Economy-wide effects of climate-smart agriculture in Ethiopia

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Abstract:

Promoting climate-smart agriculture (CSA) is now a common policy in many developing countries. Yet researchers rarely quantify CSA's economic value as opposed to traditional input-intensive technologies, particularly CSA's contribution to economy-wide indicators, such as economic growth and poverty reduction. This study applied a bioeconomic modeling approach to quantify the economy-wide effects of promoting CSA and traditional input-intensive technologies (fertilizer and irrigation) in Ethiopian cereal systems. We combined a cropping systems model with a computable general equilibrium model that was linked to a poverty module. We simulated the economy-wide effects for 40-year sequences of variable climate with and without climate change. Our results suggest that adopting CSA technologies (related to no tillage and integrated soil fertility management) on a quarter of Ethiopia's maize and wheat land (approximately 900,000 hectares) would increase national gross domestic product (GDP) by an average US $146 million annually and assist 367,000 people to move out of poverty. This benefit exceeds the GDP gain of US $95 million and poverty reduction of 105,000 people expected from a similarly-sized expansion of fertilizer and irrigation. Results also suggest that the gains from CSA are greater with climate change and that CSA improves stocks of soil organic carbon.

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Keywords
Agri-food system; CGE model; climate-smart agriculture; economic growth; Ethiopia; poverty

1 Introduction

The expected adverse effect of climate change on crop productivity presents a looming challenge for millions of people, especially in Africa (Adesina, 2010). Agrarian countries are particularly vulnerable, mainly because they are home to most of the world's smallholder farmers (Samberg *et al.*, 2016). Among the wide range of development options, climate-smart agriculture (CSA) has the potential to help these vulnerable farmers because CSA has, in short, the objectives of improving agricultural productivity, building resilience to climate change, and reducing emissions from agriculture (Lipper *et al.*, 2014).[1] Calls exist to increase investments at the national scale for climate-smart practices (Beddington *et al.*, 2012), international organizations are starting to incorporate CSA into their programs, and CSA lies at the intersection of policy and science (Saj *et al.*, 2017). The incorporation of CSA today recognizes that CSA has benefits even without climate change. Moreover, many of the technologies that are often labelled as CSA enhance productivity even without climate change (Pretty *et al.*, 2006).

Our study asked one question: *how do different combinations of CSA and traditional input-intensive technologies such as mineral fertilizer and irrigation for maize and wheat affect economy-wide indicators in Ethiopia for different climates?* Our economy-wide indicators include gross domestic product (GDP), agri-food system (AFS) value added, and poverty. Our study links a biophysical-economic modelling approach to estimating the economy-wide benefits and trade-offs associated with CSA. We use crop models to estimate the yield impacts of technologies such as CSA, crop water source (i.e., irrigation or rainfed), and mineral fertilizer (hereafter fertilizer); and then couple these effects with a spatially-disaggregated computable general equilibrium (CGE) and microsimulation model that measures CSA's effect on the national economy and household poverty.

There are relatively few studies that quantify the economy-wide effects of CSA, despite the growing recognition of the potential of CSA, and its many variants, in developing countries—although CSA studies at the farm-household scale exist. Many of these farm-household scale studies use household data to econometrically examine the adoption of CSA or the effect of CSA on crop yields (Pender and Gebremedhin, 2008; Kassie *et al.*, 2010; Arslan *et al.*, 2015; Shiferaw and Holden, 1998; Kato *et al.*, 2011). Some studies explicitly study how CSA affects income or poverty (Abdulai, 2016; Di

[1] We discuss the use of the terms "CSA" and "technologies" in our Supporting Information (SI1).

Falco and Veronesi, 2013). Others have simulated the *ex-ante* effect of soil and water conservation practices on household welfare (Holden and Shiferaw, 2004), plus labor constraints to the uptake of these practices (Ruben *et al.*, 2006). Overall, a moderate consensus exists that CSA can improve farm-household food security, income, and environmental sustainability. A study at the national scale can help identify the possible role of CSA within agricultural investment plans, with calls existing for greater investments at the national scale in climate-smart practices (Beddington *et al.*, 2012). Evidence on the effects of CSA at the national scale can help support investment decisions. Estimates of the costs and benefits from CSA investments are important for better understanding the role of CSA in promoting food security and economic development (Engel and Muller, 2016). It is important to measure the potential contribution of CSA to national development. Such an approach should (i) account for spillover impacts throughout and beyond the agri-food system; and (ii) assess the opportunity costs of CSA technologies by comparing them with more traditional input-intensive technologies such as fertilizer and irrigation.

Some economy-wide studies exist that combine crop and CGE models to assess the effects of climate on Ethiopian agriculture. Extant literature has used CGE models to examine the economy-wide effects of climate change in Ethiopia (Gebreegziabher *et al.*, 2016; Yalew, 2016; Arndt *et al.*, 2011; Robinson *et al.*, 2012). None of the above studies directly consider possible policy responses within the agricultural sector, despite the above studies quantifying climate change effects. For example, Robinson *et al.* (2012) considered the economy-wide implications of expanding irrigation area compared with road expansion. We supplement the above studies by providing a comparison within the agricultural sector of CSA technologies vs. traditional input-intensive technologies for cereal crops. Compared with earlier CGE studies, we provide a more granular examination of crop technologies that are agronomically sound and possibly buffer against climate change. We disaggregate results by agro-climatic zones to highlight spatial heterogeneity associated with changes in crop management.

Illustrating this heterogenous effect generates evidence for policymakers to address improving the productivity and resilience of the agricultural sector through better crop management.

