

ABSTRACT

Title of Dissertation: RISKS TO FOOD AVAILABILITY AND ACCESS FROM CLIMATE POLICIES: AN INTEGRATED ASSESSMENT OF REGIONAL FOOD AVAILABILITY AND ACCESS WITH ALTERNATIVE CLIMATE MITIGATION STRATEGIES TO 2050

Yiyun Cui, Doctor of Philosophy, 2016

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Although mitigating GHG emissions is necessary to reduce the overall negative climate change impacts on crop yields and agricultural production, certain mitigation measures may generate unintended consequences to food availability and access due to land use competition and economic burden of mitigation. Prior studies have examined the co-impacts on food availability and global producer prices caused by alternative climate policies. More recent studies have looked at the reduction in total caloric intake driven by both changing income and changing food prices under one specific climate policy. However, due to inelastic calorie demand, consumers' well-being are likely further reduced by increased food expenditures. Built upon existing literature, my dissertation explores how alternative climate policy designs might adversely affect both caloric intake

and staple food budget share to 2050, by using the Global Change Assessment Model (GCAM) and a post-estimated metric of food availability and access (FAA).

My dissertation first develop a set of new metrics and methods to explore new perspectives of food availability and access under new conditions. The FAA metric consists of two components, the fraction of GDP per capita spent on five categories of staple food and total caloric intake relative to a reference level. By testing the metric against alternate expectations of the future, it shows consistent results with previous studies that economic growth dominates the improvement of FAA.

As we increase our ambition to achieve stringent climate targets, two policy conditions tend to have large impacts on FAA driven by competing land use and increasing food prices. Strict conservation policies leave the competition between bioenergy and agriculture production on existing commercial land, while pricing terrestrial carbon encourages large-scale afforestation. To avoid unintended outcomes to food availability and access for the poor, pricing land emissions in frontier forests has the advantage of selecting more productive land for agricultural activities compared to the full conservation approach, but the land carbon price should not be linked to the price of energy system emissions. These results are highly relevant to effective policy-making to reduce land use change emissions, such as the Reduced Emissions from Deforestation and Forest Degradation (REDD).

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CLIMATE POLICIES**
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ACCESS WITH ALTERNATIVE CLIMATE MITIGATION STRATEGIES TO
2050

by

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Dedication

To Wang, Hong and Cui, Maozeng, my parents who have raised me with their endless love and taught me to be respectful and persistent.

To Lei, Ming, my significant other who has suffered all the loneliness and remained strong and supportive while I was finishing my doctoral thesis on the other side of the globe.

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Chapter 1. Introduction

1.1. Background and research questions

Avoiding dangerous climate change and feeding 9 billion people on the planet are two intimately connected challenges in the 21st century. On the one hand, mitigating greenhouse gas (GHG) emissions is necessary to reduce wide ranging negative climate change impacts on the agriculture and food system (Wheeler and von Braun 2013; Brown and Funk 2008; Schmidhuber and Tubiello 2007). On the other hand, however, policies that respond to climate change may also generate unintended consequences to multiple dimensions of food security.

Food security is an intrinsically multi-dimensional and complex issue. The United Nations Food and Agriculture Organization (FAO) conceptualizes food security around four key dimensions (FAO, IFAD, and WFP 2012), which are often conceptualized as a pathway that can be traced from the macro-level physical *availability* to the micro-level food *access* and *utilization* with *stability* being the ability to achieve the other three dimensions as a function of time (Jones et al. 2013; Barrett 2010). All of the four dimensions are impacted by climate change. Regarding food *availability*, impacts of long-term changes in temperature and precipitation on crop yields are negative for most regions, but even worse for the current most food insecure countries in Sub-Saharan Africa and South Asia (Reinsborough 2003; Cline 2007; Knox et al. 2012; Rosenzweig et al. 2013; von Lampe et al. 2014; Porter et al. 2014). Lower yields and production may increase food prices (Nelson et al. 2014; Wiebe et al. 2015) and impact the economic *access* to food, especially for the poor consumers (Wheeler and von Braun 2013). With

respect to the biological *utilization* of food, climate change may impact human health to absorb nutrients or damage water sanitation through flood (Hashizume et al. 2008; Shimi et al. 2010). Finally, more frequent and more severe extreme weather events may interrupt the *stability* of all the above three dimensions, such as the recently observed global price shocks following large-scale droughts occurred in major food producing countries (Porter et al. 2014). Although it is necessary to mitigate climate change and reduce wide ranging impacts, certain mitigation measures may cause adverse side-effects to multiple dimensions of food security. Meeting the long-term climate goal of limiting the global temperature increase no more than 2°C compared to the pre-industrial level requires substantial reduction of GHG emissions, which will likely involve large-scale deployment of bioenergy as a fuel as well as negative emission technologies, including bioenergy plus carbon capture and storage (BioCCS), and forest protection and afforestation (Smith et al. 2015; van Vuuren et al. 2013). However, these mitigation activities tend to have profound implications on finite land and scarce water (Smith et al. 2015; Popp et al. 2011), both of which are key inputs of agricultural production and thus affect production costs and food prices (Lotze-Campen et al. 2014; Wise et al. 2009; Calvin, Clarke, Krey, Blanford, et al. 2012; van Vuuren et al. 2010; Popp et al. 2011; Krey and Clarke 2011). In addition, mitigating GHG emissions may present immediate economic burden by investing in more expensive non-fossil-fuel technologies, which hinders the near-term economic development and poverty reduction in developing countries (Jakob and Steckel 2014), and poverty is closely related to consumers' lack of ability to acquire food (Barrett 2010).

Given these complex interactions, we need to take an integrated approach for effective climate policy-making, which maximizes the synergies and minimizes the adverse side-effects between meeting the climate and other societal objectives. My dissertation therefore asks an overarching research question: “*As we enhance our ambition to meet stringent climate target over the long-run, how might different designs of climate policies impose additional risks to regional food availability and access?*” More specifically, it tries to answer a series of questions that are highly relevant to climate policy making:

- *Do we need to be concerned about the adverse side-effects on food availability and access from climate mitigation?*
- *Under what policy conditions do we need to be concerned?*
- *What is (are) the main cause(s)? (i.e. competing use of land, economic burden)*
- *How should we design climate policies so that the side-effects on food availability and access can be minimized or avoided?*

By answering these questions, my research aims to inform policy makers about one unintended social consequence – with respect to food availability and access – that might be triggered by certain mitigation measures because of the complex feedbacks between energy, agriculture, and land systems.

1.2. Literature and research gaps

Prior research has looked at the potential impacts between mitigation and food security from several different perspectives. The competition of limited land is expected to increase between the use for forest, bioenergy and agriculture (Lambin and Meyfroidt

2011; Thomson et al. 2010; West et al. 2010). One set of studies focuses on quantifying these impacts on food production and producer prices. A number of studies have recognized the competing use of land between agricultural, environmental, and ecological purposes (Rose et al. 2013; Creutzig et al. 2015; Wicke et al. 2014; Smith et al. 2015; van Vuuren, van Vliet, and Stehfest 2009). Specifically, several modeling exercises show moderate producer price increase under strong bioenergy expansion (Lotze-Campen et al. 2014; Wise et al. 2014; Popp et al. 2011), assuming future production of biomass can be integrated with food and timber production as by-products, residues or wastes. By contrast, much larger increases in global price are found with large-scale afforestation when terrestrial carbon emissions are valued (Calvin et al. 2013; Reilly et al. 2012; Popp et al. 2011).

