CO_2 emissions, agricultural productivity and welfare in Ethiopia

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Abstract

Purpose – Climate change has become one of the most important development challenges worldwide. It affects various sectors, with agriculture the most vulnerable. In Ethiopia, climate change impacts are exacerbated due to the economy's heavy dependence on agriculture. The Ethiopian Government has started to implement its climate-resilient green economy (CRGE) strategy and reduce CO_2 emissions. Therefore, the purpose of this study is to examine the impact of CO_2 emission on agricultural productivity and household welfare.

Design/methodology/approach – This study aims to fill these significant research and knowledge gaps using a recursive dynamic computable general equilibrium model to investigate CO_2 emissions' impact on agricultural performance and household welfare.

Findings – The results indicate that CO_2 emissions negatively affect agricultural productivity and household welfare. Compared to the baseline, real agricultural gross domestic product is projected to be 4.5% lower in the 2020s under a no-CRGE scenario. Specifically, CO_2 emissions lead to a decrease in the production of traded and non-traded crops, but not livestock. Emissions also worsen the welfare of all segments of households, where the most vulnerable groups are the rural-poor households.

Originality/value – The debate in the area is not derived from a rigorous analysis and holistic economy-wide approach. Therefore, the paper fills this gap and is original by value and examines these issues methodically.

Keywords Welfare, Climate-resilient green economy (CRGE), Computable general equilibrium (CGE), CO_2 emissions

Paper type Research paper

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1. Introduction

The burden of climate change is real for poor countries. Climate-related risks are also projected to increase with global warming (IPCC, 2018). Studies based on cross-sectional data (e.g. Molua, 2002; Muamba and Kraybill, 2010; Di Falco *et al.*, 2011) reported a decline in crop yields due to climate change in agriculture-based economies. This implies devastating effects on developing economies that depend heavily on agriculture (Bezabih *et al.*, 2011; Zhai *et al.*, 2009). In Ethiopia, agriculture supports the livelihoods of the majority of people and provides 80% of employment (IMF, 2012). It generates about 90% of export revenues, supplies 70% of raw materials for domestic agro-industries and contributes 43% of the gross domestic product (GDP) (MoARD, 2010). In general, agriculture accounted for the lion's share in GDP, export, labor force and it also remains the most vital sector. Though it has a vast area of fertile land and a diverse climate, the sector is highly dependent on rainfall with a scanty share of irrigation while Ethiopia is the "water tower" of Africa. The agricultural land per household is also scanty, around 0.33 hector per household (Zerayehu *et al.*, 2016).

Consequently, any negative shock to the agricultural sector can cause devastating impacts on the whole economy. To reduce the risks from climate change, the government of Ethiopia has started the implementation of the climate-resilient green economy (CRGE) strategy for the period 2010–2030. This strategy is planned to foster development and sustainability while limiting GHG emissions to around a base year's 150 Mt CO_2 emissions [1], which is 250 Mt less in 2030 than the estimated 400 Mt CO_2 emissions under a conventional development path (FDRE, 2011). Among the pillars which the CRGE is based, the agricultural sector has received priority attention to improving crop and livestock production practices for attaining higher food security and income while reducing emissions. To this end, increasing agricultural productivity and farmers' welfare are considered as gear shifter instruments that lift up the performance of agriculture.

Therefore, investigating the impact of CO_2 emissions through productivity on agricultural performance and household welfare is crucially important to support decision-makers. First, it gives an insight into the significance of pursuing GHG emissions reduction policies, by indicating the direct impacts of GHG emissions on total factor productivity (TFP) in agriculture and on household welfare. Second, it helps measure the economic gains from the implementation of the CRGE strategy.

Despite the importance of the topic, there are limited empirical studies that explicitly examine CO_2 emissions' impact on agricultural productivity and household welfare. Most of the existing studies in Ethiopia (Mideksa, 2010; Arndt *et al.*, 2011; Robinson *et al.*, 2011; Gebreegziabher *et al.*, 2011; Ferede *et al.*, 2013) estimated the economic impacts of climate change using computable general equilibrium (CGE) analysis. These studies focused on examining the economy-wide impact of climate change, focusing on productivity, food security, income distribution and the role of adaptation. However, research studies on estimating the economic impacts of CO_2 emissions through agricultural productivity are limited in number and not rigorous in methods along with the framework of CRGE. Therefore, this study aims to examine the economy-wide impact of CO_2 emission in Ethiopia with a special focus on agricultural productivity and household welfare in line with CRGE using a dynamic CGE model.

The relationship between economic activities and emissions is complex, requires an economy-wide model. The level, extent and nature of economic activities affect the amount of GHG emissions, including CO_2 emissions (Pal *et al.*, 2011; Jones and Sands, 2013). In turn, the level of CO_2 emissions and its concentration affect the economy directly or indirectly by causing climate change. While some studies (for example, Pal *et al.*, 2011) have investigated the impact of economic activities on emissions, examinations the other way around are lacking.

Specifically, the study seeks to answer the key research questions: what is the impact of CO_2 emissions on the performance of the agriculture sector? Is there any significant relationship between households' welfare and CO_2 emissions? What are the projected trend of agricultural performance and household welfare if Ethiopia follows a development path with the CRGE strategy versus a conventional economic development path? To answer these questions, the study incorporated a CO_2 emission shock into the CGE framework in the context of the Ethiopian economy, through the variation in agricultural total factor productivity induced by the emissions. The variation in productivity is derived using the technical coefficient obtained from Solow's sectoral growth accounting approach (Solow, 1957) to link the CO_2 emission and factor productivity at a baseline.