Well-developed methods exist to couple biophysical and economic models at the field or farm scale (van Wijk *et al.*, 2014; Antle *et al.*, 2017). Our method highlights the value of coupling biophysical and economic models at the sub-national and national scale. This coupling connects to the multiple methods available to examine the effects of different interventions, with randomized controlled trials (RCTs) providing a powerful tool for examining the impact of single interventions. However, Barrett and Carter (2010) write, within the context of RCTs, *“comparisons among multiple candidate interventions – so that the research can establish the opportunity cost of pursuing one intervention, not just the intervention's gross impact – remain very limited in practice due to feasibility constraints.”.* We believe that simulation methods can provide useful insights into the opportunity costs of different interventions, thus providing an alternative to RCTs.[2] Our study makes no attempt to predict actual livelihoods or economic conditions in the future, rather we aim to provide insights into how different agricultural technologies alter economy-wide indicators under alternative climates.

2 Climate and Agriculture in Ethiopia

2.1 Agriculture in the broader economy

Ethiopia’s economy shares much in common with other low-income African countries. Most of the population live in rural areas and rely on agriculture for their livelihoods (Table 1). Agriculture accounts for two-fifths of GDP and, on average, agriculture and food accounts for more than half of total household consumption. This consumption proportion is consistent with Ethiopia’s low GDP per capita and high incidence of poverty. Cereal crops are particularly important in Ethiopia, with maize and wheat together generating more than 5 percent of total GDP and 15 percent of the value of household consumption.

[2] Our Supporting Information (SI2) expands on the primary value of models and their associated uncertainties.

[Insert Table 1]

We separated Ethiopia into five agro-climatic zones defined by elevation and annual rainfall (Schmidt and Thomas, 2017). Figure 1 shows the five zones: (1) drought-prone highlands (Zone 1); (2) drought-prone and pastoralist lowlands (Zone 2); (3) humid moisture reliable, lowland (Zone 3); (4) moisture-reliable highlands growing cereals (Zone 4); and (5) moisture-reliable highlands growing enset (Zone 5). Zone 4 generates almost half of all agricultural GDP (Table 1) and is the main producer of Ethiopia's dominant cereal crops (i.e., maize, wheat, teff, and barley). In contrast, Zone 3 has the smallest population and economy, and is most dependent on the rural nonfarm sector. Farmers in Zone 3 produce a limited amount of cereals, even though cereals provide a large share of household consumption.

[Insert Figure 1]

Agriculture's importance for Ethiopia's economy extends beyond the agricultural sector itself. The broader agri-food system (AFS) includes downstream food processing, farm input production, and the trading and transporting of agricultural and food products. Together, the AFS accounts for over half of total GDP and three-quarters of total employment (Benfica and Thurlow, 2017). Agricultural exports are Ethiopia's main source of foreign exchange (for example, coffee and sesame), and so most parts of the economy depend, at least indirectly, on agriculture. Even urban households, whose farm-related incomes are limited, spend a large share of their incomes on foods, especially cereals.

Agriculture is a source of economic growth and vulnerability. Figure 2 shows annual production trends for three major cereal crops, with Figure S1 showing trends in area planted. Ethiopia has raised yields and expanded production over the past decade, driven in large part by greater adoption of fertilizers and provision of farmer extension services (Bachewe *et al.*, 2017). The share of maize farmers using fertilizers, for example, increased from 20.9 to 50.8 percent during 2002–2014, and the share of maize farmers receiving extension visits grew from 6.3 to 52.1 percent (CSO, 2002 and 2014). Wheat farmers reported similar increases in fertilizer use and extension visits.

Positive yield and production trends hide year-on-year variability. Large areas of Ethiopia receive insufficient, and too variable, rainfall for adequate crop production, with the country frequently encountering droughts and famine (Dorosh and Rashid, 2015; Cavatassi *et al.*, 2011). Furthermore, the potential effects of climate change on crop yields present concerns (Jones and Thornton, 2003; Kassie *et al.*, 2015).

[Insert Figure 2]

CSA has the potential to address some of the concerns raised above. First, severe poverty and hunger in rural areas underscores the gains from interventions that further raise cereal yields and food production, and CSA has the potential to sustainably lift yields. Second, recurrent droughts and climate variability highlight the additional need for interventions that build greater resilience into Ethiopia's cereal system and improve sustainability indicators such as soil fertility.

2.2 Climate-smart agriculture in Ethiopia

Ethiopia actively promotes the use of CSA to assist farmers improve their livelihoods and buffer against climate variability and climate change (Jirata *et al.*, 2016). Two technologies that are potentially climate-smart include no-tillage and integrated soil fertility management (ISFM) (Lipper *et al.*, 2014). No-tillage involves is a minimum tillage practice in which the crop is sown directly into soil not tilled since the previous crop's harvest. Vanlauwe *et al.* (2010) define ISFM as a "*set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions, aiming at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity. All inputs need to be managed following sound agronomic principles.*" In our study, the ISFM technology included: no-tillage;

retaining crop residues in the field; and applying all available livestock manure to fields with full uptake of the nitrogen in manure the crop. These technologies, in combination with sound agronomic practices, have the potential to address concerns of low agricultural productivity, land degradation, and more frequent climate stressors. Our Supporting Information (SI1) provide additional details on CSA in general and specifically in Ethiopia, including the connection between CSA and soil and water conservation technologies.

3 Methods

3.1 Technology and climate scenarios

Our study simulated eight technology packages for wheat and maize that included different combinations of CSA, crop water sources, and fertilizer use (T1 to T8 in Table 2). Packages T1–T4 contain no CSA technologies, but rather quantify the effects of switching from rainfed cropping at current fertilizer application rates (T1) to crops receiving double the current fertilizer application rates (T2) or crops receiving irrigation (T3), or both greater fertilizer application and irrigation (T4). Baseline cropping conditions in our study are best reflected by rainfed cropping that uses no CSA and historical fertilizer rates (T1). Farmers only irrigate 1 percent of their harvested cropland, with the rest rainfed (IFPRI and IIASA, 2016). Maize occupies approximately 20 percent of irrigated land, with wheat occupying 3.6% of irrigated land (IFPRI and IIASA, 2016).

