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ORIGINAL ARTICLE

Economywide effects of climate-smart agriculture in Ethiopia

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Abstract

Climate-smart agriculture (CSA) is an approach for transforming and reorienting agricultural systems to support food security under climate change. Few studies, however, quantify at the national scale CSA's economic effects or compare CSA to input-intensive technologies, like fertilizer or irrigation. Such quantification may help with priority setting among competing agricultural investment options. Our study uses an integrated biophysical and economic modeling approach to quantify and contrast the economywide effects of CSA (integrated soil fertility management in our study) and input-intensive technologies in Ethiopia's cereal systems. We simulate impacts for 20-year sequences of variable weather, with and without climate change. Results indicate that adopting CSA on 25% of Ethiopia's maize and wheat land increases annual gross domestic product (GDP) by an average 0.18% (US$49.8 million) and reduces the national poverty rate by 0.15 percentage points (112,100 people). CSA is more effective than doubling fertilizer use on the same area, which increases GDP by US$33.0 million and assists 75,300 people out of poverty. CSA and fertilizer have some substitutability, but CSA and irrigation appear complementary. Although not a panacea for food security concerns, greater adoption of CSA in Ethiopia could deliver economic gains but would need substantial tailoring to farmer-specific contexts.

KEYWORDS
agri-food system, climate-smart agriculture, computable general equilibrium, economic growth, Ethiopia, poverty

JEL CLASSIFICATION
C68, O33, Q54

1 | INTRODUCTION

The effect of climate change on crop yields, incomes, and human health is generally expected to be adverse (Carleton & Hsiang, 2016), and this presents a looming challenge for hundreds of millions of people (Adesina, 2010). Sub-Saharan Africa is particularly vulnerable, because its agrarian countries are home to 44 million farming households who operate on less than 5 hectares of agricultural land (Samberg, Gerber, Ramankutty, Herrero, & West, 2016). Among the range of development options available, climate-smart agriculture (CSA) could help farmers and governments reorientate agricultural systems to support food security under climate change. CSA has three objectives: (a) improve agricultural

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The code and data required to replicate the results of this study are available online: http://doi.org/10.17632/ymfk792r6n.1.

productivity; (b) build resilience to climate change; and (c) reduce agriculture's greenhouse gas emissions (Lipper et al., 2014).[1] There are high expectations of CSA. The Global Alliance for Climate Smart Agriculture, for example, envisions 500 million farmers using CSA technologies by 2030 (Carraro, 2016), leading to substantial improvements in land sustainability and poverty alleviation.

Despite high expectations and ambitious goals, there is little quantitative evidence at scales beyond the farm household on (a) the economic benefits of CSA vis-a-vis traditional input-intensive technologies, or (b) CSA's potential contribution to achieving development goals, like poverty alleviation.[2] This study addresses these two points. The objective of our study is to quantify the economywide impacts of combinations of CSA and input-intensive technologies (mineral fertilizer and irrigation) for maize and wheat production across the diverse regions of Ethiopia for three climate sequences. We quantify crop yields, national gross domestic product (GDP), agri-food system (AFS) GDP, and household poverty. Our integrated modeling approach uses biophysical and economic models to assess the potential economywide impacts and trade-offs associated with CSA and input-intensive technologies. A crop model first simulates the yield gains from adopting combinations of CSA, fertilizer, or irrigation.[3] A spatially disaggregated computable general equilibrium (CGE) and microsimulation model then simulates the impact of these yield gains on the national economy and poverty. Ethiopia provides an ideal case study, because, like many African countries, it has historically relied on input-intensive technologies to promote agricultural development (Bachewe, Berhane, Minten, & Taffesse, 2018), but has started to allocate more resources to CSA within its national agricultural investment plans (Bachewe et al., 2018; Jirata, Grey, & Kilawe, 2016).

The CSA approach was first introduced in 2010 at the First Global Conference on Agriculture, Food Security and Climate Change, and because the approach is relatively recent its economywide effects remain understudied. Most economic studies on CSA are at the farm-household scale, and estimate the determinants of CSA adoption and its effect on crop yields (Arslan et al., 2015; Kassie, Zikhali, Pender, & Köhlin, 2010; Kato, Ringler, Yesuf, & Bryan, 2011; Shiferaw & Holden, 1998). Some studies examine the effect of CSA, and its variants, on household food security, income, or poverty (Abdulai, 2016; Cholo, Fleskens, Sietz, & Peerlings, 2019; Di Falco & Veronesi, 2013). The consensus is that CSA often improves farmers' food security and incomes. To support investment planning and priority setting, quantitative estimates of the benefits and trade-offs of CSA technologies are needed (Thornton et al., 2018), particularly at the national scale (Engel & Muller, 2016). Our economywide approach accounts for spillovers throughout and beyond the AFS (across agro-ecological zones); and we assess the opportunity costs of CSA by comparing it to input-intensive technologies.

Our study also quantifies CSA's contribution to national development. There are existing studies that assess the economywide effects of climate change on Ethiopian agriculture (Arndt, Robinson, & Willenbockel, 2011; Gebreegziabher, Stage, Mekonnen, & Alemu, 2016; Robinson, Willenbockel, & Strzepek, 2012; Yalew, 2016). Few of these, however, consider investment options in the context of climate change, despite quantifying how climate change affects economic indicators. One exception is Robinson et al. (2012), who compare the economywide benefits of expanding irrigation versus extending rural road networks. In contrast, we focus on investment options within agriculture, and unlike previous studies, we provide a more granular examination of crop technologies, some of which could help with mitigation and adaptation to climate change.

2 | CLIMATE AND AGRICULTURE IN ETHIOPIA

2.1 | Agriculture in the economy

Ethiopia's economy has much in common with other African economies. Eighty four percent of people live in rural areas and rely on agriculture for their livelihoods (Table 1). Agriculture accounts for 41.7% of national GDP and food accounts for 54.1% of total household consumption. This is consistent with Ethiopia's low GDP per person and high incidence of poverty. Cereal crops are especially important in Ethiopia, with maize and wheat together accounting for 5.5% of GDP and 14.9% of household consumption.