Global producer price, however, is an indicator of food production and availability (Godfray et al. 2010). Looking at the change in global price tends to hide large regional variation from two perspectives. First, access to food, or consumers' ability to acquire food, depends on food prices, their income level and institutional factors (Barrett 2010). The same price increase thus has different impact on consumers' food access across regions due to different economic conditions (Ivanic, Martin, and Zaman 2012; de Hoyos and Medvedev 2011). Second, global price increases will not be fully transmitted to consumers or at the same rate across regions (Leibtag 2009; Dawe 2008; Dawe et al. 2015), and therefore impacts on consumer prices vary largely across regions (Brown et al. 2012; Bekkers et al. 2013). Only a few more recent studies have looked at the impacts on another dimension of food security – consumers' food access, by evaluating the reduced total caloric consumption under different mitigation strategies

(Hasegawa, Fujimori, Shin, et al. 2015; Havlík et al. 2015; Golub et al. 2013). In particular, Golub et al. (2013) examines the impacts of carbon prices on consumers' calorie consumption, however, without specifying specific climate targets. Havlík et al. (2015) looks at the change in caloric intake under a stringent climate target, but does not take into account the impact of climate mitigation on consumers' economic conditions. For developing countries, in particular, mitigation is expected to compromise economic development and poverty reduction by replacing cheap fossil fuel energy with the more expensive renewables (Jakob et al. 2014; Jakob and Steckel 2014; Barbier 2014). For example, Hussein, Hertel, and Golub (2013) finds that a terrestrial carbon sequestration policy will raise poverty in the majority of 14 developing countries. By assessing not only the combined but also individual impacts of food price and income change from climate mitigation on caloric energy intake, Hasegawa, Fujimori, Shin, et al. (2015) finds that reduction in calorie consumption depends more strongly on income change caused by mitigation cost.

Moreover, all of these analyses focus on total caloric intake as the key measure of consumers' food access. Total caloric intake, as well as the associated metric of *people at risk of hunger* – who consume below certain calorie threshold, has been widely adopted to assess long-term change in food security (Parry et al. 2004; Rosenzweig and Parry 1994; Schmidhuber and Tubiello 2007). Although calorie consumption depends on both food price and income, it is very inelastic to price change. As a result, when food prices rise, the poor are more than often to maintain caloric energy intake level at the expenses of diet diversity, nutritional quality and the consumption of other goods (Brinkman et al. 2010; Campbell et al. 2010; D'Souza and Jolliffe 2014; Torlesse, Kiess, and Bloem 2003;

Iannotti et al. 2012). Therefore, existing studies tend to underestimate the change in consumers' wellbeing by evaluating the impact on caloric intake without considering increased food expenditures.

Finally, previous analyses have more focused on the comparison of impacts between climate change and climate mitigation, but examined limited climate policy instruments. Two of the most recent studies find lower calorie consumption under scenarios with stringent climate targets compared to those with climate change impacts on crop yields, but both conclude that it is necessary to mitigate because many climate change impacts on agriculture are uncertain or difficult to model (Havlík et al. 2015; Hasegawa, Fujimori, Shin, et al. 2015). Therefore, given the overall benefits of mitigation by avoiding negative climate impacts on multiple dimensions of food security (Wheeler and von Braun 2013; Schmidhuber and Tubiello 2007), what has been missing in the literature is a more solid and important comparison between alternate climate policy designs. Different policies have different implications on land use patterns and mitigation costs, and the associated changes in global producer prices vary largely under different policy structures (Calvin et al. 2013; Reilly et al. 2012; Wise et al. 2009). Also, depending on specific policy regime adopted, regional economic outcomes can vary largely from the global average in terms of mitigation costs (Edenhofer et al. 2010; Höhne, den Elzen, and Escalante 2013; Luderer et al. 2012; Raupach et al. 2014; Tavoni et al. 2015; van Ruijven et al. 2012). Combined, the implications on food consumptions depend on which sectors and country groups will face the carbon tax (Golub et al. 2013).

Therefore, more research is needed to look at these dynamics and perspectives that have not been explored by existing studies and that could alter the results. My

research builds most directly on the work of Hasegawa, Fujimori, Shin, et al. (2015).

Like that research, my dissertation explores how the two channels that climate mitigation may affect food availability and access – changing food prices by altering land use patterns and changing income by affecting economic growth due to abatement costs.

However, my analysis is different in three important ways.

First, it looks at the change in consumers' staple food budget share, in addition to the widely adopted total caloric intake, in the context of IA models. One set of indicators that has been well established in the empirical research community of food security is closely related to household food expenditure data (Jones et al. 2013). Household food budget share has been referred as the Engel's coefficient, which moves inversely with income (Houthakker 1957). Also, the FAO has adopted the share of food expenditure by the poor as one food access indicator to compare across nations (FAO 2014). These food expenditure related indicators, however, have been mostly explored empirically, but not with respect to long-term projections. Therefore, by developing a set of new metrics based on staple food budget share and total caloric intake, my dissertation extends the use of IA models to increase insights into the drivers of long-term food availability and access.

Second, my dissertation compares between a set of three alternate climate mitigation policies for achieving a stringent climate target. These policies are designed to be illustrative to understand the potential risks associated with specific policy instruments. In particular, the policies vary with respect to whether or not and how land use change emissions are managed. This extends the analysis in Hasegawa, Fujimori,

Shin, et al. (2015) that only focuses on mitigation in the energy system, including the use of bioenergy.

Third, I employ a different modeling framework from Hasegawa, Fujimori, Shin, et al. (2015). Not only the two core modeling tools are quite different in general with respect to model structures, representation of the energy, agriculture and land use sectors, baseline assumptions, and so forth, but also my analysis takes different approaches to: (1) estimate future consumer food prices, (2) take into account the change in consumers' economic conditions due to mitigation costs, and (3) compare the impacts between the two channels through which mitigation policy may affect food availability and access. Using different methods is mainly to help us investigate whether the insights from previous studies are robust, instead of making a judgement of which one is better. More detailed information regarding methodological comparison can be found in Section 1.3 and Chapter 2.

1.3. Methodology overview

The main objective of my dissertation to explore the complex feedbacks between energy, agriculture, and land systems determines that an integrated approach for meeting both the climate goal and multiple dimensions of food security is needed, and therefore one of the Integrated Assessment (IA) models – the Global Change Assessment Model (GCAM) – is adopted.

Food security, as we discussed in the beginning, is an intrinsically multidimensional and multifaceted issue. Different approaches have been taken to address different component of this complex issue at different levels. One set literature

focuses on the micro-level food access and utilization by using empirical approach based on household survey data, which has been closely tied to nutrition and human health (Bhargava 2014; Bashir and Schilizzi 2013; Iannotti et al. 2012). Another set of literature qualitatively assesses the stability dimension (Braun 2009; Alexandratos 2008; von Braun and Tadesse 2012; Trostle et al. 2011; Jensen and Anderson 2014), or combined with micro-level data, explores the short-run impact of a system shock on other dimensions of food security (Bakhshoodeh 2010; Iannotti and Robles 2011; Martin-Prevel et al. 2012).

My dissertation, instead, is in line with the set of food security literature that use IA models or agro-economic models to assess long-term trends of the macro-level food availability and accessibility across the globe (Fischer et al. 2005; Hasegawa, Fujimori, Takahashi, et al. 2015; Parry et al. 2004; Rosenzweig and Parry 1994; Schmidhuber and Tubiello 2007). Although the temporal and spatial scopes of the modeling tool average micro-level inequality and short-term volatilities, the IA modeling approach is able to provide insights of the long-term trends along a wide range of uncertain futures. Furthermore, using the IA model allows me to explore the complex interactions between the climate, economic, energy, land use, and agricultural systems within an integrated framework.

In particular, I use GCAM 4.2, a global Integrated Assessment (IA) model that links the economic, energy, land use, water, and climate systems in a single, integrated framework. It is a market equilibrium model – prices for all markets adjust until supply and demand are equal – and runs through 2100. GCAM's bottom-up representation of the global agriculture and land-use system is fully integrated with socioeconomic drivers and the energy system. 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 fully-integrated land use system in GCAM allows me to explore the impacts of different policy approaches to manage terrestrial emissions on agricultural production. To answer my research questions, this bottom-up land system and the land use decision-making dynamic is one of the main advantages of GCAM, compare to other IA models, including the AIM/CGE model used in Hasegawa, Fujimori, Shin, et al. (2015).

To assess long-term food availability and access, I begin with the GCAM to project future calorie consumption and global market prices for staple commodities under alternate population and economic growth trajectories and climate mitigation strategies. I then estimate regional consumer prices along with future global market prices from GCAM and a post-estimated metric based on consumers' staple food budget share and total caloric intake. Chapter 2 explains each component and step of the modeling framework.

Although the IA model approach, and GCAM in particular, has many strengths to answer my research questions, there are also several limitations with the modeling framework. With respect to the IA models overall, they are designed to assess long-term trends but not system volatilities, and regional/national averages but not with-in country inequalities. Both are important components to understand different dimensions of food security.