[Insert Table 2]

Packages T5–T8 replicate the earlier combinations of water and fertilizer practices, but now include CSA. We focus on the incremental effects of introducing CSA technologies (i.e., comparing T1 with T5) mainly because we are interested in comparing CSA to traditional input-intensive technologies for cereal crops. Given the increase in fertilizer use in Ethiopia over the past decade, we will also compare the gains from CSA to a doubling of current fertilizer application rates (i.e., comparing scenarios T2 and T5). We also include irrigation as a possible alternative to CSA. We simulated all eight technology packages for three 40-year sequences of climate data, all based on the same random historical sequence: 1) historical baseline, and for climate change following the 2) Geophysical Fluid Dynamics Laboratory (GFDL-ESM2M, hereafter GFDL) global circulation model (GCM), and the HadGEM2-ES (hereafter HadGEM) GCM. These two GCMs are commonly used in East Africa (Kihara *et al.*, 2015). In total, our study included 24 scenarios.

3.2 Estimating crop yield impacts

We used the Decision Support System for Agrotechnology Transfer (Jones et al., 2003) (DSSAT) to simulate yields for maize and wheat, and to simulate the content of organic carbon in soil for each of the eight technologies (Table 2). We discuss the role of Teff in our study in our Supporting Information (SI3). For DSSAT parametrization, we characterized maize and wheat production using globally-consistent, high-resolution, gridded datasets. Details on the three 40-year sequences of climate data are in our Supporting Information (SI4). Soil inputs were taken from Han et al. (2015), with details on the soil data in our Supporting Information (SI5).

We sourced data on prevailing crop technologies from a variety of sources (Robinson *et al.*, 2015; Abate *et al.*, 2015; Potter *et al.*, 2010). Data on these technologies included dominant management practices (such as tillage and crop residue management) and inputs (such as germplasm, nutrients such as mineral and organic fertilizer, supplemental water, and pesticides) for both rainfed and irrigated land, disaggregated by agro-climatic zones where possible. We then simulate maize and wheat yields for each of the 24 scenarios in DSSAT using the data at the spatial scale of a 0.5-degree grid cell.

Baseline yields refer to simulated grain yields for historical climate using the baseline practices (T1 of Table 2). These baseline practices included conventional tillage, crop residue removal, historical rates of fertilizer application, and no use of livestock manure as a soil amendment. The baseline therefore included no CSA technologies. We simulated crop yields in every grid cell where each crop was reported to be grown in IFPRI and IIASA (2016). Our application rates of fertilizer for maize in each zone broadly represent regionally-disaggregated rates found in Abate *et al.* (2015). Average baseline fertilizer rates (kg N ha^{-1}) by zone for maize were 19 (Zone 1), 16 (Zone 2), 11 (Zone 3), 20 (Zone 4), and 10 (Zone 5), and for wheat were 64 (Zone 1), 25 (Zone 2), 89 (Zone 3), 40 (Zone 4), and 20 (Zone 5). Average manure rates (kg N ha^{-1}) by zone for maize were 31 (Zone 1), 16 (Zone 2), 10 (Zone 3), 34 (Zone 4), and 58 (Zone 5), and for wheat were 30 (Zone 1), 22 (Zone 2), 12 (Zone 3), 39 (Zone 4), and 58 (Zone 5). The manure rates were calculated based on data in Potter *et al.* (2010), who calculated spatially explicit manure inputs of nitrogen by fusing global maps of animal density and data on manure production and nutrient content over 0.5° grid cells. Using our parametrized model, we compared the baseline crop yields from DSSAT for each administrative region in Ethiopia over a 3-year period to match yields reported in IFPRI and IIASA (2016) for the same crops and regions with comparable management. We do not aim to validate our model rather we aim to ensure that simulated yields are within a reasonable range compared with statistical data. We ran DSSAT for an initial 5-year spin up period, then generated yields for the three climate sequences.

We simulated a suite of practices comprised of practices that as documented as falling within the broad scope of CSA and these include no-tillage and integrated soil fertility management (Section 2.2). No-tillage without retaining crop residues in the field as a mulch can lead to surface crust formation that increases runoff and erosion and presents challenges for sowing crops using no-tillage machinery or power. Therefore, we combined to-tillage with our ISFM practices of mulching and manure application, which both help improve soil water balances and the content of soil nitrogen.

3.3 Estimating economy-wide impacts

Economic impacts for the 24 scenarios are evaluated using a static computable general equilibrium (CGE) model that captures all income and expenditure flows between all producers and consumers in Ethiopia, as well as the government and the rest of the world. The model is a multi-period variant of the standard static CGE model (Lofgren *et al.*, 2002). The Ethiopian CGE model is calibrated to a 2010/11 social accounting matrix (SAM) (Ahmed *et al.*, 2017). The SAM separates the economy into 49 sectors within each of the country's five agro-climatic zones (Figure 1). It also separates urban areas from the rest of the economy. Our Supporting Information (SI6) provides additional details underpinning our CGE modelling approach.

Different crop technologies have different costs and benefits at the field, farm, and household scale. The CGE model uses crop yields and their prices to capture the benefits. Different technologies have different private costs to farmers to adopt in terms of resource use, both financial costs and implicit labor time, which we document in our Supporting Information (SI7).

We estimated poverty rates using a survey-based microsimulation model. Each aggregate household in the CGE model is mapped to its corresponding households in the 2010/11 Household Consumption Expenditure Survey (CSA, 2013). Changes in real consumption for each product are passed down from the CGE model to the survey. Total consumption for each household is then compared with the poverty line and their poverty status is updated. We calculated poverty using the official Ethiopian poverty line.