Ethiopia has a diverse range of agricultural production systems. To capture the diversity of agriculture, we separate Ethiopia into five agro-ecological zones defined mainly by elevation and annual rainfall (Schmidt & Thomas, 2018). Figure 1 shows the five zones: drought-prone highlands (Zone 1); drought-prone and pastoralist lowlands (Zone 2); humid moisture-reliable lowlands (Zone 3); moisture-reliable highlands growing cereals (Zone 4); and (5) moisture-reliable highlands growing enset (Zone 5). Zone 4 alone generates 45.3% of national agricultural GDP (Table 1) and is the largest producer of Ethiopia's dominant cereal crops: maize, wheat, teff, and barley. In contrast, Zone 3 has the smallest population

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[1] Section S1 in the Supporting Information discusses CSA and the words "technologies" and "resilience."

[2] The term "input-intensive technologies" captures "traditional" technologies or approaches to increasing yields (i.e., mineral fertilizer and irrigation). The term "input-intensive" primarily reflects technologies that use more physical resources, such as fertilizer or water, than technologies that are not "input intensive".

[3] Section S2 in the Supporting Information discusses the role of models in estimating crop yields, compared with other approaches.

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 people)	76.3	15.2	7.5	4.4	25.7	11.5	12.0
GDP per person (US$)	360.4	317.5	373.4	390.6	327.1	317.1	507.9
Consumption per person (US$)	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 people)	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
Maize production share (%)	100.0	10.7	7.1	5.0	65.3	11.8	0.0
Wheat production share (%)	100.0	19.7	2.0	0.0	70.0	8.2	0.0
Share of zone 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 and 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

Notes. GDP is gross domestic product calculated 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 describes each zone.
Source. Ethiopia 2010/11 CGE model (Ahmed et al., 2017).

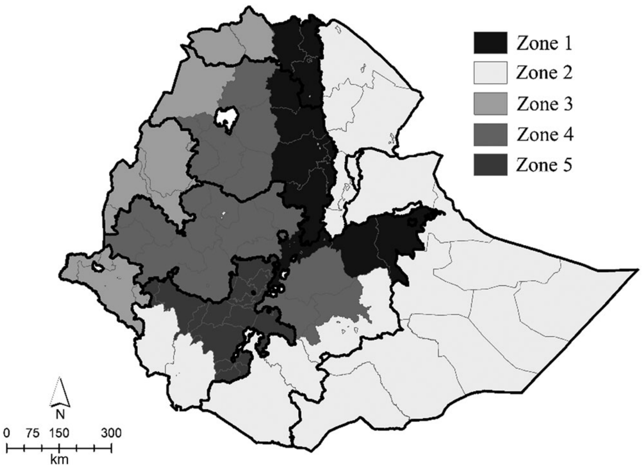

FIGURE 1 Ethiopia's agro-ecological zones
Notes. Zones: drought prone highland is Zone 1, drought prone lowland pastoral is Zone 2, humid moisture reliable lowland is Zone 3, moisture reliable highland-cereal is Zone 4, and moisture reliable highland-Enset is Zone 5.
Source. Schmidt and Thomas (2018).

and share of national GDP. Farmers in Zone 3 produce only 5% of national maize production and grow no wheat, even though cereals account for 13.9% of household consumption in the zone.

Agriculture's importance extends beyond the sector itself. Ethiopia's AFS includes downstream food processing, the production of farm inputs, and the trading and transporting of food and agricultural products. Together, the AFS generates 57.8% of national GDP and three-quarters of total employment (Benfica & Thurlow, 2017). Agricultural exports are Ethiopia's main source of foreign exchange (e.g., coffee and sesame), and so most of the economy depends, at least indirectly, on agriculture. Even urban households spend a large share of their incomes on food, especially cereals (Table 1).

Agriculture is a source of both economic growth and vulnerability. Data from FAO (2018) in Figure 2 show annual production and yield trends for maize, teff, and wheat.[4] Farmers in Ethiopia have raised yields and expanded production over the past decade, driven in part by greater adoption of fertilizers and the provision of farmer extension services (Bachewe et al., 2018; Spielman, Byerlee, Alemu, & Kelemework, 2010). The share of maize farmers using fertilizers, for example, rose from 20.9% in 2002 to 50.8% in 2014, and the share of maize farmers receiving visits from extension officers increased from 6.3% in 2002 to 52.1% in 2014 (CSO, 2002, 2014). Wheat farmers reported similar increases.

Positive yield and production trends hide year-on-year variability. Vast areas of Ethiopia frequently experience droughts and famine (Cavatassi, Lipper, & Narloch, 2011), and climate change introduces additional uncertainty for farmers (Jones

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[4] Figure S1 reports trends in annual area harvested.

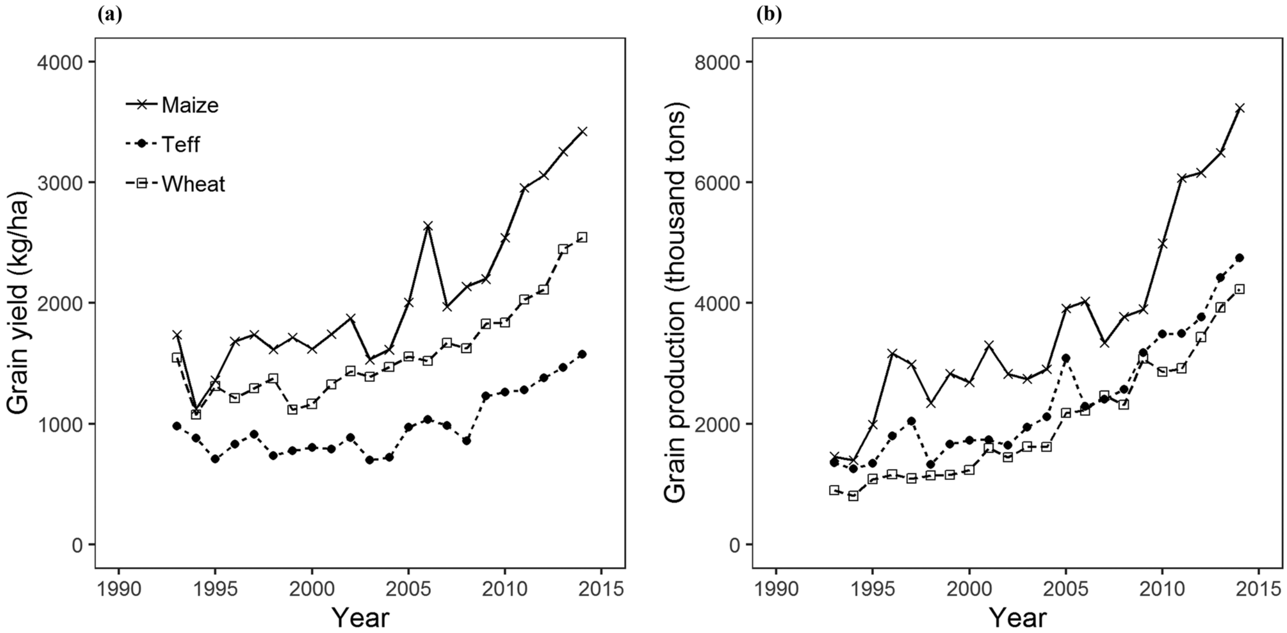

FIGURE 2 Maize, teff, and wheat yields (a) and production (b) in Ethiopia
Notes. Legend inside panel a applies to panel b.
Source. FAO (2018).

