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Evaluating the regional risks to food availability and access from land-based climate policies in an integrated assessment model

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Abstract
Mitigating greenhouse gas emissions is necessary to reduce the overall negative climate change impacts on crop yields and agricultural production. However, certain mitigation measures may generate unintended consequences to food availability and food access due to both land use competition and economic burden of mitigation. Integrated assessment models (IAM) are generally used to evaluate these policies; however, currently these models may not capture the importance of income and food prices for hunger and overall economic wellbeing. Here, we implement a measure of food security that captures the nutritional and economic aspects as the total expenditures on staple foods divided by income and weighted by total caloric consumption in an IAM, the global change analysis model (GCAM4.0). We then project consumer prices and our measure of food security along the shared socioeconomic pathways. Sustained economic growth underpins increases in caloric consumption and lowering expenditures on staple foods. Strict conservation policies affect food accessibility in a larger number of developing countries, whereas the negative effects of pricing terrestrial emissions are more concentrated on the poor in Sub-Saharan Africa, by substantially replacing their cropland with forests and affecting the production of key staples.

Keywords Food security · Household expenditures · Integrated assessment model · Shared socioeconomic pathways · Climate change · Climate policy

1 Introduction

The sustainable development goals (SDGs) identifies both eradicating hunger and mitigating climate change as a global development priorities (United Nations, 2014). Despite significant progress, rates of improvement for hunger have slowed in the most recent years (FAO et al. 2020). Persistent, large regional disparities of hunger and poverty have been further amplified through the covid-19 pandemic (Erokhin and Gao 2020; Workie et al. 2020; Farcas et al. 2021). Climate change may already be further amplifying these challenges as it has decreased agricultural productivity (Ortiz-bobea et al. 2021). However, achievements on climate mitigation may also present risks to food security. For example, some climate mitigation policies which promote the expansion of bioenergy and/or afforestation may also cause increases of food production costs due to competition of land, water, and other natural resources (Lotze-Campen et al. 2014; Hasegawa et al. 2021).

Given the importance of understanding these complex interactions, modeling using integrated assessment (IAM) and agro-economic models have investigated interactions between climate change, climate policy, food prices and hunger along alternative climate and socioeconomic futures—often using the climate scenario framework defined by the representative concentration pathways (RCPs) for climate pathways and shared socioeconomic pathways (SSPs) for the socioeconomic futures (Hasegawa et al. 2014, 2015a, b; Nelson et al. 2014; Wiebe et al. 2015; Hasegawa et al.

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2021). Many studies have looked at single dimensions of food security. For example, studies focused on the climate risks have examined measures that focus on total caloric intake, such as per capita caloric consumption (van Dijk and Meijerink, 2014), the number of people at risk of hunger, defined as national average consumption below a calorie threshold (Hasegawa et al. 2014, 2015a, b; Bijl et al. 2017), and child malnutrition, estimated in relation to total caloric intake (Nelson et al. 2010). More recent work has explored the larger economic dimensions such as welfare effects of changes in agricultural yields due to climate change on consumers (Calvin et al. 2020).

Looking at the impacts of climate mitigation on food, a number of modeling exercises have looked at global producer prices, showing moderate increases under strong bioenergy expansion (Popp et al. 2011; Lotze-Campen et al. 2014; Wise et al. 2014). Larger increases in global price are observed under terrestrial carbon emissions pricing policies due to large-scale afforestation (Popp et al. 2011; Reilly et al. 2012; Calvin et al. 2014; Doelman et al. 2018). Another set of studies evaluate the impacts on consumers' food access from climate mitigation, taking into account the impacts of food price and income change (Hasegawa et al. 2015a, b; Fujimori et al. 2018; (Golub et al. 2013; Petr Havlík et al. 2015a, b; Springmann et al. 2016). These studies, however, look at total caloric consumption, or the associated population at risk at hunger. This focus on total caloric consumption may underestimate the economic aspects of climate change on food security for the more vulnerable regions. It is more than likely that poor consumers maintain the energy intake levels by increasing food expenditures, especially on staple foods, (de Hoyos and Medvedev, 2011; Iannotti and Robles, 2011; Ivanic et al., 2012) while sacrificing dietary diversity, nutritional quality and the consumption of other essential goods (Torlesse et al. 2002; Brinkman et al. 2010; Campbell et al. 2010; Jensen and Miller, 2010; Iannotti et al. 2012; D'Souza and Jolliffe 2014).