The agronomic benefits associated with technologies that are typically categorized as climate smart (and sustainable technologies in general) often take multiple years before their benefits come to fruition, as with the case of conservation agriculture in Africa (Giller *et al.*, 2009). To assess the temporal perspective of different technologies on economy-wide indicators we calculated the net present value of differences in GDP between T5 and T4 for different annual discount rates (0 to 20%) and time horizons (3, 6, 10, and 20 years) under no climate change. Lynam and Herdt (1989) suggest using a time horizon greater than 3 to 5 years but less than 20 years when assessing the sustainability of different agricultural production systems.

4 Results and Discussion

This section presents our assessment of how combinations of different technologies and climates affect economy-wide indicators in Ethiopia.

4.1 Crop model results and discussion

We compared our crop model results with existing data from published agronomic field studies (SI, Table S1). This comparison involved examining simulated (dssat) vs. observed (reported in agronomic field studies) yield effects associated with no-tillage, isfm, and fertilizer use. Overall, our simulated effects are conservative compared with results reported in field studies, although our effects fall within the range of plausible responses observed in the field (Supporting Information, Table S1).

Table 3 displays simulation results under no climate change and reports 1) average simulated crop yields, 2) stability of yields (calculated as the coefficient of variation), and 3) the average soil organic carbon (although multiple metrics for emissions exist, Supporting Information, SI8). Overall, crop yields follow agronomic logic, for example, applying extra fertilizer and irrigation boost yields. Using CSA also lifts simulated yields. An objective of CSA is to build resilience. One indicator of resilience includes the stability of yields, although many other indicators exist. Our results suggest that CSA can increase the stability of grain yields relative to baseline practices. In addition, CSA has a modest positive benefit on the carbon content of soil (the third objective of CSA). Yields varied by agro-climatic zone because each zone had different yield-defining, yield-limiting, and yield-reducing factors. For example, CSA had a larger positive effect on maize yields in the drought prone zones (such as Zone 1) compared with effects in the moisture-reliable zones.

[Insert Table 3]

We simulated the yield effects of each technology under climate change (SI, Tables S2 and S3). Overall, we saw similar responses of the technologies regardless of climate, i.e., CSA boosts yields relative to the baseline (T5 vs. T1) under climate change and for historical climate variability (Table 3). Under climate change country-wide maize yields slightly increased and wheat yields slightly decreased—relative to no climate change. The direction of these yield changes broadly concurs with similar studies (Jones and Thornton, 2003; Kassie *et al.*, 2015; Ramirez-Villegas and Challinor, 2012). The yield change is mainly because in East Africa the GFDL and HadGEM GCMs show increased rainfall and temperature by 2040–2069, relative to historical climate (Kihara *et al.*, 2015). Our results suggest the net interactive effect of rainfall and temperature is to increase average maize yields. Spatial heterogeneity in the simulated effect of the technologies both with and without climate change existed (Table 3 and SI Tables S2 and S3).

4.2 CGE model results and discussion

The crop models estimated the impact of each technology package on maize and wheat yields for 40 years of historical climate and future climate change. We now use the CGE model to estimate the effects of each of these yield changes on national GDP and household poverty (i.e., 8 technologies × 40 years of climate × 3 climate scenarios). We used historical crop yields from FAO (2017) for the period 1993 to 2015 to econometrically estimate the correlation between maize and wheat yields and the yields of other crops in the baseline scenario. The baseline includes the effects of climate variability on all crops' yields, but the simulated technologies only affect maize and wheat yields (relative to the baseline). Our study therefore accounts for underlying sector-wide climate variability, but isolates the impact of introducing new technologies for maize and wheat.

Ethiopian farmers generally have low rates of adoption of our CSA technologies and similar soil and water conservation technologies (Jirata *et al.*, 2016; Pender and Gebremedhin, 2008; Kassie *et al.*, 2010). Rather than simulate a 100 percent adoption of each technology, we assume that only a quarter of maize and wheat land adopts each technology in Table 2. This means that 25 percent of land converts from the baseline (T1) to the alternative technology (T2–T8). We document our reasoning for the 25 percent in our Supporting Information (SI9).

Table 4 reports the average absolute change in total GDP and the number of poor people relative to the baseline (T1). Introducing CSA practices without changing water or fertilizer use (T5 in column 4) on a quarter of maize and wheat land increases total GDP in Ethiopia by, on average, $146 million per year (all $ are US $). Of this, $129 million comes from an increase in agricultural GDP, and the rest is from other sections of the agri-food system (AFS). The expansion of the AFS, which includes downstream agricultural processing and trading, comes at the expense of other parts of the economy (i.e., the increase in AFS GDP slightly exceeds the increase in total GDP). This effect of the AFS on other sectors reflects land, labor, and other resource constraints, that cause trade-offs between different agricultural value chains, and between agriculture and the rest of the economy.

[Insert Table 4]

More than two-thirds of the extra agricultural GDP for Scenario T5 occurs within Zone 4 ($85 million out of a total $129 million). This occurrence reflects the large initial size of Zone 4's agricultural sector, as well as the concentration of maize and wheat production in this zone (Table 1). In contrast, agricultural GDP in Zone 3 falls slightly, because larger increases in cereal production in other zones crowd out Zone 3's supplies to national markets. Moreover, rising incomes in other regions are less likely to generate demand for the kinds of goods and services produced in Zone 3 (i.e., the zone specializes in agricultural products with low income elasticities).

Overall, the increase in total GDP benefits poor households. Introducing CSA practices in Scenario T5 reduces the absolute number of people below the poverty line by 366,900 relative to the baseline. Note that, while the average GDP gain would accumulate every year, the poverty reduction, as reported, is a level effect (i.e., there are 366,900 fewer people each year experiencing poverty). The change in poverty is equivalent to approximately one person for every additional 2.5 hectares of maize and wheat land cultivated using CSA practices. Similarly, the GDP gain translates into an extra $162 per hectare in gross value of production, which represents a large increase over an initial gross value of production of $428 per hectare. CSA practices generate sizable economic benefits, particularly for farmers, but also for nonfarm in the AFS workers and for consumers in both rural and urban areas.