& Thornton, 2003; Kassie et al., 2015). CSA could help mitigate some of this variability or uncertainty. First, CSA could contribute to sustainably raising crop yields for poor farmers whose yields remain low compared to their potential, despite greater use of improved seed cultivars and fertilizer. Second, CSA could enhance the resilience of Ethiopia's cereal system to recurrent droughts and improve environmental sustainability through, for example, improved soil fertility and reduced soil erosion.

2.2 | Climate-smart agriculture

CSA is actively promoted to Ethiopian farmers (Jirata et al., 2016). We studied the technology of integrated soil fertility management (ISFM), a technology deemed climate smart (Lipper et al., 2014).[5] ISFM included retaining all crop residues in the field as a mulch and applying all available livestock manure to the field. Crop residues and manure are key organic inputs used in ISFM to improve crop yields (Vanlauwe et al., 2010). The CSA technologies, in general, contribute to CSA's third objective of reducing greenhouse gas emissions from agriculture.

ISFM is being promoted in Ethiopia (Bedada, Karltun, Lemenih, & Tolera, 2014), especially because Ethiopian cattle densities are among the world's highest (Robinson et al., 2014), and livestock manure can enhance soil fertility and hence crop yields. Potter, Ramankutty, Bennett, and Donner (2010) estimated that available nitrogen from manure in Ethiopia ranged from 0 to 104 kg nitrogen/ha. But, the share of manure excreted that becomes available for crop use is often low in Africa (Rufino et al., 2007). As such, our ISFM technology includes the more efficient and effective use of available manure in addition to retaining all crop residues in the field as a mulch. Farmers in Ethiopia typically use conventional tillage (Araya et al., 2016; Jirata et al., 2016) and all our simulations included tillage occurring, that is, the mechanical disturbance of soil occurred before crop sowing.[6]

3 | METHODS

3.1 | Technology and climate scenarios

We simulated eight technology packages for maize and wheat that include combinations of practices for CSA, fertilizer use, and crop water sources (T1–T8 in Table 2).[7] Our baseline technology is T1, which includes rainfed cropping (i.e., no irrigation) at historical fertilizer application rates (which are all positive quantities) and without using CSA technologies. Practices in the baseline technology include conventional tillage, crop residue removal, historical fertilizer application

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[5] Section S1 in the Supporting Information provides additional details on CSA, including its three objectives and the definition of ISFM.

[6] "Conventional" tillage refers to using tillage implements, such as the Maresha Plow, which, in general, mechanically disturb the soil unlike in no-tillage approaches.

[7] Section S3 in the Supporting Information discusses the role of teff in our study.

TABLE 2 Simulated technology packages

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

Notes. Double refers to double the baseline rate. In the baseline, a positive quantity of mineral fertilizer in kg/ha is applied in each of the five zones for both crops. All technologies simulated under three climates, based on the same random historical weather sequence: (a) historical baseline, and for climate change following the (b) Geophysical Fluid Dynamics Laboratory (GFDL-ESM2M) general circulation model (GCM), and the (c) HadGEM2-ES GCM.
Source. Authors' design.

rates, and applying no livestock manure as an organic fertilizer. Technologies T1–T4 exclude CSA technologies, but instead quantify the effects of doubling historical fertilizer application rates (T2), using irrigation (T3), and simultaneously doubling historical fertilizer application rates and using irrigation (T4). Ethiopian farmers irrigate only 1% of cropland—the rest is rainfed (You et al., 2017). The CSA technology refers to the use of ISFM. Technologies T5–T8 replicate the above fertilizer and irrigation combinations, but now, in addition, include CSA technologies.

We simulated each of the eight technology packages for three 20-year sequences of weather data. The baseline sequence is a randomly drawn weather pattern from the historical record (i.e., rainfall and temperature during the main cropping season).[8] The two climate change sequences used the same baseline weather patterns but overlay projected average changes in temperature and rainfall drawn from (a) the Geophysical Fluid Dynamics Laboratory (GFDL-ESM2M, hereafter GFDL) general circulation model (GCM); and (b) the HadGEM2-ES (hereafter HadGEM) GCM. For GCM selection, there are five GCMs that we have access to and contain the climate input data necessary for the crop modeling, and have been downscaled and bias corrected (Hempel, Frieler, Warszawski, Schewe, & Piontek, 2013): GFDL, HadGEM, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M. From these five GCMs, we selected GFDL and HadGEM because they reflect a range of projected temperature and rainfall outcomes by 2050 but are not outliers compared to other GCMs. For example, GFDL suggests cooler and drier weather in Ethiopia in 2050 compared to the other five GCMs, whereas HadGEM suggests warmer and wetter weather in 2050 in Ethiopia compared to the other five GCMs. Researchers often use these two GCMs in East Africa (Kihara et al., 2015). Our study therefore included 24 scenarios: eight technologies across three climates.

3.2 | Simulating crop yields

The Decision Support System for Agrotechnology Transfer (Jones et al., 2003) (DSSAT) is used to simulate maize and wheat yields for the eight technologies. Crop models, like DSSAT, simulate plant growth and its expected response to soil and weather conditions based on crop physiology, soil science, and meteorology.[9] We calibrated crop model parameters to gridded data on maize and wheat production (at a 5 arc-min spatial resolution) with soil inputs from Han, Ines, and Koo (2015).[10] We drew information on prevailing crop management from multiple sources (Abate et al., 2015; Potter et al., 2010; Robinson et al., 2015), including data on practices, such as tillage, crop residue management, and inputs (e.g., seed cultivars, mineral and organic fertilizer, pesticides, and crop water source).