2. Conceptualization of CO_2 emission and its effects

Productivity growth in agriculture is vital for the development of the sector and the whole economy in agriculture-dominated economies. Several studies in developing countries (such as Evenson *et al.*, 1999; Fan *et al.*, 1999; Pasha *et al.*, 2002; Bachewe, 2012) have used growth accounting analysis and reported that growth of TFP in agriculture has been the prime driving force behind overall economic growth. In Ethiopia, the growth in total agricultural production has been largely driven by expansion in grains production (Bachewe, 2012). This growth in agricultural production was caused by favorable weather conditions in main cereal-growing areas, enhanced government support to smallholder farmers, improvement in yields and expansion in the area under cultivation (IMF, 2012). In addition to this, the agricultural price has received great attention as it is a transmission mechanism for any shocks. Miodrag *et al.* (2016) in this regard examine the effect of climate change on agricultural productivity through higher food prices and find that climate change can have detrimental impacts on agricultural welfare. They also predict that global losses could increase substantially if international trade is more restricted.

Agriculture is a source of GHG and a sector that is vulnerable to such emissions (IPCC, 2007). According to the World Bank (2013), agriculture generates between one-fourth and one-third of global GHG emissions, from both on-farm activities (about 10%-12% of global emissions) and land-use and land-cover (LULC) change to cropland (an additional 12%-20%), as LULC changes from forest and pasture to croplands releases to soil and biomass carbon. GHG emission from agriculture is dominant in Ethiopia; for 2010, about 50% of Ethiopian GHG emissions are attributable to the agriculture sector, of which livestock accounts for the largest share, followed by crop production (FDRE, 2011). Livestock generates GHG emissions mainly in the form of methane emissions arising from digestion processes and nitrous oxide emissions arising from excretions. GHG emissions from livestock in Ethiopia were estimated at 65 Mt CO_2 equivalent in 2010 (FDRE, 2011).

Crop cultivation contributes to the concentration of GHG emissions mainly due to the use of modern fertilizer and N_2O emissions. GHG emissions in 2010 from fertilizer use and N_2O emissions from crop residues reintroduced into the soil were approximately 10 Mt CO_2 emissions and 3 Mt CO_2 emissions, respectively. These emissions can cause climate change (IPCC, 2007), which, in turn, may affect agricultural productivity. In addition to reducing agricultural productivity, especially in tropical regions, climate change directly affects poor people's livelihood and assets, including health, access to water and other natural resources, homes and infrastructure (World Bank, 2010).

Besides, the reduction of CO_2 does not only affect environmental impact but also it has a multidirectional distributional issue of social equity and poverty reduction across households. For instance, it is environmentally senseful to lessen GHG emissions from the livestock, which accounts for 40% in Ethiopia. However, it could be very challenging to shift from beef to poultry production in reality, as it has a substantial cost of social disturbance. This claims to conduct a rigorous analysis of environmental and social impact assessments to achieve both green and inclusive approaches (Steve *et al.*, 2013). Then, policy instruments such as high productivity and clean technology need to be designated to trigger green economic transformation by maximizing the synergies and minimizing trade-offs among CRGE strategies (ECA, 2015). On the other hand, CO_2 driven high temperature could lead to losses in labor productivity, and hence labor income (Yann *et al.*, 2019). They found that every trillion tons of CO_2 emitted could cause global GDP losses of about half a percent. A decrease in labor income makes the poor society to be highly vulnerable to various shocks and leave them in abysmal poverty (McGuigan *et al.*, 2002).

Several studies have applied partial, as well as general equilibrium approaches to estimate the economic impacts of climate change and variability at both sectoral and economy-wide levels. Using partial equilibrium analysis, Molua (2002), Muamba and Kraybill (2010), Di Falco *et al.* (2011) and Nkegbe and Kuunibe (2014) investigated the impact of climate change on agriculture and food security. Molua (2002) related farm-level income to precipitation change and estimated the significance of farmers' climate adaptation in Southern Cameroon using a Ricardian approach. Using a similar approach, Muamba and Kraybill (2010) estimated the livelihood impact of rainfall variation in the Mt. Kilimanjaro region of Tanzania. Nkegbe and Kuunibe (2014) also examined the impact of climate variability on household welfare in Ghana using trend equations and a Ricardian approach.

Edoja *et al.* (2016) also applied a time series econometrics to investigate the dynamic relationship among CO_2, agricultural productivity and food security over the period 1961 to 2010. The findings indicate that there exists a long-run relationship among them and unidirectional causality from CO_2 to food security. In the other study, Joo *et al.* (2015) find that there was no unidirectional causality from economic growth to energy consumption, from CO_2 emissions to energy consumption and from economic growth to CO_2 emissions. These results suggest that energy consumption can induce economic growth but not vice versa in Chile.

Valin *et al.* (2013) also examines the reverse effects of climate change on agricultural productivity using partial econometric analysis and also finds that closing yield gaps by 50% for crops and 25% for livestock by 2050 would decrease agriculture Ekpenyong and Ogbuagu (2015) also indicate the existence of a negative relationship between agricultural productivity and climate change and 100% increase in greenhouse emission will lead to 22.26% decline in AGP. Vasco *et al.* (2019) evaluate the effect of CO_2 on the growth performance, welfare and health of Atlantic salmon post-smolts and regressions showed that growth significantly decreased linearly with increasing CO_2. Frances *et al.* (2017) also find little evidence for differences in the yield response to warming and the magnitude of CO_2 fertilization is instead a much larger source of uncertainty.