One alternative to CSA is to apply more fertilizer to maize and wheat land. Scenario T2 (column 2 in Table 4) doubles fertilizer application rates instead of introducing CSA practices. The impacts on total GDP and poverty are much smaller than in the CSA scenario (T5). Total GDP increases by only $25 million per year and the number of poor people falls by 61,700—the latter is equivalent to one person assisted to move above the poverty line for every ten hectares of maize and wheat land using double the quantity of fertilizer. The benefits of CSA would therefore appear to greatly outweigh the benefits from increased fertilizer use. However, our simulations exclude the cost to the public sector to incentivize either the adoption of CSA practices or expanding irrigation potential or fertilizer rates. Our simulations also exclude changes in private costs associated with switching from the baseline. Using CSA either increases or decreases labor costs depending on the specific CSA technology considered, for example, no-tillage can reduce labor demands but isfm can increases labor demands, mainly through greater time required to collect, store, and spread livestock manure. The provision of extension services might be far costlier per hectare (for the public sector) than the policies (for example, subsidies) needed to increase fertilizer use. However, our findings indicate that the CSA scenario (T5) would need to cost 4 to 5 times more than the fertilizer scenario (T2) for the two scenarios to generate similar economy-wide benefit-cost ratios (measured using either increase in total GDP or reduction in poor people).

The remaining scenarios indicate that using irrigation without CSA (T3) generates larger economic benefits than using more fertilizer without CSA (T2). There are some synergies from combining fertilizer and irrigation (T4), although these synergies are modest and insufficient to surpass the gains from using CSA alone (T5). As shown in Table 4, the GDP gain in Scenario T4 of $95 million per year is only slightly larger than the sum of T2's gain of $25 million and T3's gain of $62 million, and it is well below T5's gain of $146 million. Finally, economic benefits are larger when CSA practices are combined with other technologies, although the relative importance of fertilizer and irrigation differs compared to the non-CSA scenarios. For instance, the GDP gains from combining CSA and fertilizer (T6) are much larger than the gains from combining CSA and irrigation (T7). Overall, combining CSA, irrigation, and greater fertilizer use (T8) leads to the larger GDP gains and reductions in poverty, although CSA remains the dominant source of these benefits.

As mentioned earlier, the second objective of CSA is to enhance a country's resilience to climate stressors. Figure 3 shows the distribution of changes in total GDP per year (top panel) and poor population (bottom panel) across the 40 years of randomly drawn historical climate events (relative to the baseline). The figure uses box and whisker plots to represent the shape of the distribution – the box indicates the middle two quartiles (20 of the randomly drawn climate years) and the whiskers indicate the upper and lower quartiles (10 years each). The line dividing the box shows the median and the cross shows the average.

[Insert Figure 3]

Four results in the figure need highlighting. First, climate variability causes variation in year-on-year indicators in all scenarios. No technology can fully eliminate the adverse effects of climate variability. Second, GDP rises and poverty falls in all but one out of 320 technology/climate permutations, indicating that almost all the technologies simulated add to the economy's resilience to climate shocks. Third, using only CSA practices (T5) leads to higher GDP and lower poverty than simply doubling fertilizer rates (T2). The smallest GDP gain in the T5 Scenario ($111 million) is more than twice the largest GDP gain in the T2 Scenario ($52 million). Finally, the CSA-only scenario (T5) lead to greater

GDP variability (i.e., the range of GDPs is wider in T5 than in T2), along with increasing GDP by more than only doubling fertilizer rates (T2). We find the result even more pronounced for poverty numbers. If resilience is defined by a sustained increase in GDP or a reduction in poverty relative to the baseline, then CSA unambiguously enhances resilience.

Finally, we consider the impact of climate change. We do not "age" the economy to match the climate change projections. As such, the thought experiment for the final set of scenarios asks what the economic impact of climate change would be if the changes to the climate system that are projected for mid-century happened in today's economy (over and above historical climate variability). We simulate a shift in the average climate using two GCMs with no change in the variability of climate (Supporting Information, SI4). Table 5 reports changes in total GDP and the poor population relative to the baseline, which we benchmarked to a historical sequence of climate years. Columns 1 and 3 in Table 5 replicate the total GDP results from Table 4.

[Insert Table 5]

Results suggest that under climate change we have higher GDP and less poverty than under historical climate conditions, connected to the overall increase in maize yields (maize had greater production than wheat). The GDP gains from using CSA only (T5) averaged $146 million per year under current climate conditions, but rise annually to $160 million in the GFDL GCM and $149 million in the HadGEM GCM. Including climate change leaves our earlier conclusions unchanged; i.e., with or without climate change gives the same ranking of each technology's contribution to GDP or poverty reduction. Climate change therefore further strengthens calls to apply CSA technologies in cereal systems, although gains are still largest when the model combined CSA with other technologies. We conclude that our findings are robust to the two climate change scenarios we considered, although uncertainties always exist in modelling studies (Supporting Information, SI2).

5 Conclusion

We studied the economy-wide effects of using CSA and traditional input-intensive technologies in cereal systems in Ethiopia for different climates. To generate our results, we used an integrated modelling approach based on a series of models calibrated to baseline economic and biophysical data. Using modest adoption rates, results suggest that CSA has the potential to lift GDP by, on average, $146 million annually and assist 367,000 people to move above the national poverty line, which exceeds gains from an input-intensive approach, with gains greater under climate change relative to past climate. To strengthen policy dialogues, additional information on costs to convert land to CSA or more input-intensive technologies are required. Economy-wide estimates will no doubt strengthen if we captured changes in the private costs to farmers from adopting different technologies, as discussed in our Supporting Information (SI7). Studies such as ours help add evidence for making agriculture investments because we compared a baseline with both CSA and traditional input-intensive technologies. Our study provides evidence of the gains associated with a range of alternative investments, which can be challenging to capture using other methods such as randomized controlled trials.