With respect to GCAM in particular, this version does not include a demand response to price changes for crops or substitution between different food commodities (Kyle et al. 2011). Also, differences in regional diet composition are assumed to reflect

regional preferences and the share of individual commodities in the shares of individual food crops or animal commodities are fixed at the 2010 levels (Kyle et al. 2011). On the other hand, GCAM is very flexible to switch the production between crops, and has completely free global trade of agricultural commodities. Specifically, because of this free global trade, price of an agricultural commodity from GCAM is cleared at the single global market equilibrium. By contrast, many general equilibrium (GE) models, like the AIM/CGE model used in Hasegawa, Fujimori, Shin, et al. (2015), differentiate domestic and imported commodities and thus also generate regional prices by adjusting tariffs for imports. Given the trade function in GCAM, I take a different approach to estimate future regional consumer prices. It is based on alternate assumptions along with the single global market price from GCAM, by using empirical relationships with historical data.

Moreover, compared to the AIM/CGE model, GDP in GCAM is exogenously determined and thus does not capture either the impact of mitigation costs or the feedbacks to agricultural income due to changing food prices. To assess the impact of mitigation costs on food availability and access by changing economic conditions, I take a two-step's modeling experiment that involves adjusting GDP offline with abatement costs. Finally, I conduct a decomposition analysis of the metric to distinguish the impacts between the two channels of effects – changing food prices and changing income, while Hasegawa, Fujimori, Shin, et al. (2015) compares between runs with and without land competition with bioenergy to achieve ambitious climate mitigation. In summary, these different approaches from earlier studies are taken because I try to explore new perspectives of food availability and access under new conditions, by using a different

modeling tool that has advantages to explore the land system feedbacks with climate mitigation.

1.4. Dissertation structure

The rest of my dissertation starts with the development of the metric of food availability and access (FAA). Chapter 2 first reviews existing metrics that have been adopted for long-term assessment using IA models or agro-economic models, by discussing their strengths and weaknesses, and identifies that it is challenging to find an appropriate metric that can be assessed using IA models. It then proposes a new metric of FAA with two main components. Specifically, the metric is defined as the fraction of GDP per capita spent on staple food weighted by total caloric intake. The metric is then compared with another widely adopted metric from FAO using historical data. Next, the modeling framework to estimate long-term FAA is introduced, including: the core modeling tool – GCAM, the adjustment of GDP with abatement costs, the estimates of consumption and global market prices of staple food along with socioeconomic development and policy scenarios with GCAM, the estimates of regional consumer prices based on empirical relationship with the global market price from GCAM using historical data, and the presentation of the base year FAA conditions using the methods developed above.

Chapter 3 runs a series of experiments to better understand the metric and test its robustness. It explores how variations of these interacting drivers will affect long-term regional FAA. Specifically, it looks at three dimensions of uncertainty: population and

economic growth, the evolution of regional consumer prices, and shocks to global prices, such as those caused by drought.

Chapter 4 presents the core results to answer my research questions that under what policy conditions we need to be concerned about the unintended consequences to FAA from climate mitigation, by using the set of new metric and methods developed in Chapter 2. It extends previous analysis to explore a range of alternative climate policy instruments, including carbon price on the energy system emissions alone or on terrestrial emissions as well, or with two levels of natural land protection in each region. To understand the underlying causes, it not only investigates the combined but also the separate effects of the two channels – changing food prices due to land use competition and changing income due to abatement costs – through which global climate policies may impact regional FAA.

Chapter 5 discusses the policy implications specific to climate policies in the land use sector. Results from Chapter 4 are applied to inform land use policies with respect to how to minimize or avoid the potential unintended outcomes to food availability and access with more carefully designed policies. Chapter 5 focuses on the land use policies in practice at both international and national level, such as the Reduce Emissions from Deforestation and forest Degradation (REDD), and national policies with several case countries, including Brazil, Indonesia and a few African countries.

Finally, Chapter 6 concludes first with a recap of the key results that answer my research questions. It then discusses broader policy implications beyond land use policies, such as measures that improve agriculture and food systems while limiting cropland expansion, such as sustainable agricultural intensification, food chain resilience,

as well as demand-side management. Research caveats, contributions, and future research directions are discussed in the end.

Chapter 2. Assess food availability and access with a new metric (FAA)

Food security is an intrinsically multidimensional and multifaceted issue. The Food and Agriculture Organization (FAO) of United Nations categorizes food security with four key dimensions: availability, access, utilization, and stability (FAO, IFAD, and WFP 2012). These four dimensions are often conceptualized as a pathway that can be traced from the macro-level physical availability to the micro-level food access and utilization with stability being the ability to achieve these three dimensions as a function of time (Jones et al. 2013; Barrett 2010).

Given the complexity of food availability and accessibility, it is challenging to find a metric to be examined using IA models. This chapter first reviews a number of indicators that have been widely adopted for long-term assessments, by discussing their strengths and weaknesses. Based on the review of existing metrics, it then develops a new metric of food availability and access, FAA, as well as a set of methods to post-estimate the metric using outputs from one of the Integrated Assessment (IA) model – the Global Change Assessment Model (GCAM).

2.1. Existing metrics for long-term assessment

A diverse set of tools and models, including IA and agro-economic models, have been employed to explore long-term trends of the macro-level food availability and accessibility across the globe (Fischer et al. 2005; Hasegawa, Fujimori, Takahashi, et al. 2015; Parry et al. 2004; Rosenzweig and Parry 1994; Schmidhuber and Tubiello 2007). IA and agro-economic models are able to investigate the effects of multiple uncertain and interacting drivers such as population, economic growth, and climate change on different

aspects of food security. Given the complexity and multiple dimensions of food security, a number of indicators have been adopted, such as total caloric consumption, nutritional status, and international food prices, by using model outputs either directly or with post-estimation techniques (van Dijk and Meijerink 2014). However, there are limitations in terms of using these indicators to assess long-term food availability and access.

It is very common to look at total caloric intake or metrics that are based on total caloric intake, such as prevalence of undernourishment (PoU), or the number of people at risk of hunger, which is defined and calculated as *the population whose total caloric consumption is below certain national threshold*, in the IA modeling community (Hasegawa, Fujimori, Takahashi, et al. 2015; Parry et al. 2004; Parry, Rosenzweig, and Livermore 2005; Fischer et al. 2005; Rosen et al. 2014; Schmidhuber and Tubiello 2007). Another example of the total calorie-based indicator is child malnutrition, which is estimated using an empirical relationship with average caloric availability (Nelson et al. 2010). Although total caloric intake and the total calorie-based measures may capture the impact of changing income on food access, they may not well capture the impact of changing food prices. Because calorie demand are inelastic, consumers' well-being are likely further reduced by increased food expenditures. Rising food prices tend to increase food expenditures as well as poverty (Ivanic and Martin 2008; Ivanic, Martin, and Zaman 2012).

Total calorie intake is unresponsive to price changes because of two main causes. First, because demand for food is relatively price inelastic (Andreyeva, Long, and Brownell 2010; Green et al. 2013), higher prices or large price shocks, such as those caused by severe drought, may cause small changes in consumption level but large

increases in food expenditure and large declines in welfare of the poor (de Hoyos and Medvedev 2011; Ivanic, Martin, and Zaman 2012). Second, increasing prices may decrease nutritional quality instead of total calorie intake, as consumers try to maintain the level of energy consumption at the expense of dietary diversity (Jensen and Miller 2010). While there is evidence that higher prices do cause some reduction in total calorie intake particularly for households with higher baseline calorie intake (Iannotti and Robles 2011), households with low baseline caloric consumption – the most food insecure – are less likely to reduce total energy, but rather shift consumption toward staple commodities, with associated declines in nutritional quality (Brinkman et al. 2010; Campbell et al. 2010; D’Souza and Jolliffe 2014; Torlesse, Kiess, and Bloem 2003; Iannotti et al. 2012). Perhaps counter-intuitively, rising prices for staple commodities can increase both the share of calories from, and total consumption of, staples (Skoufias 2003). Maintaining total calorie consumption in the face of rising staple prices requires shifting consumption away from, still comparatively more expensive, animal and non-staple crop foods.