Here, we develop a new approach to estimate the economic dimensions of hunger that may arise due to changes in income and changes in food prices under climate policies that can be implemented in an IAM, the global change analysis model (GCAM4.0). Our measure builds upon previous efforts to emphasize the effects on the more vulnerable regions by calculating the portion of the income spent on five key staple foods and accounting for the relative importance of these gains by normalizing the total caloric intake in a region divided by the total caloric intake of the US. First, we elaborate this measure and show how to deploy this measure in the GCAM4.0 along different regional food price scenarios and socioeconomic scenarios. Second, we evaluate the effects on food availability and access from stringent climate targets. We use our measure to separate the two channels of potential impacts between changing food prices because of land-use competition and changing income due to abatement costs. Third, we compare the impacts between three illustrative policy instruments in the land-use sector. Finally, we develop recommendations of moderating the potential food security risks from climate policies. We do not model the highly uncertain climate change impacts on crop yields, but rather focus on comparing the unintended consequences between alternate mitigation policies, acknowledging their overall benefits of avoiding dangerous climate change impacts.

2 Methods and data

2.1 Study design

To estimate the changes in food security, we show our analytical approach in Figure 1. We start with the SSP that provide the baseline information on GDP and population (O'Neill et al. 2014; Riahi et al. 2017). These socioeconomic scenarios have been developed to evaluate alternative dimensions of socioeconomic development through the 21st century. This allows exploration of a range of potential impacts from alternative policies. We then use the global change assessment model (GCAM4.0) to estimate the mitigation costs and the changes to producer food prices of achieving long-term climate targets under alternate designs of land-based mitigation policies. First, the abatement costs are subtracted from the exogenously defined GDP trajectories from the SSPs. Second, these adjusted GDP pathways are used an input to GCAM 4.0to estimate the long-term change in food consumption and global producer food prices along the alternative climate mitigation policy scenarios. Third, we use empirical models to estimate how regional consumer prices could evolve relative to global market prices from GCAM4.0 that reflect current relationships between producer and consumer prices in each region. Finally, the regional food availability and access conditions are evaluated through the post-estimation process of our two-dimensional measure of food accessibility. We describe each part of this framework below.

2.2 The global change analysis model (GCAM4.0)

The global change analysis model (GCAM4.0) is an integrated human-earth system model that links the economic, energy, land use, water, and climate systems in a single, integrated framework. GCAM4.0 captures interactions between improvements in technology and productivity over time, demand changes due to changing population and income levels, and the resulting global market-clearing prices of primary and secondary energy and agricultural and forest products through 2100 at a 5-year interval.