SI: Supporting Information

Supporting information related to this study are in the online file "Ethiopiacsacge_si_icae.docx" available here: https://www.dropbox.com/s/z01r5icp9jgi6i1/Ethiopiacsacge_si_icae.docx?dl=0

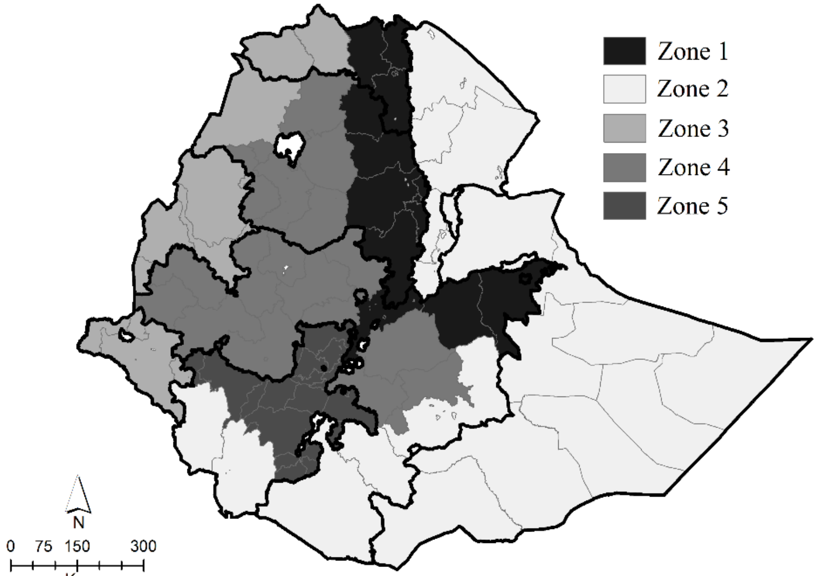
Tables and Figures

Table 1. Structure of the Ethiopian Economy in 2010/11

	National	Rural Zone 1	Rural Zone 2	Rural Zone 3	Rural Zone 4	Rural Zone 5	Urban Centers
Population (million)	76.3	15.2	7.5	4.4	25.7	11.5	12.0
GDP per capita ($)	360.4	317.5	373.4	390.6	327.1	317.1	507.9
Consumption per capita ($)	322.9	289.1	332.2	350.6	299.4	286.1	434.9
Food share (%)	54.1	55.6	65.8	53.0	53.4	58.1	46.3
Cereals share (%)	14.9	19.6	10.5	13.9	17.6	10.9	11.6
Poor population (million)	22.6	3.9	2.2	0.9	8.2	4.0	3.3
Poverty headcount rate (%)	29.7	26.0	30.1	19.6	32.1	34.8	27.9
Share of national GDP (%)	100.0	17.5	10.1	6.3	30.6	13.2	22.2
Agriculture GDP	100.0	23.7	8.9	6.0	45.3	16.0	0.0
Share of regional GDP (%)	100	100	100	100	100	100	100
Agriculture	41.7	56.5	36.7	39.7	61.8	50.5	0.0
Crops	30.4	37.4	19.5	29.6	48.0	40.5	0.0
Maize	2.6	1.6	1.8	2.0	5.5	2.3	0.0
Wheat	2.9	3.2	0.6	0.0	6.6	1.8	0.0
Livestock, forestry	7.9	14.7	12.3	4.9	9.0	7.5	0.0
Industry	11.5	12.4	11.0	9.9	4.1	1.9	27.4
Services	46.8	31.1	52.4	50.4	34.0	47.5	72.6

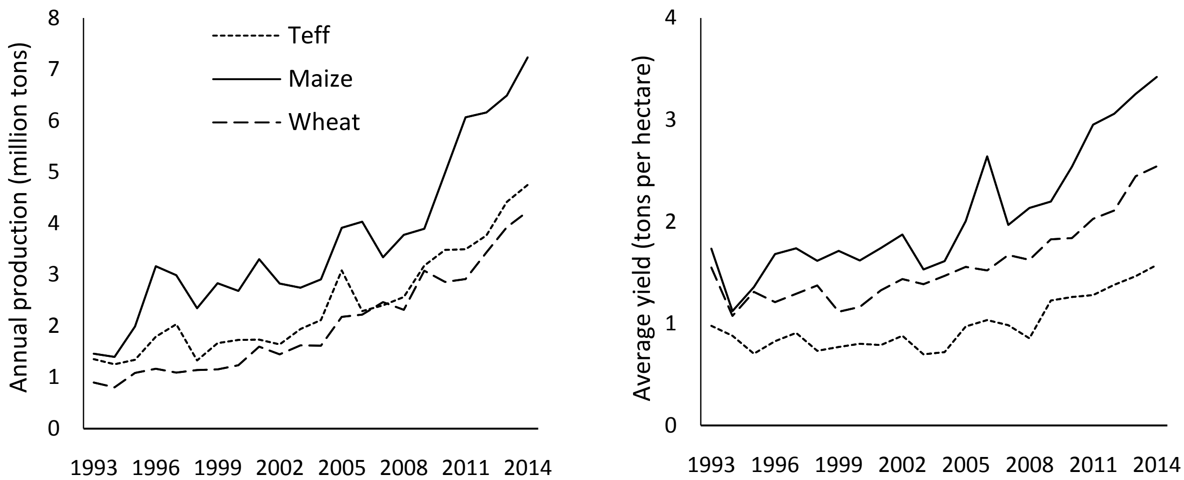
Source: Ethiopia 2010/11 CGE model (Ahmed *et al.*, 2017).
Notes: GDP is gross domestic product measured at factor cost and in 2010/11 dollars (unadjusted for purchasing power differences across countries). Poverty headcount rate is the share of population with consumption below the official national poverty line.