The partial equilibrium analysis, however, fails to incorporate the economy-wide impacts of climate change due to general equilibrium feedback effects and interdependence among various sectors (Carri, 2008; Gebreegziabher *et al.*, 2011). As a result, there has been increasing use of CGE models in economy-wide climate change impact analysis. Thurlow *et al.* (2009) estimated the impacts of climate change on economic growth and poverty in Zambia. Zhai *et al.* (2009) also modeled the potential long-term impacts of global climate change on agricultural production and trade in China using an economy-wide and found that climate change would adversely affect global agricultural productivity up to 2080. Elshennawy *et al.* (2013) developed a multi-sectoral intertemporal general equilibrium model with forward-looking agents and simulated the effects of climate change on aggregate consumption, investment and welfare up to 2050 in Egypt. Pal *et al.* (2011) constructed an environmentally extended social accounting matrix (ESAM) and concluded the indirect impact of GHG emissions must be incorporated to understand the economy-wide impacts.

The results of partial equilibrium studies (Molua, 2002; Muamba and Kraybill, 2010; Nkegbe and Kuunibe, 2014) consistently reported negative impacts of climate change on agriculture through reductions in crop production, farm revenue and productivity and, as a result, reduced food security. Similarly, general equilibrium model analyzes (Thurlow *et al.*, 2009 for Zambia; Elshennawy *et al.*, 2013 for Egypt; Zhai *et al.*, 2009 for China) have indicated negative impacts of climate change and variability on the performance of the overall economy. These negative impacts of climate change on the economy become less intense as the share of agriculture in GDP declines (Zhai *et al.*, 2009). Adaptation measures could reduce the climate-induced loss in GDP (Elshennawy *et al.*, 2013).

In Ethiopia, Gebreegziabher *et al.* (2011) modeled the impacts of climate change on the overall economy using dynamic CGE modeling and simulated the impacts of climate change-induced variations in land productivity for the period 2010–2060. Amsalu *et al.* (2018) added different crop yield projections and add a regionalization to the country-wide CGE results and shown that climate change negatively influences country-wide GDP and make regional value-added GDP uneven. Robinson *et al.* (2011) also simulated the economic impacts of climate change up to 2050 and linked an Ethiopian multi-sectoral regionalized dynamic CGE model with a system of country-specific crops, hydrology, road and hydropower engineering models. Ferede *et al.* (2013) explicitly included different agro-ecological zones in estimating the short-run economic impacts of climate change, represented by changes in temperature and precipitation, using a CGE model.

Di Falco *et al.* (2011) indicated the negative impact of climate change on agriculture, whereas climate adaptation affects farm productivity positively. According to Gebreegziabher *et al.* (2011), the projected reduction in agricultural productivity may lead to 30% less average income, compared with the possible outcome in the absence of climate change. Robinson *et al.* (2011) also indicated that, without externally funded climate adaptation investments, Ethiopia's GDP in the 2040s will be up to 10% lower than under the counterfactual with a baseline of no climate change. Moreover, Ferede *et al.* (2013) reported negative effects of climate change on economic growth, production activities and household livelihoods.

3. Methodology

3.1 Data

This study uses the economy-wide detailed data set presented in the 2005/2006 Ethiopian social accounting matrix (SAM) developed by the Ethiopian Development Research Institute (EDRI, 2009). This data set represents the flow of economic resources and transactions among economic agents in 47 activities disaggregated into 14 agricultural, 19 industrials, 1 mining and 13 service sectors. There are also 93 commodities disaggregated into 25 agricultural, 27 industrials, 3 mining and 38 service sectors. Capital is also disaggregated into land for rural poor, land for rural non-poor, livestock for rural poor and livestock for rural non-poor and non-agricultural capital. Households are disaggregated into four groups, namely, rural poor, rural non-poor, urban poor and urban non-poor. The SAM also presents 17 tax accounts, as well as aggregated into direct tax, sales tax and tariff (EDRI, 2009).

In addition to the data detailed in the 2005/2006 SAM, this study also utilizes economy-wide data on variables, namely, CO_2 emissions, agricultural GDP, growth rates in agricultural labor, arable land and agricultural capital formation from the Central Statistics

Agency (CSA), World Bank and Ministry of Finance and Economic Development (MoFED) of Ethiopia. The study also uses the baseline estimated CO_2 emission level of the year 2010 as indicated in Ethiopia's CRGE strategy and take projected CO_2 with CRGE and without-CRGE scenarios for the period 2010–2030, assuming a constant growth rate. Then, these long-term time series data are used for simulation exercise to examine the impact of CO_2 emission-induced agricultural TFP on economy-wide performance using dynamic CGE modeling.

The description of the main variables used in this study is presented in Table 1.

3.2 Computable general equilibrium modeling and CO_2 emission shock transmission approach

The dynamic CGE model is calibrated to 2006 SAM that comprises a database that shows the flow of economic resources and transactions among economic agents (EDRI, 2009). In a CGE model, there are a set of supply- and demand-side equations. In supply-side models, producers are price takers in output and input markets and maximize profits using constant returns to scale technologies. Demands for the primary factors are derived from Constant Elasticity of Substitution (CES) value-added functions, whereas the demand for intermediate inputs by commodity group is determined by a Leontief fixed-coefficient technology (Robinson *et al.*, 2011). Producers' decisions between production for domestic and international markets are governed by the constant elasticity of transformation functions. Ethiopia faces perfectly elastic world demand curves for its exports at fixed world prices under the small country assumption. Relative prices for import and export commodities are used to determine the profit-maximizing equilibrium ratio of exports to domestic goods in any traded commodity group.