Some other studies examine global and regional producer prices that are directly generated from IA or agro-economic models. For example, a number of global leading agro-economic models explored future global food production, demand, and resulting prices across different socioeconomic and climate change impacts scenarios (Nelson and Shively 2014; von Lampe et al. 2014). In this exercise, changes in world food prices due to increasing population and income were different both in magnitude and sign and highly dependent on models’ assumptions over the yield improvement rates and other features of the food system (Valin et al. 2014). The effect of long-term climate change

impacts on crop yields resulted in consistently higher world prices compared to the reference scenario without climate impacts across all participating models (Nelson et al. 2014). More recent studies extend the analysis by including a broader range of socioeconomic scenarios and find the same result (Havlík et al. 2015; Wiebe et al. 2015). Other factors also cause higher prices, including resource competition with bioenergy (Lotze-Campen et al. 2014), and strong mitigation policies that cover land-use change emissions (Havlík et al. 2015).

The food price estimates in these studies are either global market-clearing prices or regional producer prices. However, understanding food access requires information of the market prices faced by consumers, while producer prices are only one component of consumer prices. There can be large variability in consumer prices across countries. These differences are due to factors like income level, transportation costs, exchange rates, producer and consumer subsidies, trade restrictions, and other policy interventions (Bakhshoodeh 2010; Dawe and Maltoglou 2014; Brown and Kshirsagar 2015; Dawe et al. 2015).

As far as we discussed, both total caloric intake and global and regional producer prices have some limitations in assessing long-term food availability and access. In the next sections, I develop a new metric that incorporates the staple food budget share and total caloric intake, by using outputs from GCAM and taking into account consumer food prices, income and average caloric intake at the regional level.

2.2. A new metric of FAA with two components

One set of indicators that has been well established in the empirical research community of food security, but not in the IA modeling framework, is closely related to household

food expenditure data (Jones et al. 2013), and the household food budget share has been referred as the Engel's coefficient, which moves inversely with income (Houthakker 1957). Also, the FAO also adopts the share of food expenditure by the poor as one food access indicator to compare across nations (FAO 2014). Therefore, the proposed metric incorporates both the staple food budget share and total caloric intake.

The measure, FAA, or the consumption adjusted staple expenditure as % of average income, is defined as the share of GDP per capita spent on staple food commodities, weighted by relative total caloric intake. The mathematical expression is shown in Equation 1:

$$FAA_{(s,r,t)} = \frac{\sum_i^5 C_{(s,r,t,i)} \times P_{(s,r,t,i)}}{I_{(s,r,t)}} \times \frac{E_{(US,2010)}}{E_{(s,r,t)}}$$

Equation 1

Where:

$FAA_{(s,r,t)}$ = food availability and access of region r in year t under scenario s

$C_{(s,r,t),i}$ = consumption per capita of staple commodity i of region r in year t under scenario s

$P_{(s,r,t),i}$ = consumer food price of staple commodity i of region r in year t under scenario s

$I_{(s,r,t)}$ = GDP per capita of region r in year t under scenario s (as indicative of the average income)

$E_{(s,r,t)}$ = daily caloric energy consumption per capita of region r in time t

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

The proposed metric is the product of two parts. The first part reflects the average share of income spent on staple foods in a region. A large fraction can occur when income is low, consumption is high, and/or prices are high. I focus on staple food commodities, including corn, rice, wheat, other grains, and roots and tubers, not only because staples

tend to be the main energy sources for the poor, but also considering that the share of dietary consumption of staple goods is an indicator of nutritional status. Therefore, the first part captures both a nutritional and economic component of food access: at the same level of total caloric intake, high consumption of staples is an indicator of low nutritional quality, and low levels of economic access occur when a high share of income is used to purchase staples. In fact, once energy intake is sufficient, consumption of staples tends to decrease as income increases, so these measures reinforce each other.

The second part of the metric compares the regional average daily total calorie intake to a reference value (United States in 2010). Total calorie consumption reflects availability of food as well as basic nutritional status, and varies across regions. For consistency with the expenditure piece, the regional value is placed as the denominator, so that lower caloric consumption generates a higher value and indicates lower food availability. And as the product of the two pieces, higher values of the metric signal worse FAA conditions.

We compare our metric FAA with an FAO indicator of food access, the prevalence of undernourishment (FAO, IFAD, and WFP 2014), using real country-level data from 2003 to 2008. The general trends in distribution and magnitude across countries are consistent between the metrics (Figure 2.1). Both identify Sub-Saharan Africa as the worst, while slightly disagree about several countries in Asia. The FAO metric depends on income level and distribution that more closely links to poverty and total caloric intake, and thus indicates similar food access conditions in the poor Asian and African regions. Our FAA metric, by also accounting for regional variability of consumer prices, shows better food

access in the poor Asian countries, suggesting that consumers in these countries may face lower staple food prices than consumers in the poor Africa.

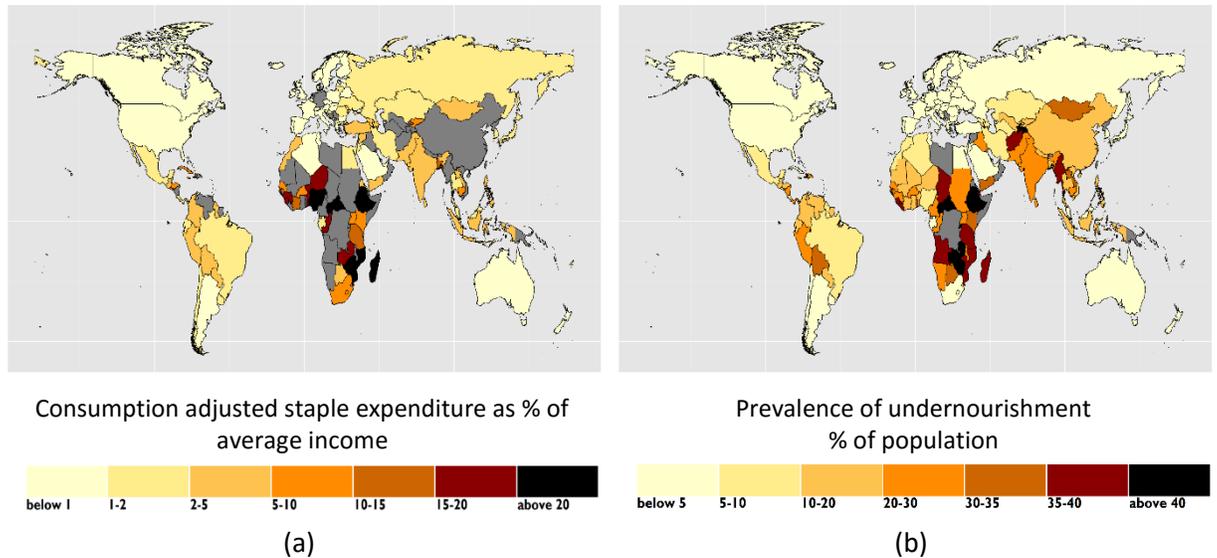


Figure 2.1 Food availability and access by country with historical data, average 2003-08 Reflected in: (a) our FAA metric of consumption adjusted staple expenditure as % of average income; and (b) FAO metric of prevalence of undernourishment

2.3. Model long-term FAA

With the proposed metric, I employ the Global Change Assessment Model (GCAM 4.2) to explore the impacts of mitigation on regional FAA under a set of scenarios, by taking into account alternate climate policy designs and socioeconomic pathways, the effects of both changing income and food prices from climate mitigation, regional variability of consumer prices, and the resulted change in both staple food budget share and total caloric intake. The modeling framework is shown in Figure 2.2.