Figure 1. Ethiopia's Agro-Climatic Zones



Source: Schmidt and Thomas (2017)

Figure 2. Historical Yields and Production for Major Cereals in Ethiopia, 1993-2014



Source: FAO (2017).

Table 2. Technology Packages simulated

Technology package	CSA practices	Crop water source	Fertilizer application rate
T1	No	Rainfed	Baseline
T2	No	Rainfed	Double
T3	No	Irrigated	Baseline
T4	No	Irrigated	Double
T5	Yes	Rainfed	Baseline
T6	Yes	Rainfed	Double
T7	Yes	Irrigated	Baseline
T8	Yes	Irrigated	Double

Source: authors' design. Double refers to double the Baseline rate. All scenarios run for three climates.

Table 3: Simulated Grain Yields and their Variability under no Climate Change.

	Simulated technology packages							
	(T1)	(T2)	(T3)	(T4)	(T5)	(T6)	(T7)	(T8)
CSA practices?	*No*	*No*	*No*	*No*	*Yes*	*Yes*	*Yes*	*Yes*
Water source	*Rainfed*	*Rainfed*	*Irrigated*	*Irrigated*	*Rainfed*	*Rainfed*	*Irrigated*	*Irrigated*
Fertilizer application	*Baseline*	*Double*	*Baseline*	*Double*	*Baseline*	*Double*	*Baseline*	*Double*
Average yield (t ha^{-1})								
Maize Zone 1	2.09	2.17	2.98	3.19	3.72	3.93	4.16	4.45
Zone 2	2.17	2.42	2.57	2.93	2.98	3.38	3.06	3.46
Zone 3	2.43	2.61	2.67	2.85	2.78	2.97	2.69	2.87
Zone 4	2.42	2.72	2.91	3.28	3.51	3.89	3.48	3.87
Zone 5	1.85	1.9	2.78	2.94	2.68	2.75	2.85	2.96
Wheat Zone 1	1.43	1.49	1.64	1.73	1.91	1.95	1.92	1.97
Zone 2	1.29	1.32	1.57	1.61	1.78	1.79	1.87	1.88
Zone 3	1.32	1.38	1.53	1.6	1.61	1.68	1.65	1.72
Zone 4	1.58	1.62	1.76	1.81	2.09	2.11	2.11	2.15
Zone 5	1.38	1.42	1.5	1.54	2.1	2.11	2.1	2.12
Coefficient of variation								
Maize Zone 1	0.22	0.21	0.3	0.27	0.16	0.14	0.21	0.19
Zone 2	0.17	0.14	0.24	0.18	0.16	0.12	0.18	0.14
Zone 3	0.26	0.22	0.28	0.24	0.25	0.22	0.27	0.24
Zone 4	0.29	0.25	0.4	0.34	0.25	0.22	0.29	0.25
Zone 5	0.19	0.19	0.18	0.14	0.13	0.12	0.16	0.13
Wheat Zone 1	0.13	0.11	0.14	0.1	0.09	0.08	0.1	0.08
Zone 2	0.13	0.13	0.11	0.09	0.1	0.1	0.08	0.08
Zone 3	0.13	0.12	0.1	0.07	0.1	0.08	0.09	0.07
Zone 4	0.06	0.05	0.07	0.05	0.05	0.04	0.05	0.04
Zone 5	0.08	0.06	0.08	0.06	0.05	0.05	0.06	0.06
Soil organic carbon content (t ha^{-1})								
Maize Zone 1	146	146	136	136	149	150	141	141
Zone 2	114	114	108	109	117	118	114	115
Zone 3	112	112	105	105	113	113	108	109
Zone 4	139	140	130	130	141	142	134	135
Zone 5	124	124	114	114	125	125	118	119
Wheat Zone 1	142	138	130	130	141	140	132	132
Zone 2	128	128	122	122	129	129	125	125
Zone 3	120	117	113	113	121	119	115	115
Zone 4	136	135	129	129	138	137	132	132
Zone 5	145	145	139	139	148	149	144	144

