enhance the climate-smartness of farming systems and to orient agriculture sector toward a low-carbon pathway, also in the context of the Nationally Determined Contributions (Branca et al., 2021).

7. Conclusions

The assessment of the bundled economic and mitigation benefits of a set of CSA practices for smallholder agriculture, conducted here controlling also for key variables that affect these outcomes, demonstrates that several practices do offer the potential for improving smallholders' incomes under climate risk, therefore contributing to enhance resilience, although the means of incentivizing their uptake are different. Negative marginal abatement costs for most practices indicate synergies between livelihood increase and climate change mitigation. Such results can be applied to develop policy and planning strategies and investment programs to promote cleaner and sustainable production which could be replicated in similar agroecological contexts. They strengthen the case for public support of CSA practices within concrete implementation of the Nationally Appropriate Mitigation Actions, the National Adaptation Programmes of Action and the post-2020 national commitments under the UNFCCC Paris Agreement.

Novelty features of the analysis and its scientific value-added include: an interdisciplinary approach linking farm economics with the ecological impact of climate-smart agriculture; isolation of the specific impact of the practices controlling for other variables, including weather and agroecological zones; use of a unique dataset of various farming practices adopted by households under different climatic contexts, in two countries of Southern Africa where data are often a constraint; a cross-country comparison supporting CSA innovation scale-up at the regional level. The integrated economic-ecological approach applied here is technically challenging, but its results are particularly valuable given the data scarcity on sustainable agriculture practices in the Southern Africa. Agricultural national statistics in Malawi and Zambia do not systematically collect, record and analyse information differentiating by management type. The technology classification adopted here, together with the economic and ecological indicators, data collection approach and the methodology will be useful for the institutions involved in quantitative analyses to be replicated and scaled-out for wider policy environmental analysis.

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