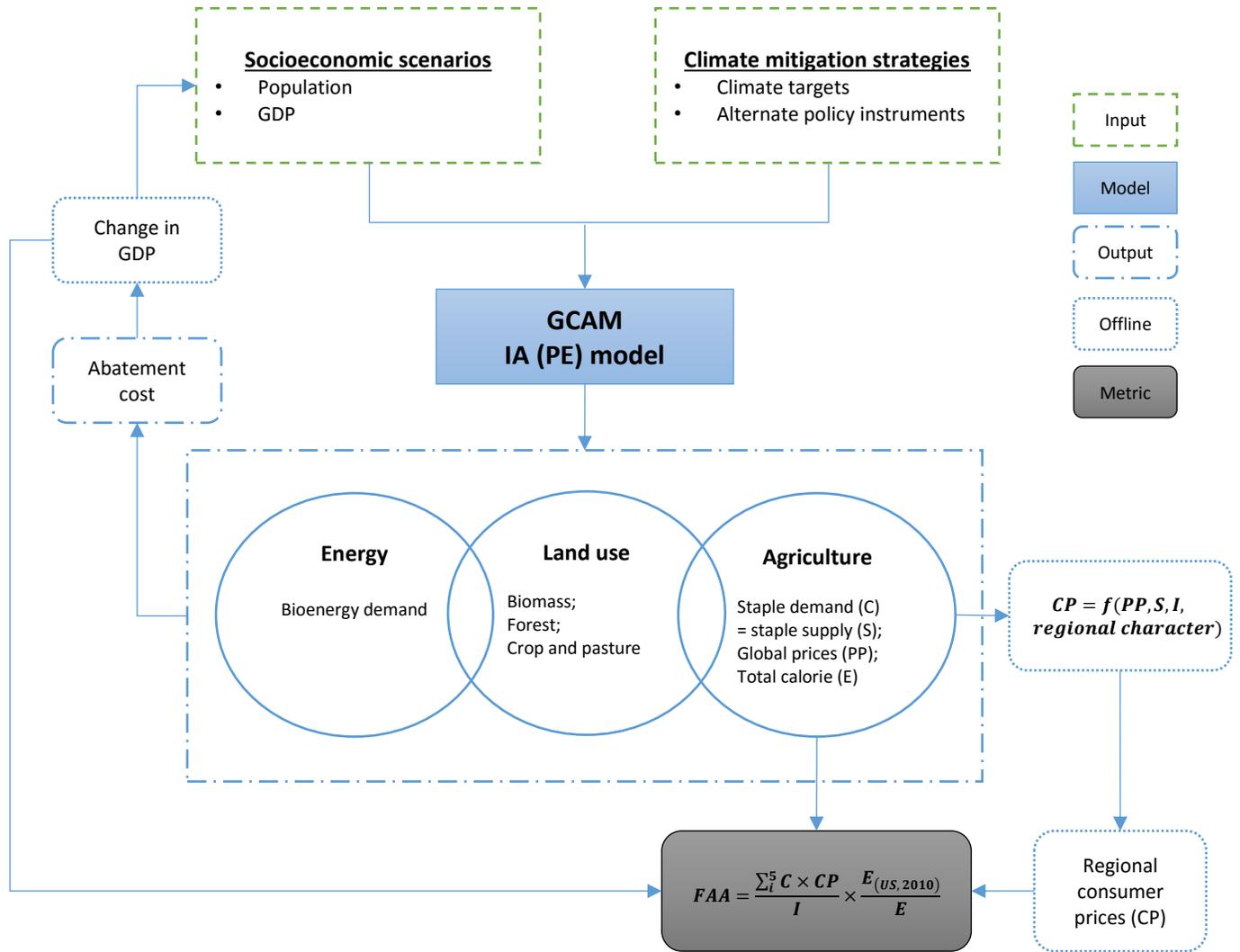


Figure 2.2 Modeling framework

In the next subsections, I explain each of the key components in the modeling framework. First, the core modeling tool, GCAM, is introduced, and how it estimates changes in food consumption and global prices along different expectations of population and GDP growth. Second, a two-step’s modeling experiment that takes into account the effect of income changes due to abatement costs is presented. Third, the effects of land-use competition from climate mitigation on global market prices is described. Fourth, the

empirical relationships to model future regional consumer prices with the global market prices from GCAM are developed using historical data. And finally, the regional FAA conditions in the base year are presented using the post-estimation process.

2.3.1. The Global Change Assessment Model (GCAM)

The Global Change Assessment Model (GCAM) is partial equilibrium model that links the economic, energy, land use, water, and climate systems in a single, integrated framework¹. It has been extensively applied in climate research to examine the effects of different mitigation strategies as well as climate change impacts (Calvin, Clarke, Krey, van Ruijven, et al. 2012; Thomson et al. 2011; Wise et al. 2009; Nelson et al. 2014; Kriegler et al. 2013). GCAM captures interactions between improvements in technology and productivity over time, demand changes due to increasing exogenous population and income levels, and the resulting global market-clearing prices of primary and secondary energy, agricultural and forest products through 2100 at a five-year interval.

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 GCAM, comprised of 32 geopolitical regions, overlaid with 18 Agro-ecological Zones (Calvin et al. 2014). Each of the 283 land use regions is comprised of up to 18 land use types – 12 crops, pasture, forest, grassland, shrub land, other arable land, and biomass – that are fully integrated into the economic system, as well as the exogenous categories of tundra,

¹ More documentations can be found at <https://wiki.umd.edu/gcam>.

rock/ice/desert, and urban land. The decision of land use is based on the relative profitability among alternative uses (Calvin et al. 2013).

Under different population and economic growth scenarios, both regional consumption and global prices will change in GCAM. Total food demand is directly driven by both population and income levels. All else equal, more people will require more food. Similarly, higher incomes will result in higher demand, particularly for consumers with currently very low income and consumption levels. In these scenarios, crop yields improve at exogenous, regionally-specific rates that are consistent with the FAO forecasts (Kyle et al. 2011), so increased demand, either from higher income or larger populations, will cause agricultural production to expand into less productive land, decreasing average yields and increasing global prices.

2.3.2. Model income change with abatement costs in GCAM

As GDP are exogenously decided in GCAM, in order to investigate the effect of changing income (GDP per capita) due to abatement costs on FAA, I conduct a two-step's modeling experiment to adjust the exogenously decided GDP.

Specifically, in the first run of each policy scenario, I obtain regional abatement costs in each five-year interval period, which, as discussed, are affected by both the policy tool and socioeconomic pathway. GCAM simulates the optimal carbon price and emission pathways to reach the climate target with each alternative policy tool (Figure A15 and Figure A16 in Appendices), and the associated regional abatement costs are measured in term of the area under marginal abatement cost curves.

I then calculate the new GDP trajectories through 2100 by subtracting the original GDP by abatement costs in each period offline. These adjusted new GDP growth

trajectories are next translated into equivalent labor productivity growth pathways, to be used as exogenous inputs in the second run of the policy scenarios. The second run repeats the first run's emission pathway and policy design to reach the climate target. Theoretically, with the adjusted GDP per capita, both food demand and global market prices will be affected in the second run, and thus the impact of changing income due to abatement costs is incorporated.

2.3.3. Model food price change with land use competition in GCAM

GCAM's land-use system includes 18 land use types – 12 crops, pasture, forest, grassland, shrub land, other arable land, and biomass – that are fully integrated into the economic system, as well as the exogenous categories of tundra, rock/ice/desert, and urban land. The decision of land use is based on the relative profitability among alternative uses (Calvin et al. 2013). The feature of fully-integrated land use system in GCAM allows me to explore the impacts of policies that protect natural land or value land use change emissions on agricultural production. Moreover, the link between energy and agriculture/land use sectors through bioenergy allows me to explore the impacts of policies that tax energy system emissions on agricultural production.

The agricultural sector in GCAM 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. We define this market equilibrium price as global producer price, in differentiating from the regional consumer prices that we will post estimate. With increased demand, either from higher income or larger populations, agricultural production tends to expand into less productive land, decreasing average yields and increasing global prices, which, however, may be

offset by the regionally specific rates of yield improvement (Wise and Calvin 2011; Kyle et al. 2011). However, when the available land for agriculture is limited or reduced due to the expansion of other more profitable competing use, the cost of food production is thus increased, so is the global producer price, until the agricultural product becomes more profitable. Therefore, with the adopted climate target and alternative policy instruments in our scenarios, the relative profitability of forest and bioenergy – two mitigation options – increases, which may restrain agricultural expansion or even replace crop production. As food demand keeps growing, global food price raises so to compete with the land use type for mitigation.