The crop model simulated maize and wheat yields for each of the 24 scenarios in every grid cell where You et al. (2017) report the crop being harvested. Our scenarios included expanding irrigation and fertilizer use. We designed crop management in DSSAT to reflect local contexts, subject to data availability. For example, we used zone-scale manure application rates, as observed in Potter et al. (2010). Manure rates (kg nitrogen/ha) in the CSA technologies 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). Baseline fertilizer application rates were guided by data available in Abate et al. (2015) and were 20 kg nitrogen/ha for both crops. Maize was grown with a short maturity improved cultivar and wheat was grown with the Kubsa improved cultivar. Maize and wheat were grown as a monoculture.

We calibrated DSSAT by adjusting model parameters so that average crop yields for the baseline technology in each zone over the 20-year no climate change sequence mimicked the yields in You et al. (2017) for the same crops and zones under comparable management practices. Model evaluation involved two steps. First, we assessed how simulated zone-scale yields from the calibrated DSSAT model compared with the yields reported in You et al. (2017). Comparisons considered three statistics: average yields, mean absolute error, and normalized root mean square error. This assessment was based on the 20-year simulation sequence for the baseline

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[8] Section S4 in the Supporting Information provides more details on the three 20-year sequences.

[9] Figure S2 provides a schematic of DSSAT.

[10] Section S5 in the Supporting Information describes the soil data.

technology package under no climate change and for each crop and zone. Second, we compared simulated yields with yields reported in agronomic field trials from Ethiopia for practices relevant to our study, including mineral fertilizer and CSA technologies. We therefore evaluated the model's ability to mimic the baseline technology and capture the observed treatment effects of different practices.

The baseline included no CSA technologies. For simulating irrigation, DSSAT computed the available water capacity of the soil each day throughout the growing season. DSSAT triggered irrigation if available water capacity fell below 50% of field capacity and irrigation continued until available water capacity filled up back to 100% field capacity on the given day. This approach broadly follows water management by farmers in low-input cropping systems who regularly monitor soil moisture, and irrigation occurs once water available for plants falls below a specific threshold.

We ran DSSAT to generate simulated yields for the 24 scenarios. We calculated area-weighted average yields in each zone and yield variability in each grid cell. Each grid cell had a specific area of maize and wheat and we used these areas as weights to compute an area-weighted average yield at the zone scale in each simulation year. To consider resilience, we focused on "production" resilience by calculating the temporal stability of grain yields within a grid cell for each technology over the 20-year sequence of weather under no climate change, expressed as standard deviation divided by the average yield over the same years.[11]

3.3 | Simulating economywide effects

We simulated the economic impacts of the 24 scenarios using a static 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.[12] We used a static CGE model (Lofgren, Harris, & Robinson, 2002) to simulate the scenarios in Table 2. Supply-side changes, such as those caused by weather variability, lead to excess demand for the affected products, and supply-demand imbalances that the model then mediates through changes in prices in product and factor markets. Changes on the supply side that are large or affect large sectors in the economy generate economywide spillover effects. Maize and wheat are important production sectors and consumer products (Section 2), and changes to these crops' yields affect downstream sectors like grain milling and grain trade. Changes to farm incomes and consumer prices will also affect real consumption levels. The CGE model tracks changes in income distribution, allowing for an assessment of poverty impacts based on both income and price effects. Overall, CGE models are a helpful tool for capturing the direct and indirect effects of weather variability and for linking production to incomes and poverty.

The Ethiopian CGE model is calibrated to a 2010/11 social accounting matrix (Ahmed, Tebekew, & Thurlow, 2017). The model separated the national economy into 49 sectors and six subnational regions, that is, five rural agro-ecological zones and one region containing all urban areas. Producers in each sector and region combine intermediate and factor inputs (i.e., land, labor, and capital) to produce output that they then supply to national product markets. Producers can substitute between factors, albeit imperfectly, in response to changing factor prices. The model fixes total factor supply in each region, implying that cultivated cropland area is independent of crop yields. Land cannot be reallocated between crops in response to weather variability. Farmers can, however, reallocate labor between crops, livestock, and nonfarm activities, subject to a sector's technologies and the degree of factor substitutability. Within each region, we separate labor into three education-based categories, and capital into crop, livestock, mining, and "other" categories.

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 only the benefits of the technologies. The costs to adopt and maintain the technologies are an important part of CSA and would no doubt vary based on individual farmer contexts.[13] We used historical crop yields from FAO (2018) between 1993 and 2015 to generate correlation coefficients between maize and wheat yields and the yields of other crops in the baseline scenario. The baseline included the effects of weather variability on all crops' yields, but the simulated technologies only affected maize and wheat yields (relative to the baseline). We therefore isolated the economywide effects of different technologies for maize and wheat considering weather variability. Ethiopian farmers have low rates of adoption of our CSA technologies and similar soil and water conservation technologies (Jirata et al., 2016; Kassie et al., 2010; Pender & Gebremedhin, 2008). Instead of simulating 100% adoption for each technology in the CGE model, we simulated scenarios where 25% of maize and wheat land adopts each technology in Table 2.[14] Therefore, 25% of land in the CGE model converts from the baseline to T2–T8.

The model captures interactions with the rest of world, including imports and exports. The decision to supply foreign or domestic markets (or demand foreign or domestic goods) is determined by changes in relative prices. The ease at which producers and consumers can substitute between markets

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[11] Section S1 in the Supporting Information discusses the multiple dimensions of resilience.

[12] Tables S1 and S2 provide the model's variables and equations.

[13] Section S6 in the Supporting Information documents the scope of private adoption costs for farmers.

[14] Section S7 in the Supporting Information provides details on the justification for the 25% adoption rate, including for the irrigation technologies.