The study uses the dynamic CGE model based on SAM 2006 due to the following advantages and reasons. The dynamic CGE model considers the entire economy in the sense of general equilibrium and enables a comparison of the benchmark and counterfactual policy scenarios. It also runs a simulation for economy-wide impacts of exogenous shocks and assesses the welfare effect based on the household survey. Besides, it incorporates the dynamic nature of structural change and market interactions and feedbacks. Exceptionally, it produces disaggregated results at the micro-level and/or aggregated at the macro-level.

Table 1. Description of the variables

Variables	Description	Measurement unit
Agricultural total factor productivity	Total factor productivity in agriculture is the portion of output not explained by the number of inputs, namely, labor, capital and arable land used in agricultural production	Constant domestic price
CO_2 emissions	Carbon dioxide equivalent GHG emissions from the various economic activities in the country. These include agriculture, forestry, industry, power, transport and buildings and associated businesses	Metric tons
Household population	Household population refers to the actual number of people, including poor and non-poor in rural and urban areas. The number of households and household size has been taken from Ethiopia's 2005/2006 SAM (EDRI, 2009)	Number
Agricultural GDP	GDP from various production activities in the agriculture sector	Constant domestic price year 2000
Arable land	Area of land suitable for growing crops	Hectare
Agricultural labor	Labor input used in agricultural activities such as livestock and crop production	Number

Once the standard CGE model is specified, all model equations are run using GAMS software based on the codes illustrated in the CGE manual (Hans *et al.*, 2002).

Concerning the demand side, households are also price takers. Households receive factor income from the production sector plus net transfer income; pay direct taxes and save according to their respective saving propensities. Household consumption expenditure is allocated across commodities according to a linear expenditure system specification (Robinson *et al.*, 2011). The government also receives revenue from direct and indirect taxes and net transfers from the rest of the world and pays transfers to households. Residual revenue after government consumption expenditure is saved (with budget deficits representing negative savings). All savings from households, government and the rest of the world are collected in a savings pool from which investment is financed.

The CGE framework is also built on a set of "macro-closure" rules to maintain the macroeconomic balance. Investment, government demand and aggregate consumption are assumed as fixed shares of total domestic absorption. Savings rates are assumed to adjust to finance investment. The time path of the current account is exogenous in foreign currency terms and the real exchange rate adjusts to maintain external balance. Conversely, the fiscal deficit is assumed to be endogenous. Because the government demand is taken as a fixed share of absorption and all tax rates are held constant, government income depends on the level of economic activities. Another assumption in CGE models is full employment and free movement of factors across various sectors. Capital accumulation is modeled with annual resolution. The model adopts the principle that new investment is allocated across sectors in response to the rate of return differentials but installed equipment remains immobile. Long-run sectoral factor productivity growth is specified exogenously. In a CGE model, the decisions of consumers, producers and investors change in response to changes in economic conditions driven by different sets of climate outcomes, as do market outcomes (Ferede *et al.*, 2013; Robinson *et al.*, 2011). In our case, GHG emissions are assumed to influence the economic well-being of households by affecting agricultural productivity and then producing general equilibrium feedback effects. Hence, the study used the CGE model to analyze the interrelationship between GHG emission and agriculture performance and welfare.

In our study, the study examined the impact of CO_2 emissions through agricultural total factor productivity. To estimate the total factor productivity in agriculture, the study adopted Solow's (1957) growth accounting framework. According to this model, growth in Total Factor Productivity (TFP) is attributed to that part of the growth in output which cannot be explained by growth in factor inputs such as land, labor and capital. Hence, the growth in TFP is equivalent to the growth in technical change. In addition to demographic change and economic development, technology is an important driving force in greenhouse gas emissions (IPCC, 2007; Hang and Yuan-sheng, 2011). Although CO_2 emission cannot cause progress in technology, its level and intensity can be illustrated by the paths of development in the energy system and resources, including land-use patterns which are determined by the level of technology and input utilization (IPCC, 2007). That is, the study used CO_2 emissions as a proxy for the state of technology because the level of byproducts and pollution from production processes and input utilization can be determined by the technology used or adopted. In Solow's approach, total agriculture output (YA) is taken as the function of technology (At) in a given period/time *t* and the factors of production such as labor (L), capital (K) and arable land (*l*) used in agricultural production.

$$Y_A = A_t F(L,\ K,\ l) \tag{1}$$

Assuming A_t as Hicks neutral, an improvement in technological progress increases the level of output without affecting the marginal product of inputs, i.e. causes no change to the coefficients of factors in a basic growth accounting equation. This kind of technical progress shifts the production function over time by a uniform upward displacement of the entire function (Chen *et al.*, 2003). Differentiating equation (1) with respect to time gives:

$$g_{GDP_t} = g_{Y_t} = g_{A_t} + \alpha g_{L_t} + \beta g_{K_t} + \gamma g_{l_t} \tag{2}$$

where g stands for the growth in the allied variables. Our variable of interest is g_{At} which represents Solow's residual or the rate of growth of agriculture TFP_A at time t. Coefficients α, β and γ represent respective shares of labor, capital and arable land in total agricultural output. Assuming constant returns to scale (CRS) production technology, the sum of the share of the factors (α, β and γ) equals one. Rearrange equation (2) gives:

$$g_{A_t} = g_{TFP_{At}} = g_{GDP_{At}} - (\alpha g_{AL} + \beta g_{AK} + \gamma g_l) \tag{3}$$

From equation (3), it is possible to calculate growth in agriculture total factor productivity using yearly data for agriculture GDP, and agricultural labor, capital and arable land growth rate. From the 2005/2006 Social Accounting Matrix for Ethiopia, with disaggregated relative factor shares in production, the values of α, β and γ are found to be 0.754, 0.102 and 0.144, respectively (EDRI, 2009). These values are used as coefficients of factors of agricultural production in the calculation of total factor productivity in agriculture.