2.3.4. Estimate regional consumer prices based on empirical relationships

Many IA models, including GCAM, estimate global market-clearing (van Dijk and Meijerink 2014) or domestic producer prices that include regional transport cost functions (Havlík et al. 2015; Biewald et al. 2015). However, neither global nor domestic producer prices provide accurate estimates of consumer prices or hence food expenditures (Brown et al. 2012). Using producer prices will both underestimate consumers' food expenditures and obscure regional variability in consumer prices. In this section, I develop two empirical models to estimate regional consumer prices, as a function of global market prices and other factors.

2.3.4.1. Alternative assumptions of regional consumer prices in 2050

Differences between consumer prices and producer prices, also called price or distribution margins, are caused by costs along the food supply chain from agricultural production to food processing and distribution sectors (Smith 1992). These other costs

are larger in higher income countries (Adamopoulos 2008) – the price of producing crops represents a smaller share of consumer food prices as income increases. This difference in margin between rich and poor countries is important when producer price shocks: the pass-through to consumer price will have a larger proportional effect in lower-income regions. Moreover, consumer prices will also be affected by other country-specific factors, such as transportation costs, exchange rates, producer and consumer subsidies, trade restrictions and other policy interventions (Bakhshoodeh 2010; Dawe and Maltsoğlu 2014; Brown and Kshirsagar 2015; Dawe et al. 2015).

To estimate future regional consumer prices, I develop empirical relationships with variables such as the United States' producer prices (as a proxy of global market prices), regional food supply, and income. The choice of variables was determined by theory – these variables represent known correlated of consumer prices – and data availability, both historic and model outputs. This approach is not intended to be a structural analysis of consumer food prices, but to use historical correlations to estimate long-term consumer prices in a simple and straightforward way.

Moreover, I explore uncertainty around how regional consumer prices may change over time by employing two models that represent different possible ways of price evolution in 2050. Consumer prices are influenced by many factors, some of which may interact (e.g., income level and institutions) and there may be unobservable, unchanging country-level characteristics. The two methods are developed based on two alternative assumptions about the change of these regional characteristics except for income (Table 2.1).

Table 2.1 Two scenarios of changes in regional consumer prices over time

	Main assumptions
The segmented market (Equation 2)	Regional consumer prices will change with the global market prices, the average food supply, and the average income levels (GDP per capita), regional fixed effects persist.
The integrated market (Equation 3)	Country-specific characteristics will be negligible, and regional differences are only due to the relative labor costs (GDP per capita).

$$CP_i = \beta_0 + \beta_1 \cdot US.PP_i + \beta_2 \cdot \ln(supply/cap_i) + \beta_3 \cdot \ln(GDP/cap) + region\ dummies$$

Equation 2 – the segmented market

$$CP_i = \beta_0 + \beta_1 \cdot US.PP_i + \beta_2 \cdot \ln(GDP/cap)$$

Equation 3 – the integrated market

Where:

CP_i = Regional consumer price of staple commodity i

$US.PP_i$ = US producer price of staple commodity i, as a proxy for the global equilibrium price

$supply/cap_i$ = food supply per capita of staple commodity i

GDP/cap = GDP per capita

$region\ dummies$ = GCAM region fixed-effects variables

2.3.4.2. Data

I build separate models for each of the five staple commodities using historical data from several different sources: (1) domestic consumer food prices from the International Labor Organization October Inquiry (LABORSTA Internet 2014), (2) the United States' producer prices from the Food and Agriculture Organization (FAOSTAT 2014b), (3) national food supply from the FAO food balance sheets (FAOSTAT 2014a), (4) population from the United Nations (United Nations 2012), and (5) GDP in PPP from the Penn World Table (PWT7.1) (The Penn World Table 2012). The available data set covers the time period of 1985 to 2008. The United States' producer prices are employed

as a proxy of the global market prices in order to be consistent with GCAM calibration of the base year global equilibrium prices (Kyle et al. 2011).

Most of the original data are reported at the national or subnational level, and this section explains how these data are processed and aggregated to the 32 GCAM regions, using consistent methods by which agriculture and socio-economic base year data are calibrated in GCAM (Kyle et al. 2011).

ILO consumer price data are collected from individual national authorities and combined with little harmonization. It reports food prices in local currency at either national or subnational level from 1985 to 2008. The first step to clean the ILO data is to calculate the national price when more than one observations are reported in each country-year. I take the simple average of all reported numbers to make it consistent across all countries given the extremely low availability of subnational data in certain regions. However, it may create bias when subnational consumer prices are not representative, especially when non-representative price data are averaged for the single country regions in GCAM. For example, in the case of China, all of the five reported subnational observations come from cities, which are likely to overestimate national consumer food prices. One possible solution is to use the income-weighted national average for China. This adjustment, however, may have to be performed on a case-by-case basis for other countries, depending on the nature of bias from reported observations as well as data availability at the subnational level. To make it simple and transparent, we did not make any subnational adjustment.

The second step is to harmonize currencies. National prices in nominal local currency are first converted to nominal US dollar by applying the International Monetary

Fund (IMF) based exchange rates²; and then adjustments are made in the case of change of currency or hyperinflation occurred during the time period of 1985 to 2008³; and finally, all prices are transformed to constant 2005 US dollar by applying the GDP deflators reported by the US Bureau of Economic Analysis⁴. The same deflators are used for converting US producer prices and national GDP that are originally reported in nominal dollar to the constant 2005 US dollar.

The third step is to harmonize the food items covered by different sources. Both the ILO consumer food price database and the FAO food balance sheets cover a long list of food items, of which we focus on 5 categories, including corn, rice, wheat, other grains, and roots and tubers. The harmonizing method between GCAM commodities and FAO definition of food items can be found in Kyle et al. (2011), and Table 2.2 shows what are available in the ILO database and how they pair with the GCAM commodities as well as FAO food items.

Table 2.2 List of GCAM commodities and ILO and FAO food items

GCAM commodity	ILO food item	FAO food item
Corn	Corn (maize), flour	Maize
	Corn (maize), whole grain	
Rice	Rice, long grain	Rice (Paddy Equivalent)
Wheat	Wheat flour, white	Wheat
	Wheat flour, whole	
Other Grain	Sorghum	Barley
		Cereals, other
		Millet

² Data source: The National Accounts Main Aggregates Database, United Nations Statistics Division, <http://unstats.un.org/unsd/snaama/dnllist.asp>. In this database, the IMF reported market exchange rates are first selected, and other IMF rates (official rates or principal rates) are used when market rates are not available.

³ Conversion rates between the old and new currencies can be found at <http://faostat.fao.org/site/564/default.aspx>

⁴ Table 1.1.9. Implicit Price Deflators for Gross Domestic Product.

<http://www.bea.gov/iTable/iTable.cfm?ReqID=9&step=1#reqid=9&step=1&isuri=1>

		Oats
		Rye
		Sorghum
Root & Tuber	Cassava	Cassava
	Potatoes	Potatoes
	Sweet potatoes	Sweet potatoes
	Yams	Yams
		Roots, Other

For corn and wheat, ILO provides consumer prices of two different products under each commodity respectively. However, we cannot further differentiate the two products on the FAO side, and both the US producer prices and consumption data are reported for one item only. Thus, I decide to use the consumer price of corn flour to approximate the consumer price of corn given higher data availability between the two corn products⁵, and similarly use the consumer price of white wheat flour to approximate the consumer price of wheat. For other grains, the ILO price data are only available for one item – sorghum, and thus the consumer price of other grains is approximated by the consumer price of sorghum. On the other hand, the US producer price of other grains is the production-weighted average of the producer prices of five food items list under the commodity category – barley, millet, oats, rye and sorghum. For roots and tubers, both ILO and FAO cover four main food items – cassava, potatoes, sweet potatoes, and yams. Therefore, I use the consumption-weighted average to estimate consumer price of roots and tubers, and the production-weighted average to estimate producer price.

⁵ Except for India, Indonesia and Pakistan, all of which are single-country regions in GCAM but only have the prices of whole grain corn reported. To reduce missing data at the regional level, we instead use the prices of whole grain corn for the three countries. We also tried estimating the corn flour prices for the three countries using a simple linear relationship between the prices of the two products based on data of countries where two prices are available. But the estimates are not comparable to the prices of other food commodities in the three countries.