TABLE 3 Yield effects of each treatment from DSSAT and from agronomic trials

Data source	Crop	Treatment	Indicator	Minimum	Maximum	Average	Median	N
DSSAT	Maize	ISFM	% change in yield between ISFM and no ISFM	−31	44	8	8	
Agronomic trial	Maize	ISFM		–	–	–	–	–
DSSAT	Wheat	ISFM		−3	56	14	12	
Agronomic trial	Wheat	ISFM		−25	351	91	11	6
Adimassu et al. (2017)	All	ISFM	Change in yield between ISFM and no ISFM (kg/ha)	−959	3,917	739	494	83
DSSAT	Maize	ISFM		−362	689	158	126	
DSSAT	Wheat	ISFM		−7	544	179	165	
DSSAT	Maize	Mineral fertilizer	Nitrogen-use efficiency	31	142	71	65	
Agronomic trial	Maize	Mineral fertilizer		30	147	81	74	1
DSSAT	Wheat	Mineral fertilizer		6	128	53	50	
Agronomic trial	Wheat	Mineral fertilizer		6	44	22	20	2

Notes. Agronomic trial data for individual crop percent change exclude the aggregate data reported in Adimassu et al. (2017). ISFM denotes integrated soil fertility management. Nitrogen-use efficiency is kg grain harvest per kg mineral fertilizer applied in nitrogen form. Average is an unweighted average across all studies (for agronomic trials) and across all five agro-ecological zones and simulation years (from DSSAT) for no climate change. *N* is the number of studies. All studies consider rainfed agriculture in Ethiopia. Data from agronomic field trials are from peer-reviewed journal articles extracted from the Web of Science using the following search criteria on July 26, 2017, where TS denotes topic: (TS = [Ethiopia] and TS = [manure or fertilizer] and TS = [maize or wheat] and TS = [yield]) and language: (English) and document types: (Article).

depends on the magnitude of initial trade flows and elasticities of substitution. The latter are drawn from Dimaranan (2006). The model allows the economy to adapt to weather variability by increasing imports or reducing exports, but the real exchange rate will adjust to ensure equality between the total demand and supply of foreign exchange.

The CGE model separates households in each zone into expenditure quintiles. Households earn incomes based on their factor endowments, and spend these on consumption, taxes, and savings. Lower income households in rural areas tend to earn more of their income from farming and allocate a larger share of their budget to consuming agricultural and food products. The model includes subsistence incomes and consumption patterns. Urban households earn no farm income but rely on rural farmers for food.

All taxes on incomes and products are paid to the government, who combines these with foreign aid and borrowing to pay for public consumption and investment spending. Public and private savings are pooled and used to finance total investment. Total nominal investment and public and private consumption spending are in fixed proportions, implying that the damages from variations in weather are distributed throughout the macroeconomy.

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 Income and Consumption Survey (CSA, 2013). The CGE model passes down changes in real consumption for each product to the survey-based microsimulation model. The survey-based model then compares total consumption for each household to the poverty line and updates their poverty status. We reported changes in total GDP and the total number of poor people in Ethiopia. Poverty is calculated using the official Ethiopian poverty line (the national poverty headcount rate).

Finally, we examine how climate change affects the performance of different technologies in an economywide context. We did not age the economy to match climate change projections. As such, the scenarios under climate change ask what the economic effect of climate change may be if the changes to climate that researchers project for mid-century happened in today's economy (over and above historical weather variability).

4 | RESULTS

4.1 | Crop yield effects

To evaluate the yield effects estimated using our crop model, we compared them to agronomic field trial data. As shown in Table 3, our simulated yield effects were, on average, more conservative than those from field trials, but they fell within observed ranges. For example, our simulations indicated that ISFM increased grain yields by an average 169 kg/ha (range −362 to 689 kg/ha), whereas the field trials averaged 739 kg/ha (range −959 to 3,917 kg/ha). For the baseline

TABLE 4 Simulated grain yields under historical climate conditions

	Average yields for the eight technology packages (tons/ha)							
	T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**
CSA technologies?	*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*
Maize Zone 1	1.73	1.86	2.40	2.46	1.89	1.95	2.50	2.53
Zone 2	1.34	1.44	1.62	1.72	1.42	1.49	1.69	1.77
Zone 3	2.05	2.36	3.35	3.45	2.22	2.42	3.42	3.50
Zone 4	2.24	2.56	2.33	2.63	2.51	2.68	2.58	2.74
Zone 5	1.79	1.88	1.86	1.94	1.90	1.95	1.95	1.98
Wheat Zone 1	1.31	1.34	1.84	1.89	1.44	1.46	1.92	1.97
Zone 2	1.12	1.27	1.24	1.39	1.22	1.34	1.33	1.44
Zone 3	1.50	1.63	2.75	2.95	1.66	1.79	2.85	3.06
Zone 4	1.49	1.59	1.95	2.10	1.77	1.86	2.21	2.35
Zone 5	1.42	1.56	1.74	1.95	1.66	1.79	2.00	2.17

Notes. Area-weighted zonal averages across a 20-year sequence of variable weather. Tables S4 and S5 report yields under climate change. Baseline fertilizer is historical mineral fertilizer application rate. CSA is climate-smart agriculture. Figure 1 describes each zone. Table S6 reports the percentage changes.
Source. Authors' calculations.

technology with no climate change, our mean absolute error ranged from 41 to 581 kg/ha, with an average across zones, crops, and years of 171 kg/ha. Average simulated grain yields were 1,600 kg/ha compared with an average yield of 1,631 kg/ha from You et al. (2017). The normalized root mean square error ranged from 3% to 44% and averaged 13%. Grain yields have steadily increased over time in Ethiopia (Figure 2), and yields observed post-2011 exceed yields simulated in T1 because we calibrated our crop model against spatially disaggregated yield estimates from You et al. (2017) that has a baseline year of 2005.

Table 4 reports yield effects under a scenario of no climate change. Overall, crop yields followed agronomic logic, that is, applying more fertilizer or irrigation increased yields. Yields were always higher under CSA, independent of any changes in fertilizer or irrigation. When averaged across crops and zones, the T8 technology package that combines CSA with input-intensive technologies (i.e., doubling fertilizer rates and irrigation) had the greatest yield gains (relative to the baseline). Similar yield gains existed from combining CSA with irrigation (T7) and input-intensive technologies without CSA (i.e., T7 vs. T4). Irrigation with baseline fertilizer rates (T3) had a greater positive affect on yields than combining CSA with a doubling of fertilizer (T6) or using CSA with baseline fertilizer rates (T5). Finally, doubling fertilizer rates (T2) produced the smallest yield gain relative to the baseline.