After estimating total factor productivity in agriculture using sectoral growth accounting, the CO_2 emission impacts entered the CGE model in the form of a shock to agricultural total factor productivity induced by the CO_2emission. The study used $C0_2$ equivalent GHG emissions, which come from various economic activities in the country, instead of $C0_2$ stock, which is the measure of accumulated $C0_2$ emission from past worldwide economic activities. Although emissions from all economic sectors would have an impact on productivity by causing climate change, it is difficult to find a direct relationship between CO_2 emission and agricultural productivity. This is because emissions come not only from the agricultural sector but also from other economic activities, including the service and industrial sectors. Indeed, emissions from other sectors may not directly explain the output level in agriculture. However, some technological progress can reduce emissions and increase productivity by improving energy efficiency. In most cases, the level of technology used is also different among sectors in the economy. Thus, the relationship between technology and emission is complex (Hang and Yuan-sheng, 2011), implying that the relationship between agricultural productivity and emission is also not exact. To derive CO_2 emission-induced agricultural total factor productivity, the study calibrated the elasticity coefficient of ATFP with respect to CO_2 using the specification as follows:

$$ATFP = (CO_2\, emission)^{\beta} \tag{4}$$

Where ATFP is agriculture TFP and β is a coefficient to be used as CO_2 emission induced ATFP in the CGE model. By taking the natural logarithm on both sides of the above equation and obtain:

$$ln^{ATFP} = ln^{(CO_2 emission)^{\beta}} \tag{5}$$

$$ln^{ATFP} = \beta\, ln^{CO_2\ emision} \tag{6}$$

$$\beta = \frac{ln^{ATFP}}{ln^{CO_2\ emision}} \tag{7}$$

Finally, the coefficient β is calibrated using the values of ATFP and CO_2 emissions at the baseline. At the 2006 baseline, ATPF is set to be 1% (0.01) and the CO_2emissions are 120.89 Mt. By inserting these values into equation (7), the elasticity coefficient of ATFP with respect to CO_2 emissions are found to be −0.96. The study used this elasticity value to derive the CO_2 emissions-induced change in TFP and simulate its impact on agricultural performance and household welfare for the period 2010-2030.

3.3 Specification of dynamic baseline path and simulation scenarios

To estimate CO_2 emissions' impact on agricultural productivity and households' welfare, it calibrated the model to the 2005/2006 SAM of Ethiopia (EDRI, 2009) and specified a hypothetical dynamic baseline path to 2030 (S1) that reflects the trends in economic development, policies and priorities with no change in CO_2 emissions but includes the observed historical pattern of emissions. The baseline provides a counterfactual trajectory for growth and structural change of the economy in the absence of changes in CO_2 emissions. This serves as a basis for comparison with the various GHG emission scenarios.

In the baseline, underlying rates of labor force growth, trend productivity growth, world prices, foreign aid inflows, tax rates and government policies toward investment are assumed to be exogenous. In a dynamic path, the study then specified the growth rate of labor, arable land, capital accumulation and depreciation following NBE (2010) and World Bank (2010). Accordingly, the growth in labor supply is consistent with the projected annual population growth of 2.4%. The average annual growth rate of cultivated land across the modeled period is 3.1%. Capital accumulation is an endogenous outcome of saving and investment and is assumed to increase by 11.5% with a 5% depreciation rate. Following the IMF economic growth projection for Ethiopia, the baseline average annual GDP growth rate over the simulation period (2010-2030) is set to be about 6.5% (IMF, 2012).

Furthermore, the study formulated the GHG emissions scenarios following the Ethiopian CRGE strategy (FDRE, 2011). In the business-as-usual (S2) scenario, GHG emissions increase with the expansion of economic activities. In this scenario, the country is assumed to pursue non-CRGE strategies and the economy grows under a conventional growth path. Under this scenario, GHG would more than double from 150 Mt CO_2 emissions equivalent in 2010 to 400 Mt CO_2 equivalent in 2030 (FDRE, 2011). The third scenario (S3) evaluates the case of a targeted trend of GHG emissions, planned to be achieved through the implementation of the CRGE strategy, through 2030 (i.e. the 250 Mt of CO_2 emissions scenarios in 2030 and the "with-CRGE" intervention scenario).

The study simulated the impact of the CO_2 emissions on agricultural productivity and household welfare with and without CRGE. Although the Ethiopian CRGE strategy has a target of limiting CO_2 emissions to 150 Mt, compared to 400 Mt if the country did not pursue a CRGE strategy, the study considered that CO_2 emissions to be reduced by 37.5% instead of 64% in 2030 and become modest about net-zero emission growth and set the level of CO_2 emissions at 250 Mt level in 2030 with CRGE intervention by considering the limited greening technologies, institutions and sequestration capacity of the country. Green economy strategies of other countries also target percentage reductions instead of net-zero emission growth. For instance, Kenya targets a 30% reduction, which is not a net-zero emission level (MENR Kenya, 2015). Net-zero emission is also demanding given high growth targets in key economic sectors and lack of strong enforcement of the environmental laws intended to reduce emissions caused by existing and new economic initiatives of developing countries.