In the fourth step, a country-panel data set is built combining data from different sources in a consistent way, including consumer prices and total consumption of staple commodities, as well as total GDP and total population. I then aggregate national data to the 31 GCAM regions⁶: regional consumer prices are consumption-weighted average of national prices, and regional per capita consumption of staples and regional per capita GDP are generated using regional total population dividing total consumption and total GDP respectively.

It should be noticed, however, only the country-year observations that have no missing value for all variables in that year are included in regional aggregation. For example, consumer prices of corn are available for only three Eastern African countries⁷ in 1985, and thus not only the regional corn price but also total regional GDP, population and corn consumption are based on the three countries' data in 1985. In most cases, it is the consumer prices that constrain the number of observations included for regional aggregation. The magnitude of missing data across years is another drawback of the ILO data, especially for countries where national data collection is insufficient. The problem can be moderated when aggregating to the 31 regional level as the proportion of missing data is reduced substantially, but regional bias may exist when a few countries dominate the data in certain years. Table 2.3 provides descriptive statistics at the regional level.

⁶ Excluding Taiwan that has no agricultural data.

⁷ They are Burundi, Comoros and Rwanda.

Table 2.3 Descriptive statistics for the aggregated regional data

Variable		N (31*24=744)	% of missing	Mean (std. dev)	Description	Unit	Data source
CP	Corn	417	43.95%	1.19 (1.05)	Regional consumer price of each grain staple commodities	2005US\$/kg	ILO
	Rice	662	11.02%	1.21 (0.91)			
	Wheat	654	12.10%	0.80 (0.54)			
	Other Grain	140	81.18%	0.81 (0.69)			
	R&T	679	8.74%	0.73 (0.64)			
US.PP	Corn	24	0%	0.12 (0.03)	US producer price of each grain staple commodities	2005US\$/kg	FAO
	Rice	24	0%	0.2 (0.06)			
	Wheat	24	0%	0.16 (0.04)			
	Other Grain	24	0%	0.12 (0.02)			
	R&T	24	0%	0.17 (0.02)			
supply.pcap	Corn	744	0%	25.12 (30.11)	Per capita consumption of each grain staple commodities	kg/capita	FAO
	Rice	744	0%	33.37 (39.98)			
	Wheat	744	0%	76.04 (49.11)			
	Other Grain	744	0%	9.97 (13.77)			
	R&T	744	0%	62.62 (41.48)			
GDP.pcap		732	1.61%	10574.01 (11190.35)	Per capita GDP (in PPP)	2005US\$/capita	PWT7.1/ UN
GCAM region dummies	Corn	26	16.13%	n/a	GCAM regions (excl. Taiwan)	n/a	n/a
	Rice	31	0.00%				
	Wheat	31	0.00%				
	Other Grain	14	54.84%				
	R&T	31	0.00%				

2.3.4.3. Regression results

Table 2.4, each column for one individual staple commodity, shows the OLS estimates of the segmented market model. Similarly, Table 2.5 lists the OLS results of the integrated market model. As expected, regional consumer prices tend to positively related with global market prices (as indicative by the United States' producer prices) and GDP per capita, but negatively related with average staple food supply. All estimates of the region dummies are compared to the consumer prices in Australia and New Zealand, and a missing value indicates that historical consumer price data are not available for that staple commodity in that region.

Table 2.4 OLS estimates of the segmented market model (with robust error)

	<i>Corn</i>	<i>Rice</i>	<i>Wheat</i>	<i>OtherGrain</i>	<i>Root_Tuber</i>
Intercept	-0.66 (1.34)	0.77 (0.61)	1.26 *** (0.34)	-1.20 (1.75)	-0.62 (0.53)
US.PP	1.91 (1.01)	2.27 *** (0.29)	2.08 *** (0.22)	4.18 ** (1.46)	1.58 *** (0.44)
ln(supply.pcap)	-0.12 * (0.06)	-0.20 *** (0.03)	-0.27 *** (0.05)	0.04 (0.09)	-0.27 *** (0.05)
ln(GDP.pcap)	0.38 ** (0.14)	0.04 (0.06)	0.09 ** (0.03)	0.35 * (0.16)	0.26 *** (0.05)
GCAM regional dummies (compared to Australia_NZ):					
USA	n/a	0.12 * (0.05)	-0.59 *** (0.06)	n/a	-0.24 * (0.11)
Africa_Eastern	-1.11 * (0.57)	-0.43 * (0.21)	-0.67 *** (0.18)	-1.06 (0.81)	0.16 (0.20)
Africa_Northern	-1.18 * (0.48)	-0.40 ** (0.15)	-0.47 *** (0.12)	-0.51 (0.44)	-0.16 (0.14)
Africa_Southern	-1.17 * (0.55)	-0.25 (0.20)	-0.51 *** (0.14)	-1.69 *** (0.46)	0.40 * (0.20)
Africa_Western	-0.83 (0.51)	0.07 (0.20)	-0.43 ** (0.15)	-1.37 * (0.68)	0.57 ** (0.22)
Brazil	-1.82 *** (0.31)	-0.03 (0.11)	-0.60 *** (0.08)	n/a	-0.17 (0.14)
Canada	n/a	0.88 *** (0.11)	0.02 (0.07)	n/a	-0.52 *** (0.11)
Central America and Caribbean	-1.36 *** (0.31)	0.12 (0.15)	-0.57 *** (0.07)	-1.44 * (0.57)	0.09 (0.16)
Central Asia	-1.64 *** (0.40)	-0.37 ** (0.14)	-0.40 *** (0.11)	n/a	-0.26 (0.14)

China	-1.96 *** (0.40)	-0.39 * (0.18)	-0.78 *** (0.11)	n/a	-0.25 (0.16)
EU-12	-2.01 *** (0.31)	-0.44 *** (0.09)	-0.62 *** (0.07)	-1.62 *** (0.39)	-0.53 *** (0.11)
EU-15	-1.32 *** (0.27)	0.76 *** (0.06)	-0.30 *** (0.07)	n/a	-0.21 (0.11)
Europe_Eastern	-1.76 *** (0.41)	-0.44 ** (0.15)	-0.60 *** (0.09)	n/a	-0.20 (0.14)
Europe_Non_EU	-0.63 (0.32)	0.52 *** (0.13)	-0.18 (0.10)	n/a	-0.48 *** (0.11)
European_FTA	1.57 *** (0.46)	1.25 *** (0.13)	0.14 (0.07)	n/a	-0.10 (0.11)
India	-1.92 *** (0.43)	-0.14 (0.19)	-0.90 *** (0.11)	-1.69 ** (0.57)	-0.45 ** (0.16)
Indonesia	-1.67 *** (0.43)	-0.12 (0.16)	-1.09 *** (0.10)	n/a	-0.33 * (0.15)
Japan	n/a	3.56 *** (0.23)	0.47 *** (0.08)	n/a	1.87 *** (0.16)
Mexico	-1.96 *** (0.35)	-0.18 (0.11)	-0.66 *** (0.07)	-1.97 *** (0.34)	-0.21 (0.14)
Middle East	-1.17 ** (0.45)	0.37 ** (0.12)	-0.35 *** (0.08)	-0.52 (0.75)	-0.43 *** (0.12)
Pakistan	-1.91 *** (0.40)	-0.33 * (0.16)	-0.72 *** (0.12)	n/a	-0.62 *** (0.16)
Russia	n/a	-0.49 *** (0.11)	-0.62 *** (0.08)	n/a	-0.39 ** (0.12)
South Africa	-0.53 (0.47)	0.21 (0.11)	-0.29 ** (0.09)	-1.48 *** (0.41)	-0.26 (0.13)
South America_Northern	-1.69 *** (0.38)	-0.26 * (0.12)	-0.45 *** (0.08)	-0.58 (0.55)	-0.16 (0.13)
South America_Southern	-1.39 *** (0.35)	0.01 (0.11)	-0.15 (0.08)	-1.89 *** (0.49)	-0.18 (0.13)
South Asia	-0.57 (0.39)	-0.08 (0.19)	-0.96 *** (0.11)	n/a	-0.33 (0.17)
South Korea	n/a	1.52 *** (0.10)	-0.74 *** (0.06)	n/a	0.28 (0.15)
Southeast Asia	-0.35 (0.26)	-0.12 (0.14)	-0.39 *** (0.09)	-1.20 (0.71)	-0.36 ** (0.14)
Argentina	-1.58 *** (0.28)	0.40 ** (0.13)	-0.47 *** (0.09)	n/a	-0.27 * (0.12)
Colombia	-1.43 *** (0.36)	-0.15 (0.11)	-0.77 *** (0.10)	n/a	-0.05 (0.13)
Num. obs.	417	662	654	139	679
Adj. R^2	0.75	0.85	0.76	0.56	0.82