The effect of technologies on yields varied across agro-ecological zones (Table 4). Yield gains for maize and wheat were smaller in the drought-prone zones than in the moisture-reliable zones. Moreover, although the largest yield gain in all zones came from combining CSA with input-intensive technologies, the source of the next largest yield gain differed across zones. Finally, CSA's effect on yields exceeded the effects of doubling fertilizer in two zones for maize and in three zones for wheat. Agro-ecological conditions are an important factor influencing the effectiveness of CSA, but the benefits of CSA are consistently positive in all zones.

For "production" resilience, our results suggested that CSA increases the stability of grain yields compared with the baseline technology (measured at the grid cell scale).[15] The average temporal coefficient of variation (CV) at the grid cell scale was lower in most zones and for most crops if CSA was used. Keeping the fertilizer rate and water source the same, adding CSA always decreased the CV. For example, for T5 versus T1 under no climate change, the reduction in CV averaged 6.32% across zones and crops, and for T7 versus T3 the reduction in CV averaged 8.22%.

We also simulated yield effects under climate change.[16] Overall, we found that responses to the different technologies were similar under baseline and climate change scenarios. For example, average yield gains from CSA were greater than yields in the baseline (T5 vs. T1) for both climate change and no climate change scenarios. National maize yields were slightly higher under climate change, and wheat yields were slightly lower (relative to no climate change).

4.2 | Economywide effects

The CGE model simulates the economic effects of the above estimated changes in maize and wheat yields. We impose yield changes on 25% of total maize and wheat land. Table 5 reports

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[15] Table S3 reports the CV for the simulated yields.

[16] Tables S4 and S5 report these yields.

TABLE 5 Estimated effect on GDP and poverty under historical climate conditions

	Average absolute annual change in GDP or poor population with technology packages relative to the baseline package (T1)						
	T2	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**
CSA technologies?	*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*
National GDP (million US$)	33.0	81.1	116.7	49.8	72.0	124.8	150.1
Agri-food system GDP	32.8	83.6	119.3	50.5	72.8	127.9	153.5
Agriculture GDP	28.7	75.6	107.0	45.1	64.8	115.0	137.6
Rural Zone 1	1.0	22.4	23.1	4.3	4.9	24.6	25.3
Rural Zone 2	0.6	2.2	3.0	0.2	0.9	2.3	3.1
Rural Zone 3	1.1	6.5	6.4	0.3	1.0	6.3	6.3
Rural Zone 4	24.5	42.2	70.1	37.5	54.0	76.6	96.4
Rural Zone 5	1.5	2.3	4.4	2.8	4.0	5.1	6.5
National GDP /hectare (US$)	36.7	90.1	129.7	55.3	80.0	138.7	166.8
Agriculture GDP	31.9	84.1	118.9	50.1	72.0	127.8	152.9
Poor population (thousand people)	−75.3	−189.6	−268.3	−112.1	−165.0	−284.7	−336.3

Notes. Baseline technology package (T1) is rainfed maize and wheat cropping with unchanged fertilizer application and no adoption of CSA technologies. Average annual changes are the average across the 20-year sequence of variable weather. Doubling of fertilizer application rate is relative to baseline rates. CSA is climate-smart agriculture. Figure 1 describes each zone. Table S7 reports the percentage changes in GDP.

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

average absolute changes in national GDP and in the number of poor people, relative to the baseline (T1) for no climate change. Introducing CSA technologies without changing fertilizer or crop water use (T5) increased national GDP per year by, on average, 49.8 million US$ (hereafter $), which is a 0.18% gain. Of this, $45.1 million came from an increase in agricultural GDP, with the rest coming from other sections of the AFS. Eighty three percent of the extra agricultural GDP from adopting T5 occurred within Zone 4 ($37.5 million out of a total $45 million). A doubling of fertilizer rates (T2) increased national GDP by $33.0 million per year (0.12%), which was less than the increase from adding CSA onto baseline fertilizer rates (T5). Using irrigation without CSA (T3) generated larger gains in national GDP than applying more fertilizer without CSA (T2). There were some synergies from combining fertilizer and irrigation (T4), as the gain in T4 exceeded the sum of the gains from T2 and T3. Economic benefits were greater if CSA was combined with input-intensive technologies, relative to adding CSA to baseline fertilizer rates. The largest economic benefits occurred by combining CSA with the input-intensive technologies, here different synergies appeared between technologies.

For synergies, the gains from using CSA bundled with other packages followed the same trend as the crop yield trends. Using CSA with baseline fertilizer rates produced a gain of $49.8 million compared to the baseline (T5 vs. T1).

Comparing the extra gains from combining technologies, the extra gain in national GDP from using CSA was greatest when CSA was applied to irrigated fields that had baseline fertilizer rates ($124.8 million in T7 and $81.1 million in T3, giving an extra gain of $43.7 million). Adding CSA onto irrigated fields with double the baseline fertilizer rates saw national GDP increase by $33.0 million (T8 minus T4). Adding CSA onto rainfed fields with double the baseline fertilizer rates saw national GDP increase by $39.0 million (T6 minus T2).

Overall, the increases in national GDP benefited poor households. The changes in poverty followed the pattern of changes in GDP, with the ranking of the changes in national GDP the same as the ranking of the changes in poverty, for example, T8 has the largest gain in national GDP and the largest fall in poverty and T5 had the sixth largest gain in national GDP and the sixth largest fall in poverty. Introducing CSA technologies in T5 reduced the number of people below the poverty line by 112,100, relative to the baseline. Although the average GDP gains accumulated every year, the poverty alleviation, as reported, is a level effect (i.e., 112,100 fewer people each year below the poverty line). Similarly, the national GDP gain translated into an extra $55.3/ha in gross value of production in T5. The initial national GDP/ha of arable land was $1,788/ha, calculated as national GDP divided by all arable land for all crops in Ethiopia in 2010/11.