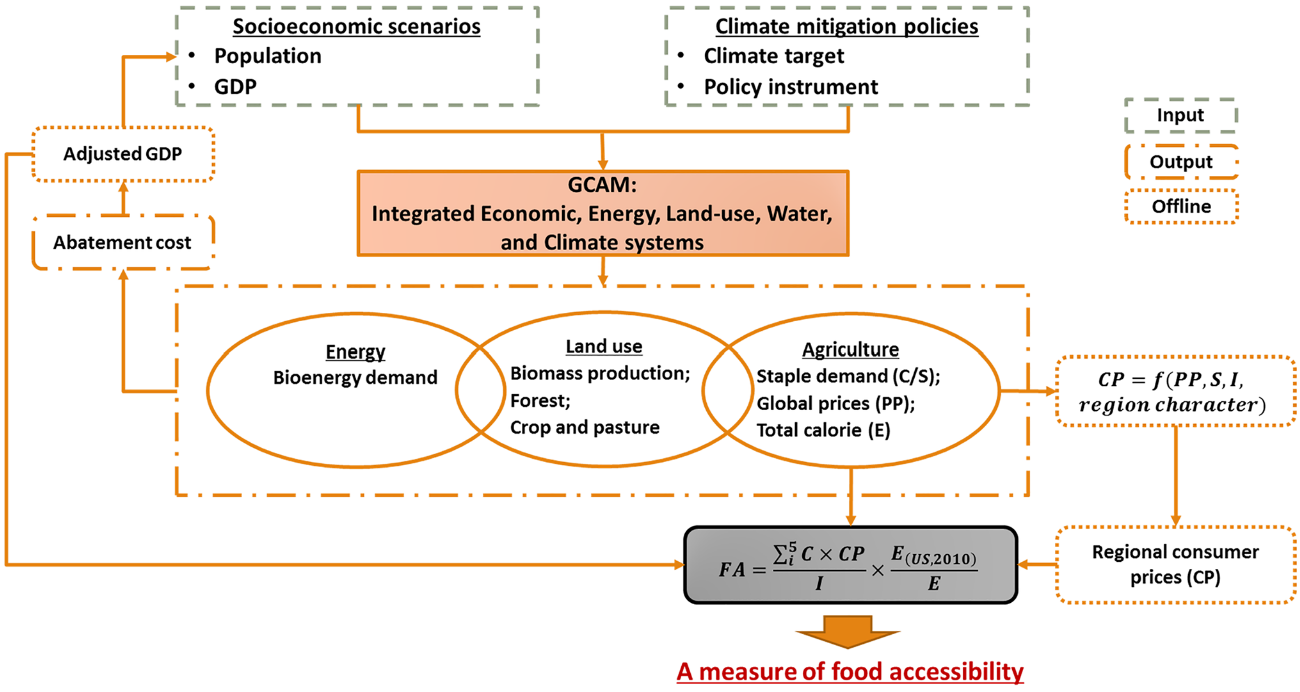


Fig. 1 Modeling framework

The agricultural sector is composed of 12 globally traded crop commodities and five animal product commodities. Yields in each land use region are calibrated to historic data, with regionally specific rates of yield improvement (Wise and Calvin 2011; Kyle et al. 2011). There are a total of 283 agriculture and land use sub-regions in GCAM4.0, comprised of 32 geopolitical regions, overlaid with 18 Agro-ecological Zones (Calvin et al. 2014). GCAM4.0's bottom-up representation of the global agriculture and land-use system is fully integrated with socioeconomic drivers and the energy system, with a Heckscher-Ohlin trade framework. The link between energy and agriculture/land use sectors through bioenergy allows us to explore the impacts of policies that price energy system emissions on agricultural production. Also, the feature of a fully integrated land use system in GCAM4.0 allows us to explore the impacts of different policy approaches to manage terrestrial emissions on agricultural production. This bottom-up land system and the land use decision-making dynamic is one of the main advantages of GCAM4.0, compared to other IA models used in prior research (Hasegawa et al. 2015a, b). Further, GCAM4.0 captures interactions between improvements in agricultural productivity over time, demand changes due to increasing population and income levels, and the resulting market-clearing prices at the global level. This market equilibrium price is a global producer price, calibrated to the historical producer price in the United States (Kyle et al. 2011).

In Sect. 2.5, we describe how to estimate and model regional consumer prices in GCAM4.0. GCAM undergoes regular updates and is currently in version 5.4. Thus, it should be noted that the approaches described in Sect. 2.5 are specific to version 4.0. More information is available at jgcri.github.io.

2.3 Climate policy and socioeconomic scenarios

We explore four different policy options in the land use sector to meet stringent climate targets of 450 ppm CO_2 concentration along the two alternative socioeconomics trajectories as defined in the new of the SSPs: SSP1 and SSP3 (Table 1). These SSPs characterize two divergent socioeconomic futures—SSP1 (Sustainability) and SSP3 (Regional Fragmentation). Two reference scenarios are also presented as the hypothetical baseline, without considering the potential climate change impacts (Ref-NoCC). Thus, our analysis focuses on the costs of specific mitigation strategies, without discussing the overall benefits of mitigation—the avoided or reduced climate change impacts on crop yields, food production, and other damages.