4. Results and discussion

4.1 CO_2 emission impacts on agricultural productivity

Simulation results indicated that a CO_2 emissions-induced decline in agricultural total factor productivity has an adverse impact on agricultural productivity. This is directly tailored with the prediction conducted by IPCC (2018) as climate-related risk increase with global warming. As indicated in Table 2, agricultural real GDP decreases from baseline 144.64 to 135.86bn Birr, which is 6% lower by 2030 under the scenario without CRGE, supported by some theoretical and empirical pieces of evidence such as Edoja *et al.* (2016), Valin *et al.* (2013), Di Falco *et al.* (2011) and Amsalu *et al.* (2018). On the other hand, under the scenario with CRGE, agricultural real GDP decreases by approximately 4.6%, from baseline 144.64 to 137.87bn Birr by 2030. This implies that the decrease in real GDP is low if the country implements the CRGE strategies in comparison to the scenario of abandoning the CRGE policy (FDRE, 2011). This is an incentive for the government to highly engage in the implementation of the CRGE policy as it reduces the effect of CO_2.

Considering particular production activities in the agriculture sector, CO_2 emissions have a negative impact on teff, maize and wheat, which are traded and non-traded agricultural products. Production of teff might decline from 10.53bn Birr at present to 9.88 by 2030 with CRGE versus 9.69bn Birr without CRGE. This implies that, if there is no CRGE intervention, CO_2 emissions-induced decline in agricultural factor productivity leads to a 7.9% decrease in teff production. Under the implementation of CRGE, the impact of CO_2 emissions on teff production is reduced to 6.1%. The negative impacts of CO_2 emissions-induced reduction on agricultural factor productivity are more pronounced for maize and wheat production under both scenarios, implying that the responsiveness of agricultural activities various across the behaviors of producers in the activities. By 2030, the production of maize and wheat is projected to be about 10.3% and 13.4% lower with and without CRGE than what it would be in the baseline scenario. The results indicated that maize and wheat production will decrease from baseline 16.39bn to 14.7 and 14.19bn Birr with and without CRGE. The explanation for the negative impact of CO_2 emissions is that GHG can change the amount and timing of rainfall; this, as well as increasing temperature, can endanger crop production. The reduction in teff, maize and wheat can endanger food security because these are the main

Table 2. Impact of CO_2 Emissions on Agriculture Production by 2030 (in billions)

Agricultural production	Baseline	With CRGE	Without CRGE
Teff	10.53	9.88	9.69
Maize and wheat	16.39	14.70	14.19
Export crops (oilseeds, pulses, coffee and others)	22.78	20.88	20.32
Non-traded agricultural products	47.11	44.21	43.35
Livestock	47.81	48.18	48.29
Agricultural real GDP	144.64	137.87	135.86
Total real GDP	553.7	544.26	541.50

Source: Authors' CGE model simulations consumption commodities in major crop-producing areas of the country. This is also supported by Valin *et al.* (2013) and Ekpenyong and Ogbuagu (2015). It also implies that the CO_2 emission problem remains a challenge to Ethiopia, as the major agricultural activities respond in the reverse direction even under the CRGE scenario, but by far it is better in comparison with the other scenario. The level of a decrease amount varies agricultural activities, implying that there might be a substantial cost of social upheaval as explained by Steve *et al.* (2013).

Moreover, CO_2 emissions have a negative impact on the production of major agricultural export commodities. The main agricultural export commodities included in our simulation are coffee, oilseeds, pulses and khat. With CRGE, the production of primary export commodities declines from baseline 22.78bn Birr by 8.3% to 20.88bn Birr by 2030. Without CRGE, the production of export commodities decreases to 20.32bn Birr by 2030, which is about 10.8% lower as compared to the baseline (Table 2). In addition to traded agricultural commodities, CO_2 emissions- induced reduction in factor productivity affects the production of non-traded agricultural commodities. Due to CO_2 emissions, without CRGE, the production of non-traded commodities is lower by 8% than what it would be in the baseline scenario. With CRGE, the decline in the production of non-traded commodities becomes 6.1%. The result indicates that the production of non-traded commodities decreases from the baseline 47.11bn Birr to 44.21 and 43.35bn Birr under CRGE and without CRGE by 2030. One of the differences between traded and non-traded commodities attributed to the structure of pricing ranged from farm get price to final domestic price and final global price. Pricing is an issue and a strong mechanism that conveys the effect of CO_2 on the production and commodities of agriculture as noted by Miodrag *et al.* (2016).

Unlike the effect on crop production, the effect of CO_2 emissions on livestock is positive. Livestock production increases in both with and without CRGE. In specific terms, livestock production increases from baseline 47.81 to 48.18 and 48.29bn Birr by 2030 with and without CRGE, respectively. This result is partly consistent with the findings of Gebreegziabher *et al.* (2011), who found a positive effect of climate change on livestock production until 2030, although their results turn negative beyond 2040 and 2030 (approximately) for the case of moisture-sufficient cereals- based and drought-prone highlands, respectively. However, it may have a serious societal distribution effect among the livestock producers, requiring a meticulous investigation on social impact assessment to secure both green and inclusive economy (Steve *et al.*, 2013). The important implication of our finding is that livestock production as an alternate source of income can reduce risks pertaining to GHG emissions and climate change.