For variability in the economywide indicators, Figure 3 shows the distribution of changes in national GDP per year (panel a) and poor population (panel b) for the different technologies across the 20-year sequence of historical climate (relative to the baseline technology T1). No technology eliminated the effects of weather variability. National GDP rose and poverty fell in all of 420 technology and climate

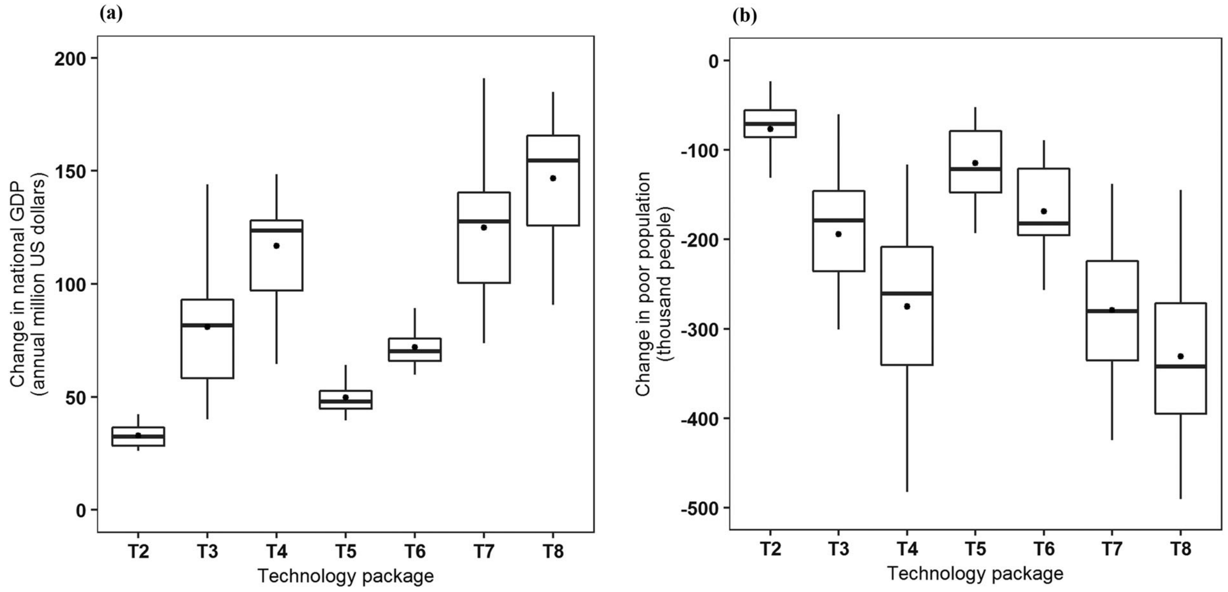

FIGURE 3 Boxplot for variation in national GDP and poverty effects under historical climate conditions

Notes. The baseline technology package (T1) is rainfed maize and wheat cropping with baseline fertilizer application rate and no adoption of CSA technologies. T2–T4 have no CSA technologies and T5–T8 have CSA technologies. T2, T5, and T6 are rainfed, and T3, T4, T7, and T8 are irrigated. T3, T5, and T7 have the baseline fertilizer application rate and T2, T4, T6, and T8 have double the baseline fertilizer application rate. Boxes indicate the middle two quartiles and the whiskers indicate the upper and lower quartiles. The line dividing the boxes shows the median and the circle shows the average.

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

TABLE 6 Effect on GDP and poverty for three climate scenarios

Technology package	Average absolute annual change in GDP (million US dollars)			Average absolute annual change in poor population (thousand people)		
	Historical	**GFDL**	**HadGEM**	**Historical**	**GFDL**	**HadGEM**
T1	0.0	7.1	8.6	0.0	−12.4	−12.7
T2	33.0	38.8	39.7	−75.3	−82.7	−84.7
T3	81.1	81.0	80.1	−189.6	−192.7	−186.9
T4	116.7	113.5	111.5	−268.3	−264.8	−257.9
T5	49.8	55.7	56.6	−112.1	−123.4	−123.5
T6	72.0	77.4	77.8	−165.0	−175.3	−174.9
T7	124.8	121.4	119.2	−284.7	−280.1	−275.4
T8	150.1	145.0	142.1	−336.3	−321.9	−314.5

Notes. The baseline technology package (T1) is rainfed maize and wheat cropping with baseline fertilizer application rate and no adoption of CSA technologies. T2–T4 have no CSA technologies and T5–T8 have CSA technologies. T2, T5, and T6 are rainfed, and T3, T4, T7, and T8 are irrigated. T3, T5, and T7 have the baseline fertilizer application rate and T2, T4, T6, and T8 have double the baseline fertilizer application rate. Historical is based on historical sequence of climate years (Section S4 in the Supporting Information), GFDL is Geophysical Fluid Dynamics Laboratory (GFDL-ESM2M) general circulation model (GCM) and HadGEM is the HadGEM2-ES GCM. Table S8 reports the percentage changes in GDP and poverty.

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

combinations (7 technologies, 3 climates, and 20 years). Using CSA in combination with baseline fertilizer rates (T5) led to higher national GDP and lower poverty than doubling fertilizer rates (T2). The smallest gain in national GDP of $39.6 million over the 20-year weather sequence from using CSA in combination with baseline fertilizer rates (T5) was similar in magnitude to the largest GDP gain of $42.4 million from doubling fertilizer rates (T2).

Table 6 reports changes in national GDP and the poor population relative to the baseline with and without climate change. The columns labeled historical report the national GDP results from Table 5. The ranking of the technologies for how adoption of the technologies changed national GDP and poverty was the same with and without climate change, for example, T8 gave the largest increase in national GDP and poverty alleviation with and without climate change and T5 always gave the sixth largest gain regardless of the weather sequence used.

5 | DISCUSSION

Our integrated modeling approach coupled biophysical and economic models to simulate the economywide effects of crop technologies in Ethiopia with and without climate change. Our approach allowed us to disentangle some of the complexity involved in assessing the yield and economic effects of crop technologies at the national scale. A first step in coupling biophysical and economic models is an assessment of how the biophysical model simulates different technologies. Our comparison of the simulated crop model results against data from field trials suggested that our model was within the range of plausible responses of yields to different technologies. Our simulated increase in average yield from using ISFM was below the 739 kg/ha reported in Adimassu, Langan, Johnston, Mekuria, and Amede (2017); however, these authors' results are derived from a mixture of sources, including agronomic field trials, where manure was often applied in quantities that exceeded available farm manure resources. The quantity of manure in our ISFM technology aligned with manure production from reported livestock densities (Potter et al., 2010), but in the field trials manure quantities were generally unrelated to livestock densities, because they were experiments. For the effect of climate change on national yields, we found modest increases in maize yields and modest falls in wheat yields. The direction of these yield changes matched similar modeling studies (Jones & Thornton, 2003; Kassie et al., 2015; Ramirez-Villegas & Challinor, 2012). The direction of the change was 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). However, substantial uncertainty exists in future climate projections in East Africa, where, for example, a climate paradox implies that rainfall has declined in the past decades but may increase in the future (Souverijns, Thiery, Demuzere, & Lipzig, 2016). Our results suggested that average maize yields increased because of the net interactive effect of rainfall and temperature, among other factors.