Our focus is on policy instruments that are illustrative of possible policy designs. In the first three policy scenarios, a global carbon price is placed on fossil fuel and industrial emissions from the energy system (FFICT), with three different levels of land use restrictions: 0%, 90%, or 99% of natural land in each of the 32 GCAM4.0 regions. The land use

Table 1 Socioeconomic and policy scenarios combinations

Scenario name	Sectors subject to carbon price	Level of natural land protection	Climate temperature target	Population and GDP trajectories
SSP1-Ref-NoCC	NoPolicy	None	No target	SSP1
SSP1-450-ffict	Energy	None	> 2 °C	
SSP1-450-ffict-prot90	Energy	90% in each region		
SSP1-450-ffict-prot99	Energy	99% in each region		
SSP1-450-uct	Energy and land use	None		
SSP3-Ref-NoCC	NoPolicy	None	No target	SSP3
SSP3-450-ffict	Energy	None	> 2 °C	
SSP3-450-ffict-prot90	Energy	90% in each region		
SSP3-450-ffict-prot99	Energy	99% in each region		
SSP3-450-uct	Energy and land use	None		

policies explored here protect not only forests (e.g., REDD) but also other types of natural land. Agriculture expansion to other types of natural land accounts for a large portion of emission leakages as well as loss of biodiversity (Popp et al. 2014). In the fourth policy scenario, the carbon price is equally implemented on terrestrial emissions from the land use sector—a Universal Carbon Tax (UCT)—adding an incentive to increasing natural carbon stocks. We focus on scenarios that achieve a less than 2 °C temperature target by the end of the century.

2.4 A new measure of food accessibility

One of our key contributions is to develop a measure of food accessibility (FA) that allows us to decompose the effects on income and the effects on food prices (Eq. 1). This measure combines the consumers' staple food budget share, and the basic nutritional status through total caloric intake level. Consumers' staple food budget share is defined as the fraction of average income (indicated by per capita GDP) spent on staple foods in a region. We focus on staple commodities—corn, rice, wheat, other grains, and roots and tubers—to concentrate on the most food insecure population, whose main caloric energy source is staples. To highlight the change in level, we also normalize the economic measure by the average total caloric intake in a region relative to the reference value of the United States. We use the average daily caloric consumption of the United States in 2010 as a benchmark to approximate a high degree of caloric sufficiency. We note that this does not imply that the US diet or caloric intake is ideal. Rather as a country with one of the highest caloric intakes, this allows us to develop an intuitive consumption adjusted value. This consumption-adjusted staple expenditure as % of average income reveals larger regional inequality because the most food insecure regions tend to have lower total caloric intake and higher staple food budget share. It provides additional information about the nutritional quality of food consumption. Higher consumption of staple foods relative to total consumption indicates low diet diversity and nutritional quality. For a comparison of our measure with the prevalence of undernourishment, a commonly used metric for food security, is shown in Supplemental Information, Fig. S1).

We calculate this value over the regions that are presently implemented in the GCAM4.0 (Sect. 2.3). A higher value on this FA measures denotes worse conditions.

$$\mathrm{FA}(r,s,t)=\frac{\sum_i^5 C(i,r,s,t)\times P(i,r,s,t)}{I(r,s,t)}\times\frac{E(\mathrm{US},2010)}{E(r,s,t)} \quad (1)$$

where

$C(i,r,s,t)$= consumption per capita of commodity i of region r in year t under scenario s.

$P(i,r,s,t)$= consumer food price of commodity i of region r in year t under scenario s.

$I(r,s,t)$ = GDP per capita (as a proxy for average income) of region r in year t under scenario s.

$E(r,s,t)$ = daily caloric energy consumption per capita of region r in time t under scenario s.

$E(\mathrm{US},2010)$ = daily caloric energy consumption per capita of US in 2010 (3542 kcal/capita/day; this is the GCAM4.0 baseline value calibrated with the FAO historical data).

2.5 Estimating consumer food prices

While GCAM4.0 has several advantages for modeling the interactions of climate policy and food systems, it produces global market prices rather than the regional consumer prices that are needed to estimate food accessibility. A limited number of IAMs, such as AIM, calculate consumer prices directly by applying tax and tariff as well as exchange rates to producer prices (Hasegawa et al. 2014, 2015a, b) and a smaller number of these IAMs also estimate domestic producer prices using regional transport cost functions (Biewald et al. 2015; Havlík et al. 2015a, b). GCAM4.0, however, similar to many IAMs and agro-economic models only estimates global market-clearing prices of agricultural commodities.