At the economy-wide level, the results indicate a negative impact of CO_2 emissions on real GDP. By 2030, real GDP is projected to be 2.2% lower than it would be under the baseline scenario. Putting this in numbers, real GDP declines to 541.5bn Birr from the baseline projection of 553.7bn Birr without CRGE. This negative impact on real GDP is consistent with the findings of existing climate change studies, for example, a case study by Elshennawy *et al.* (2013) in Egypt and the research of Robinson *et al.* (2011) in Ethiopia. They reported that, in the absence of externally funded policy-driven adaptation investments, real GDP will decline by 10% in both countries compared to what it would be under a baseline scenario without climate change.

The impact of CO_2 emissions on both real total GDP and agricultural GDP is negative. Table 3 shows the decade average percentage deviations of real GDP from the baseline path by decade from 2010 to 2030. The adverse impacts are more noticeable in the case of agriculture GDP both with and without CRGE, and the severity of losses increases over time. In the period 2021–2030, real agricultural GDP is projected to be 3.5% and 4.5%

smaller than the baseline with and without CRGE. The results indicate that the implementation of CRGE significantly reduces the adverse impact of CO_2 emissions on agriculture and the whole economy (Table 3). This promotes the CRGE strategies to reduce the risk associated with climate change. Studies by Mideksa (2010), FDRE (2011) and Ferede *et al.* (2013) also supported this finding.

4.2 CO_2 emission impacts on institutional and factor income

Both with and without CRGE, CO_2 emissions are found to have a negative influence on the annual growth rate of income earned by institutions, represented by households and the government (Table 4). As compared to the baseline scenario, the annual income growth rate of institutions – namely, public enterprises, rural poor, rural non-poor, urban poor and urban non-poor households – declined due to CO_2 emissions-induced reduction in agricultural factor productivity. The reduction in the growth rate of income is larger without CRGE than with CRGE in the case of public enterprises and rural non-poor households. On the other hand, for rural poor, urban poor and urban non-poor households, the declines in their annual income growth rates are similar with or without CRGE. This finding is also supported by the study Yann *et al.* (2019) that shows the high possibility of CO_2 emissions leads to losses in labor productivity and income, exposing the poor community to various daunting challenges.

Simulation results also revealed that CO_2 emissions have a negative impact on the income of factors of production, except in the case of livestock. As compared to a baseline scenario of no increase in CO_2 emissions, growth rates for income from labor, land and capital decreased due to the emissions-induced reduction in total factor productivity in agriculture. The negative impact of CO_2 emission is larger in the case of labor and capital than for land. However, the growth rate of livestock income slightly increases. This is in line with the increase in livestock production as a result of CO_2 emissions that are described in the preceding section.

Moreover, there is a significant difference in the emissions-induced decrease in institutional and factor income growth rates with and without CRGE. As indicated in Tables 4 and 5, the CRGE strategy might help reduce the adverse impact of CO_2 emissions

Table 3. Average deviation of real GDP from the baseline scenario by decades (percentage) 2011-2020 and 2021-2030

Production	With CRGE	Without CRGE	With CRGE	Without CRGE
Real GDP	−0.5	−0.7	−1.3	−1.8
Agricultural real GDP	−1.2	−1.5	−3.5	−4.5

Source: Authors' computation based on CGE model simulation results

Table 4. Growth rate of institutional income under various CO_2 emissions scenario (%)

Institutions* baseline with CRGE without CRGE			
Enterprises	2.68	2.65	2.63
Rural poor HHDs	11.34	11.23	11.19
Rural non-poor HHDs	33.74	33.39	33.29
Urban poor HHDs	1.95	1.93	1.92
Urban non-poor HHDs	11.34	11.24	11.20

Note: *HHDs stands for households
Source: Authors' CGE model simulations

on institutional and factor incomes even if our assumption about the level of CO_2 emissions in 2030 is higher than the level targeted in the Ethiopian CRGE strategy. The implication of this result is that implementation of CRGE initiatives can help reduce the vulnerability of the income of households, public enterprises and factors of production. This may contribute to the realization of the country's goals of reducing poverty and attaining middle-income status.

4.3 CO_2 emission impacts on household welfare

The simulated values of welfare status measured by equivalent variation (EV) for different segments of households are presented in Table 6. The net effects of an emissions-induced reduction in agricultural total factor productivity worsen the welfare of each segment of households. However, the magnitude of loss in welfare differs among the different households. The welfare loss is larger in the case of rural poor households as compared to the other segments of households. This result indicates that rural poor households might be the most vulnerable to GHG emissions and climate change impacts.

The plausible reason behind the substantial welfare loss borne by rural poor households is that the majority of these households depend entirely on agriculture. Agricultural practices in Ethiopia are highly dependent on rain-fed cultivation and alternate farming practices are limited. Moreover, rural poor households have few diversified sources of income, unlike urban households, who have relatively diverse income sources. This makes the livelihood of rural poor households the most vulnerable to GHG emissions and associated climate change and variability.