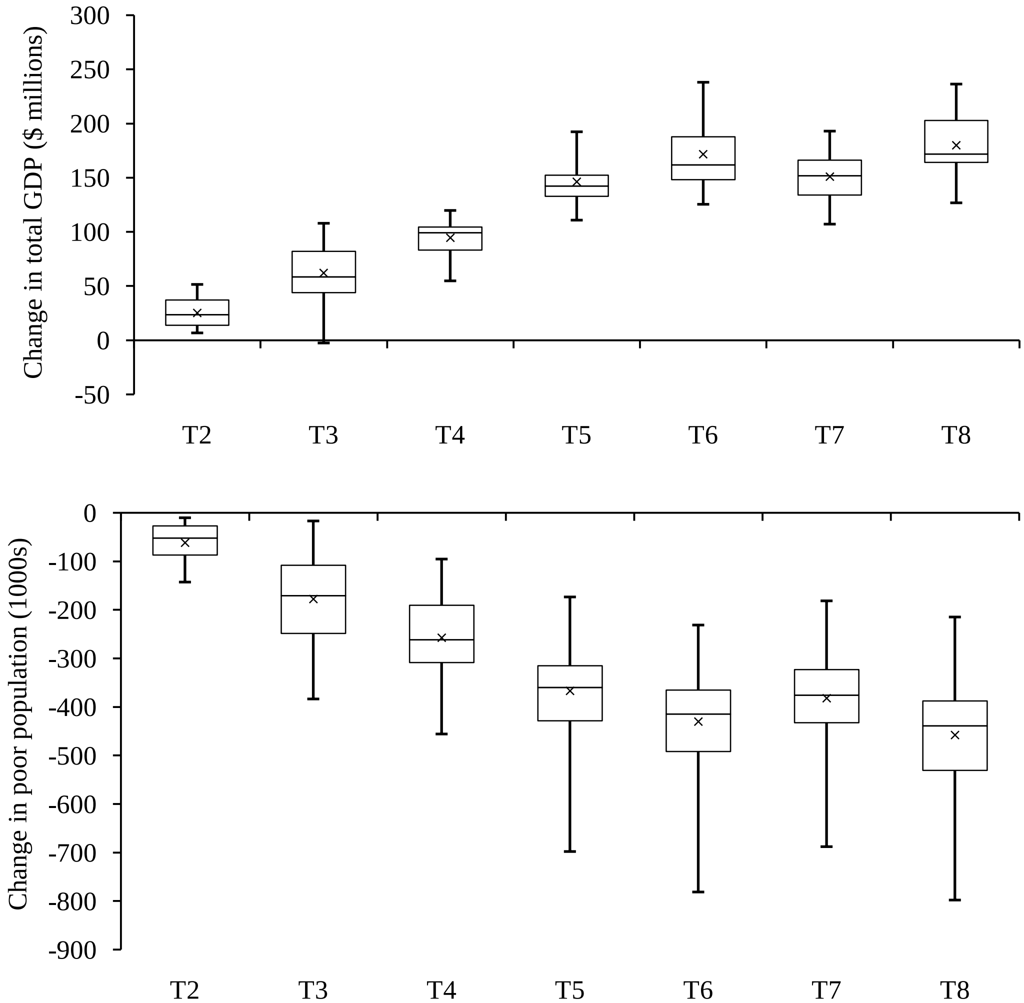
Source: authors' calculations. Notes: Average is the area-weighted zone average across the 40 years. CV is the coefficient of variation, calculated as the standard deviation over 40 years divided by average over 40 years. Yields for climate change simulations in SI Tables S2 and S3. Baseline fertilizer is historical mineral fertilizer. CSA is climate-smart agriculture, and represents the maximum yield for no-tillage and integrated soil fertility management. The zones include the (i) drought-prone highlands (Zone 1); (ii) drought-prone and pastoralist lowlands (Zone 2); (iii) humid moisture reliable, lowland (Zone 3); moisture-reliable highlands growing cereals (Zone 4); and moisture-reliable highlands growing enset (Zone 5).

Table 4. Estimated GDP and Poverty Impacts under Current Climate Conditions

	Average absolute annual change in GDP (dollars) or poor population (people) under new technology packages relative to the baseline technology package (T1)						
	(T2)	(T3)	(T4)	(T5)	(T6)	(T7)	(T8)
CSA practices?	*No*	*No*	*No*	*Yes*	*Yes*	*Yes*	*Yes*
Water source	*Rainfed*	*Irrigated*	*Irrigated*	*Rainfed*	*Rainfed*	*Irrigated*	*Irrigated*
Fertilizer application	*Double*	*Baseline*	*Double*	*Baseline*	*Double*	*Baseline*	*Double*
Total GDP ($ millions)	25.1	62.1	94.5	146.1	171.5	150.9	179.9
Agri-food system GDP	24.6	62.5	94.3	146.5	171.3	151.4	179.8
Agriculture GDP	21.1	54.8	82.1	128.5	149.7	133.0	157.3
Rural Zone 1	1.9	12.2	15.8	26.2	28.2	30.6	34.3
Rural Zone 2	1.3	1.4	3.2	3.4	5.4	3.9	5.8
Rural Zone 3	0.4	−0.4	−0.2	−0.7	−0.5	−1.2	−1.1
Rural Zone 4	17.2	31.0	51.4	85.3	102.8	83.6	102.4
Rural Zone 5	0.3	10.7	12.0	14.3	13.8	16.1	15.9
Total GDP / hectare ($)	27.9	69.0	104.9	162.4	190.6	167.6	199.9
Agriculture GDP	23.4	60.9	91.3	142.8	166.3	147.7	174.8
Poor population (1000)	−61.7	−177.5	−257.4	−366.9	−430.0	−381.8	−457.9
Per hectare (people)	−0.1	−0.2	−0.3	−0.4	−0.5	−0.4	−0.5

Source: Authors' calculations using Ethiopia 2010/11 CGE model.
Notes: Baseline technology package (T1) is rainfed maize and wheat cropping with unchanged fertilizer application and no adoption of CSA practices. Average annual changes are the average across 40 years of historical climate. Doubling of fertilizer application is relative to baseline rates. CSA is climate-smart agriculture, and represents the maximum yield for no-tillage and integrated soil fertility management.

Figure 3. Variation in GDP and Poverty Impact Estimates Under Current Climate Conditions



Source: Authors' calculations using Ethiopia 2010/11 CGE model.
Notes: Baseline technology package (T1) is rainfed maize and wheat cropping with unchanged fertilizer application and no adoption of CSA practices. T2–T8 defined in Table 2.

Table 5. GDP and Poverty Impact Estimates Under Different Climate Change Scenarios

Technology package	Average absolute annual change in GDP (million US dollars)			Average absolute annual change in poor population (000 people)		
	Current	GFDL	HadGEM	Current	GFDL	HadGEM
T1	0.0	13.3	3.6	0.0	-46.2	-22.3
T2	25.1	40.8	30.0	-61.7	-114.0	-92.9
T3	62.1	69.4	58.3	-177.5	-200.5	-177.8
T4	94.5	101.4	88.7	-257.4	-278.6	-252.3
T5	146.1	159.9	149.3	-366.9	-417.2	-397.5
T6	171.5	188.2	177.3	-430.0	-486.1	-467.6
T7	150.9	161.6	149.7	-381.8	-420.4	-397.1
T8	179.9	192.6	180.3	-457.9	-499.0	-480.1

Source: Authors' calculations using Ethiopia 2010/11 CGE model.

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