Thus, to extend these global prices to produce country-level and/or regional-level consumer prices, we develop empirical models of these relationships. These empirical models are built from regional food prices that come from the International Labor Organization (ILO) October Inquiry. We then model these prices as a function of producer prices (calibrated to US producer prices) and a small number of variables that are available in GCAM4.0 to explain the variation, including regional food supply, GDP per capita and country-level dummies to account for unobserved effects (e.g. tariffs and taxes). Detailed information about our data and our empirical investigations are provided in Supporting Information (Section S2).

3 Results

3.1 Projecting baseline food accessibility in GCAM4.0 by socioeconomic scenario

In Fig. 2, we show food accessibility as the consumption adjusted staple expenditure as % of average income for the baseline no climate policy by socioeconomic scenarios. Along all the population and GDP growth trajectories in the SSPs, both caloric consumption and the economic accessibility are improved. Long-term economic growth outpaces increases in food prices due to growing demand. Although food demand increases, GCAM4.0 modeled global market prices rise only slightly from 2010 to 2050. Increases in agricultural productivity tend to mitigate the upward pressure on global prices.

3.2 Food accessibility by climate policy and socioeconomic scenario

Although each of the policy instruments that we model achieves the same climate target, regional food accessibility looks very different across these policy options. We find that policies that strictly restrict land use (FFICT-Prot99) or price terrestrial carbon emissions (UCT) tend to have larger impacts on food access in 2050, especially under rapid population and slow GDP growth (Fig. 3). By contrast, compared to the hypothetical reference scenario with no climate change impact, the change to food access under a carbon tax on fossil fuel and industrial emissions alone (FFICT) is minimal, with intermediate effects under a land use restriction policy (FFICT-Prot90).

While the level of impact on food accessibility varies across alternate climate policies, in every scenario the impacts are concentrated in already fragile, low-income regions. Sub-Saharan Africa persist with the worst food access condition in 2050 across all scenarios. In rapid population and slow GDP growth scenarios, stress on food accessibility increases for South Asia, India, Pakistan, and Indonesia when terrestrial emissions are priced (UCT) and these negative impacts are further extended to several other regions in Central Asia, Northern Africa, and South America when 99% of natural land are protected (FFICT-Prot99). Overall, poor regions are more sensitive to both the socio-economic development uncertainty and the role of land use in the GHG mitigation policy; developed countries' food accessibility tend not to be impacted across the range of sensitivities that we test.