Next to rural poor households, the welfare of rural non-poor households is also severely affected by CO_2 emissions, followed by urban-poor and non-poor households. Urban non-poor households are least affected, partly because of their lower dependence on the climate-vulnerable farming sector. Besides, urban non-poor households have numerous sources of income, which reduce their vulnerability. Figure 1 shows the percentage decline in household welfare measured by changes in EV. CO_2 emission-induced variation in total factor productivity in agriculture leads to a reduction in households' welfare under all scenarios. Without CRGE, the welfare of rural-poor and non-poor households declines by

Factors baseline with CRGE without CRGE			
Labor	30.3	30	29.9
Land	3.9	3.84	3.82
Livestock	1.712	1.715	1.716
Capital	23.6	23.3	23.2

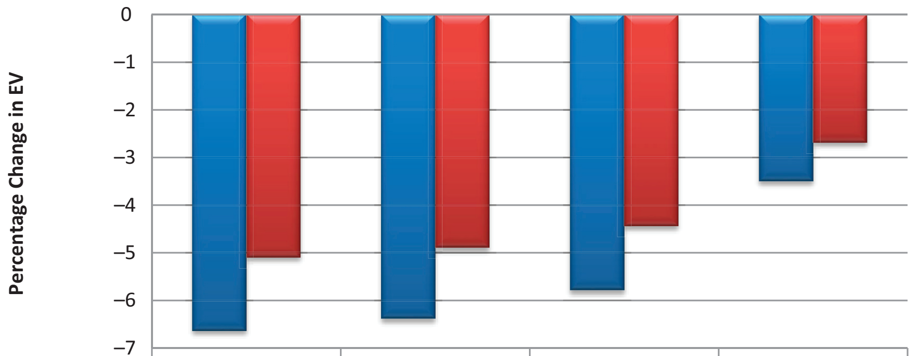
Source: Authors' CGE model simulations

Table 5. Percentage growth rate of factor income under various CO_2 emissions scenarios

Households	EV in baseline	EV with CRGE	EV without CRGE
Rural poor	0.0470	0.0446	0.0439
Rural non-poor	0.1569	0.1493	0.1469
Urban poor	0.0086	0.0082	0.0081
Urban non-poor	0.0550	0.0536	0.0531

Source: Authors' CGE model simulations

Table 6. CO_2 emission induced change in household welfare status



	Rural poor	Rural non-poor	Urban poor	Urban non-poor
Without CRGE	−6.637794554	−6.379878916	−5.782986963	−3.495682766
With CRGE	−5.096563997	−4.889840717	−4.437266697	−2.683047778

Source: 'Authors' computation based on CGE model simulation results

Figure 1. Percentage change in welfare effects with and without CRGE

6.6% and 6.3%, respectively. Under the same scenario, the reduction in welfare in the case of urban households is relatively lower as compared to their rural counterparts, reaching 5.7% and 3.5% for poor and non-poor households. Such implications of CO_2 emission over the welfare of households are reflected in the study conducted by Yann *et al.* (2019). This is followed by the analysis of income and consumption channels as well as the pricing mechanism over the distributional effect of CO_2 emission as supported by Miodrag *et al.* (2016).

As can be seen from Figure 1, reduction in welfare becomes moderate for all segments of households under the CRGE scenario. The notable implication of our findings is that the CRGE strategy can effectively reduce the impacts of GHG emissions. Under all simulation scenarios, CRGE lessens the negative impacts of CO_2 emissions on agricultural productivity, institutional and factor income and household welfare. This shows that the CRGE initiatives can not only help reduce GHG emissions while achieving the ambitious goal of middle-income status by 2025 but can also moderate the associated environmental impacts of CO_2 emissions.

5. Conclusion

Ethiopia has started the implementation of a CRGE strategy in 2010, aiming to become a low-carbon, middle-income country by 2025. This study aims to investigate CO_2 emission impacts on agricultural productivity and household welfare. CO_2 emissions-induced agricultural total factor productivity is stimulated using a dynamic CGE model. Alternate simulation scenarios were set in line with the emission targets of the Ethiopian CRGE strategy. Simulation results reveal that CO_2 emissions have a negative impact on agricultural performance. As compared to the baseline, real agricultural GDP is projected to be 3.5% and 4.5% lower in the 2020s with and without CRGE strategy scenarios, respectively. The impact of CO_2 emissions-induced reduction in agricultural factor productivity leads to a decrease in the production of agricultural traded and non-traded crops, except livestock production. The production of teff, maize and wheat, export commodities such as coffee, oilseeds and pulses and non-traded crops, declines due to the impact of CO_2 emissions both with CRGE and without CRGE during the simulation period of 2010-2030, but the impacts are worse without CRGE.

In addition, the net effect of CO_2 emissions on household welfare has been found to be negative. The welfare of all segments of households worsens due to the emissions-induced reduction in total factor productivity in agriculture. The percentage loss in welfare is more manifest in rural areas, where rural poor households are the most vulnerable. High vulnerability of the welfare of rural poor households can be explained by their heavy dependence on rain-fed agriculture for livelihood and their limited income diversification. Results indicate that proper implementation of the CRGE strategy can significantly lessen the devastating effects of GHG emissions on agriculture and particularly on household welfare, thereby promoting sustainable economic development. Therefore, in Ethiopia, more actions should be taken in agricultural and other economic sectors for the implementation of the CRGE strategy because they are timely and vital to the goal of achieving low-carbon, middle-income status.

Our results must be interpreted with caution because the study conducted an analysis of CO_2 emissions' impact only through agricultural total factor productivity. To measure the direct and indirect economic impacts, consideration of environmental accounts such as natural resource depletion, pollution and greenhouse gas effects is essential. In this regard, future efforts are needed to extend the Ethiopian 2005/2006 SAM by including environmental accounts. An ESAM can provide more insightful evidence on the economy-wide impacts of GHG, including CO_2 emissions and can help evaluate the real-time impact of effective implementation of the CRGE strategy. As simply discussed, the relationship between ATFP and CO_2 without considering other factors, which can affect ATFP, further study should also focus on using regression approaches that take into account all variables explaining ATFP.

Note

1. In this case, CO_2 emission refers to major GHG emissions converted into CO_2 equivalent emissions. In our study, the authors used the projection of CO_2 equivalent emissions, in line with the Ethiopia's CRGE strategy.

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