Our results suggested that synergies existed among technologies, where yield gains were greater depending on the combination of technologies applied. We found some substitution effects between fertilizer and CSA and some complementarities between irrigation and CSA. Adding CSA gave less of a yield change if fields already had double the baseline fertilizer rate and were rainfed compared with adding CSA onto an already irrigated field at baseline fertilizer rates. Different technologies target different yield-limiting factors, with nutrient and water management being two factors that help address yield-limiting factors (Tittonell & Giller, 2013). Both CSA and fertilizer primarily alter nutrient availability as they alter soil fertility (mainly the nitrogen content of soil), and irrigation alters plant available water. Thus, CSA and irrigation (T7) addressed two different yield-limiting factors, but CSA and mineral fertilizer (T6), in general, both target the nutrient management part of yield-limiting factors. This finding connects to Von Liebig's agronomic principle of the law of the minimum (Wakeyo & Gardebroek, 2013), where sufficient water is needed to dissolve nutrients for roots to absorb the nutrients, and if water is too limiting, the nutrient management practices, such as CSA, may be less effective. The agronomic principles translated directly into the economic benefits, where gains in national GDP from adding CSA were greater when irrigation was used, and fertilizer rates remained unchanged compared with adding CSA onto fields with double fertilizer rates. Results implied diminishing returns to CSA if double the baseline fertilizer rate was applied. Because fertilizer rates have approximately doubled each decade for the past two decades (Bachewe et al., 2018; Spielman et al., 2010), a policy adjustment toward catalyzing the use of CSA appears worthwhile canvassing.

Looking beyond the agricultural sector and into the wider AFS, CSA technologies generated economic benefits, particularly for farmers, but also for nonfarm workers in the AFS and for consumers in both rural and urban areas. 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 national GDP). This effect of the AFS on other sectors reflects land, labor, and other resource constraints, which cause trade-offs between different agricultural value chains, and between agriculture and the rest of the economy.

Our study focused on the benefits of crop technologies. It is therefore only a partial assessment because we did not consider the cost to the public sector to create incentives for the adoption of CSA doubling fertilizer rates, or expanding irrigation potential. We expect the main public investment costs for CSA to be for agricultural extension programs: CSA uses on-farm resources, rather than external inputs, so therefore requires knowledge and learning of techniques and tailoring them to local contexts. Ethiopia has a history of supporting extension programs, with public investment in extension equaling 2% of agricultural GDP (Spielman et al., 2010). Doubling fertilizer application rates may require government subsidies, or more private sector involvement and reductions in trade costs. Irrigation expansion would involve substantial investment, maintenance, and operating costs of physical infrastructure. For example, You et al. (2011) estimated the investment cost of expanding irrigation in Ethiopia to range from $1,953/ha to $5,179/ha, depending on the type of irrigation. The availability of reliable data hinders calculating the public cost of catalyzing farmers to adopt the technologies. Our modeling also excluded changes in private costs associated with switching from the baseline.[17] Using CSA can either increase or decrease on-farm labor costs depending on the specific CSA technology considered. For example, ISFM can increase labor demands, mainly through greater time required for manure management. Independent of the actual public and private costs, differences between technology benefits provided suggestive evidence on the cost difference that would switch the rank of technologies. For example, the cost to implement the CSA technology in T5 would need to be $16.4 million ($49.8 million minus $33.0 million) per year more than the cost to double fertilizer application rates (T2) for the two options to generate similar net economic benefits.

Our study examined the changes in yields and economywide indicators for a range of technology and climate combinations. These changes provide an indication of the potential benefits of the technologies and provide insights for thinking about investment planning. By taking a mechanistic modeling approach using stylized representations of the technologies, our study disregarded much of the complexity that exists at the field and farm scale related to the uptake and suitability of the technologies. Substantial tailoring of the studied technologies to individual farmer contexts would be required and there is a need to develop policy options that address the trade-offs of technology use at the field and farm scale. For example, providing alternative sources of animal feeds, fuelwood, and construction materials may increase the attractiveness of crop residue retention, as would policies that reduce tensions between free grazing and crop residue retention. The technologies with irrigation provide an indication of the technology's potential if water is nonlimiting; however, additional analyses would be required to assess if the implied irrigation water demanded in a technology is available in a specific zone.

Including climate change leaves our earlier conclusions unchanged; that is, with or without climate change gives the same ranking of each technology's contribution to national GDP or poverty alleviation. Climate change therefore further strengthens calls to apply CSA in cereal systems, although gains still appear largest when CSA technologies were combined with input-intensive technologies. Our findings are similar with and without climate change, although uncertainties always exist in modeling open systems, such as the systems we studied.[18]

6 | CONCLUSION

We simulated the economywide effects of CSA and input-intensive technologies in cereal systems in Ethiopia for three climate sequences. Our integrated modeling approach was based on a series of models calibrated to baseline biophysical and economic data. We have three conclusions from our study. First, although CSA is not a silver-bullet solution for agricultural development or a panacea for concerns about farmer food security, it can provide economywide benefits. Using a 25% adoption rate for the crop technologies, results suggest that CSA has the potential to lift national GDP by, on average, $49.8 million annually and assist 112,100 people to move above the national poverty line. These economic benefits are greater than gains from a policy that doubles fertilizer rates, but the benefits are not as great as converting rainfed crops to irrigated crops. Overall, CSA appears a beneficial option to consider in agricultural investment plans that also has environmental benefits compared with more input-intensive technologies. But, our study only focused on the potential benefits of the technologies and understanding the costs underlying each technology is critical for investment planning and priority setting. Second, we found that the greatest gains from using CSA with other technologies occurred when irrigation was also used, as opposed to doubling fertilizer rates, or using irrigation and doubling fertilizer rates. CSA and fertilizer have some substitutability, but CSA and irrigation appeared complementary and using CSA and irrigation delivered positive interaction effects. Third, CSA is motivated as an approach to cope with the realities of climate change; however, CSA is also an option for today because the relative benefits of each technology were the same with and without climate change.

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[17] Section S6 in the Supporting Information also discusses private costs.

[18] As discussed in Section S2 in the Supporting Information.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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