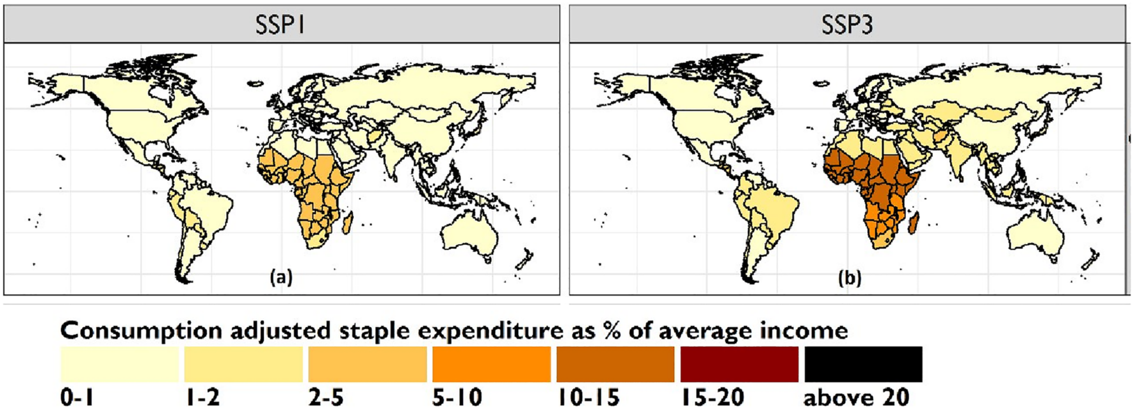
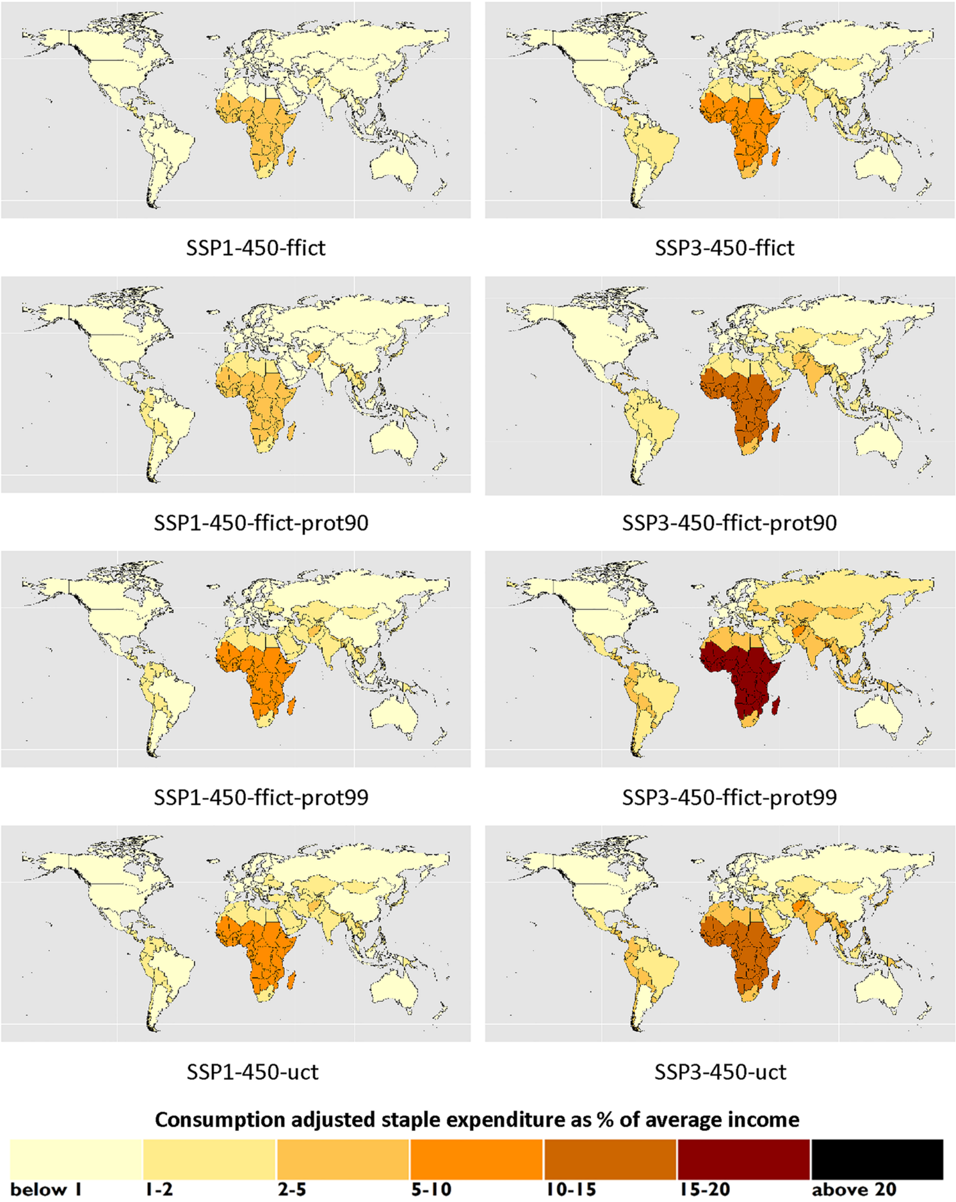


Fig. 2 Food accessibility over regional consumer prices scenarios across SSP1 and SSP3 in 2050



SSP1-450-ffict SSP3-450-ffict

SSP1-450-ffict-prot90 SSP3-450-ffict-prot90

SSP1-450-ffict-prot99 SSP3-450-ffict-prot99

SSP1-450-uct SSP3-450-uct

Fig. 3 Food accessibility in 2050 under climate target, by alternate climate policies

3.3 Decomposition of the effects on food accessibility

We find that between the two channels, impacts on the poor regions' food accessibility from certain mitigation measures are mainly caused by increased food prices due to competing use of land. We conduct a Logarithmic Mean Divisia Index (LMDI) decomposition analysis that shows that increases in the most impacted regions' consumption-adjusted staple expenditure as a percentage of average GDP (worsened food access) from the hypothetical reference scenario are almost all driven by increased staple expenditures, while the change in food access caused by decreased total caloric intake and GDP per capita due to abatement costs is negligible (Fig. 4). Therefore, policies that have higher risks to food access are mainly due to the stronger effects on global food prices.

When such increases in global prices are further transmitted to changes in consumer prices and staple food expenditure, regional outcomes vary largely and are influenced by both regional economic conditions and diet preferences. First, the poor regions not only spend a higher share of income on staple food, but also tend to experience higher percentage change in consumer prices when global prices rise. Second, under an UCT scenario, compared to more stringent land conservation scenarios, expenditures are lowered on most staple commodities except for roots and tubers—a primary staple food in Sub-Saharan Africa (Fig. 4). A policy mechanism that prices both fossil and land carbon, compared to strict land conservation policies,

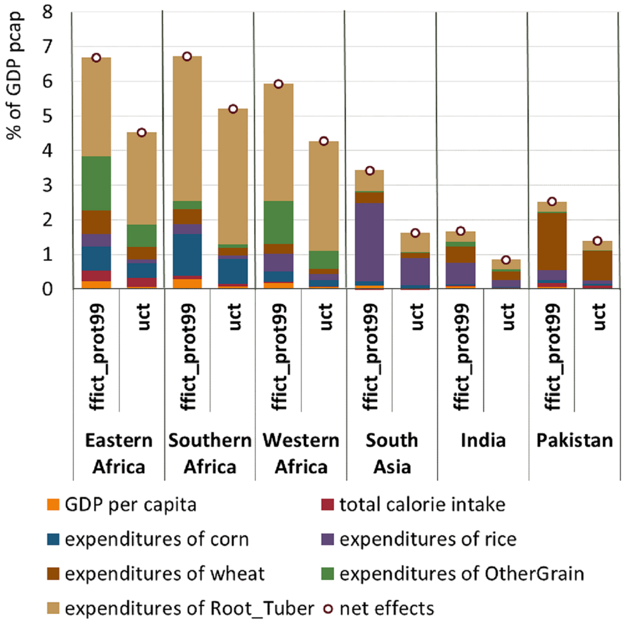


Fig. 4 Decomposition of changes in the consumption-adjusted staple expenditure as a percentage of average GDP, by selected regions and policies: increases from the reference scenario are almost all driven by increased staple expenditures, while the change in food access caused by decreased GDP per capita and total caloric intake is negligible

has greater flexibility to shift land use around the globe, lowering the impacts on food price of all staple commodities except for roots and tubers. This is because that pricing terrestrial carbon incentivizes afforestation mainly in the tropics (i.e. Sub-Sahara Africa and Brazil) and substantially shifts croplands to temperate regions (i.e. China and the United States) that have higher crop yields. As a result, production of roots and tubers, which are widely grown in Sub-Saharan Africa, are particularly affected with pricing on land carbon, as cropland in these regions is converted to forest. People in these regions are also major consumers of roots and tubers and are thus more hurt than consumers of other staple commodities.

3.4 Key limitations of our measure of regional food accessibility

The benefit of calculating this measure of food accessibility measure in GCAM4.0 is that it allows us to gain more insight into the effects of climate policy by decomposing the income and food price effects. At the same time, there are some limitations and caveats to the GCAM4.0 approach compared to other agro-economic models and IAMs that we outline here:

- Some of our choices for our measure are motivated by the availability of variables in GCAM4.0. Hence, in addition to limiting our coefficient to staple foods and using GDP per capita as a proxy for income, we are only able to calculate a country or regional average rather than investigate intra-country distributions to identify specific populations who may at greater risk of food insecurity. Additionally, we cannot generate a spatial resolution of consumer prices greater than the regional disaggregation in GCAM4.0, such as those that may be observed across a country (e.g. rural/urban).
- In GCAM4.0, only global prices are generated from agricultural markets that are modeled with a single market with unrestricted trade. In this effort, we produced consumer prices through a simplified empirical approach that allows us to estimate their relationship from the GCAM4.0 global prices. Other IAMs use different approaches to model global prices, and sometimes consumer prices that may include separate domestic markets, trade, policies, and other structural aspects of agricultural markets. In principle, we could apply any given consumer price scenario in GCAM4.0.
- Presently, there is limited demand response to price changes for crops in GCAM4.0 (Kyle et al. 2011). Although high price inelasticity may overestimate staple demand for regular consumers, it may not for the most food-insecure poor consumers—especially under circumstances of increasing food prices that we are interested in, poor consumers enhance consumption of the relatively cheaper staple calories to meet total energy demand. Also, because of this feature in GCAM4.0, increase in staple food price is not moderated by lower demand. Thus, this can be interpreted as a bounding case, where people meet their income-driven total calorie level whatever the cost. While this is not likely to be the case universally, the poorest consumers are more likely to shift their *diets toward* staple foods in the face of rising food prices, in an effort to maintain adequate energy intake, at the sake of dietary diversity and quality (Brinkman et al. 2010; Campbell et al. 2010; Jensen and Miller 2010; Iannotti et al. 2012; D'Souza and Jolliffe, 2014).

4 Conclusions and policy implications

In this paper, we implement a new approach to capture the influence of long-term income growth and fluctuations in consumer food prices on food accessibility and use this measure to explore the effects of different land-based climate policies. We show the importance of sustained economic growth over the next few decades, especially in regions presently facing food availability and access challenges. As we increase our ambition to achieve stringent climate targets, it is also important to understand the potential implications of different mitigation policy designs on food security. We find that alternative policy designs tend to have large impacts on food availability and access mainly driven by competing land use, which increases food prices. Strict conservation policies limit the competition between bioenergy and agriculture production on existing commercial land only, while pricing terrestrial carbon encourages large-scale afforestation. With large increases in global prices, sustaining caloric consumption is achieved by increasing expenditures on staple foods, potentially reducing the consumption of more nutritious foods and other essential goods.

Regional outcomes vary substantially, largely depending on regional economic condition and diet preference of staple food. Strict conservation policies affect a larger number of developing countries, whereas the negative effects of pricing terrestrial emissions is more concentrated on the poor in Sub-Saharan Africa, by substantially replacing their cropland with forests and affecting the production of roots and tubers. From a global GHG mitigation perspective, it tends to be most cost-effective when carbon stocks locate in tropical regions and food production in temperate regions. From a regional perspective, however, it may become problematic if Sub-Saharan Africa replaces most of their croplands with forests and heavily relies on imports for staple food. Additionally, GCAM4.0 assumes completely free global trade of agricultural commodities and that the location of crop production is relatively elastic. Thus, our results likely underestimate the effect, for poor land-locked countries where transportation costs could generate large uncertainty to their ability to access to global market and benefit from global trade. This analysis also does not include more complex feedback that could moderate the effects of higher food prices, such as the increase in income for food sellers (Ivanic and Martin 2008) and investments in agricultural productivity that would be motivated by higher food prices (Angelsen 2010).

Although certain land-based mitigation measures are likely to generate unintended outcomes on food availability and access, a broad range of measures can be considered for alleviating the pressures on land between competing use for carbon stocks and agricultural production (Fujimori et al. 2018). These measures include adaptation practices in the agriculture sector and the value chain of the food system, sustainable intensification that addresses the potential trade-offs between productivity improvement and environmental goals (Godfray et al. 2010; Tilman et al. 2011; Garnett et al. 2013; Smith 2013), agriculture trade liberalization that helps reduce price volatilities in the global market (Abbott 2011; Rutten et al. 2013), and demand-side management such as reducing food waste (Foley et al. 2011; Smith et al. 2013).

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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