Note: std.dev with robust error is reported in (); significant level: *** p<0.001, ** p<0.01, * p<0.05

Table 2.5 OLS estimates of the converging model (with robust error)

	<i>Corn</i>	<i>Rice</i>	<i>Wheat</i>	<i>OtherGrain</i>	<i>Root_Tuber</i>
Intercept	-3.75 *** (0.50)	-3.51 *** (0.26)	-1.02 *** (0.16)	-2.32 *** (0.48)	-2.07 *** (0.23)
US.PP	2.83 (1.72)	2.08 *** (0.45)	2.10 *** (0.40)	5.51 ** (2.03)	1.86 * (0.87)
ln(GDP.pcap)	0.55 *** (0.05)	0.49 *** (0.03)	0.17 *** (0.02)	0.32 *** (0.05)	0.29 *** (0.02)
Num. obs.	417	662	654	139	679
Adj. R²	0.33	0.39	0.22	0.24	0.26

Note: robust std.dev is reported in (); significant level: *** p<0.001, ** p<0.01, * p<0.05

Besides, I also test other model specifications, such as using linear and quadratic of the independent variables, as well as including a net trade variable, calculated by export minus import. Since GCAM does not model trade flows among regions, our choice of trade related variables is limited to net trade that can be calculated as the difference between total domestic supply and demand. Net trade is not significant in any model specification, probably indicating that the connection between global market prices and regional consumer prices is not dependent on trade, and there might be a signal effect of the global market prices to regions even not participating international trade.

2.3.5. Regional FAA conditions in the base year

By using the methods developed in section 2.3.4, this section presents the regional FAA conditions in the base year of 2010 as an illustration based on the outputs from GCAM. The two empirical models provide different insights and both have some advantages and disadvantages.

For the 2010 estimates, the segmented market model reveals greater regional inequality in consumer prices and in FAA than does the integrated market model (Figure 2.3), and is closer to what have seen in recent history (Figure 2.1). The FAA indicates

that in Eastern and Western Africa, a person who consumes average total calorie and average staple food and earns average income spend almost a quarter of his/her income on staple food, and 15 to 20 percent in Southern Africa (Figure 2.3a). These levels of consumption adjusted staple food expenditure correspond to about 239 million undernourished people, or 30 percent on average, in Sub-Saharan Africa in 2010 (FAO 2010). In comparison, Asia and the Pacific regions on average have about 16 percent undernourished population in 2010 (FAO 2010). Corresponding to FAA, the consumption adjusted staple expenditure is about 10 to 15 percent for people at the regional average in South Asia, and all other Asian regions below 5 percent (Figure 2.3a).

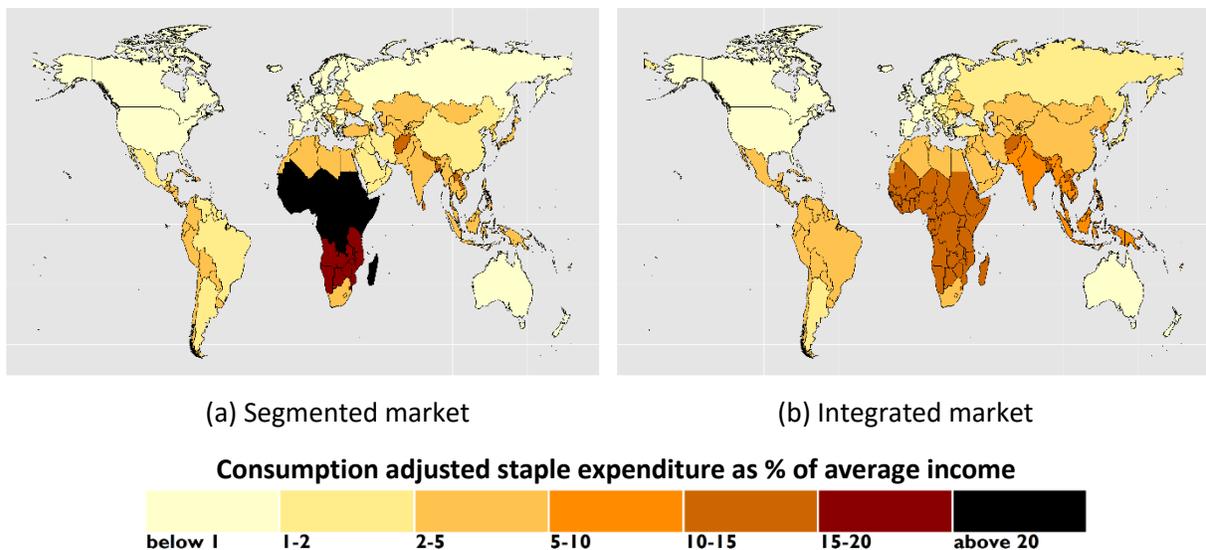


Figure 2.3 Food availability and access conditions in 2010
 By using the regional consumer prices estimated with: (a) the segmented market model; (b) the integrated market model.

The integrated market model, on the other hand, is developed to address the uncertainty of the persistence of regional fixed effects to 2050. It assumes that the fixed effects will be negligible in 2050 and regional variability in consumer prices will decline.

In reality, what we may see is a combination of some degree of convergence with some fixed-effects still in place. For example, many of the subsidies or high inventories in some Asian countries that have historically led to low domestic prices may become more and more expensive to maintain, forcing consumer prices upward. Other characteristics, such as geographic or natural resource limitations though, are less likely to entirely disappear even in the long-run.

Chapter 3. FAA under different future scenarios

This chapter aims to better understand the metric of food availability and access, FAA, by running a series of tests against alternate expectations of the future in 2050. Specifically, it explores the sensitivity of FAA to three dimensions: population and economic growth, the evolution of regional consumer prices, and shocks to global producer prices, such as those caused by drought.

First, the impact of population and economic growth on food consumption and global market prices for staple commodities are explored along five alternative population and economic trajectories, as defined by the Shared Socioeconomic Pathways (SSPs) (O'Neill et al. 2013). Second, the sensitivities of changes in regional consumer prices is explored by using the two empirical models that are developed in section 2.3.4, reflecting different ways in which regional consumer prices may evolve along with global prices in 2050. Finally, the impacts of rising food prices caused by factors beyond population and economic growth is evaluated by increasing global producer prices for staple commodities in 2050 by 100, 200 and 300 percent.

3.1. Scenario designs

I use a set of 20 scenarios to explore three uncertain dimensions in this analysis: future population and economic growth (five scenarios), evolution of regional consumer prices (two models), and the potential impact of higher and more variable global prices (three sensitivities). Each of the dimensions is described in more detail below.

3.1.1. The Shared Socioeconomic Pathways

The Shared Socioeconomic Pathways (SSPs) – provide five alternative population and GDP trajectories at the national level. I use these five development pathways as inputs into GCAM to investigate how food demand, food prices, and ultimately our FAO metric, respond to the uncertainties of regional population and income growth.

Future economic and demographic evolution is uncertain, particularly for the poorest regions. The SSPs are designed to explore a wide range of reference pathways that are independent from climate change impacts or new climate policies that can be employed consistently by different research groups (Kriegler et al. 2012). The five SSPs are defined with both quantitative indicators (GDP, population, and other demographic development variables) and qualitative storylines that further describe alternative pathways along which the world may evolve (O’Neill et al. 2013). For example, quantitatively, SSP1 has relatively high GDP growth (with an increasing equality across regions) and low population growth (Figure 3.1), while its qualitative storyline describes a world of sustainable development with more rapid and environmental friendly technological changes, reduced dependency on fossil fuels, high land productivity, and effective institutions at all levels (O’Neill et al. 2015). In contrast, SSP3 pictures a world in fragmentation and inequality with low GDP and high population growth (Figure 3.1) and slow technological changes and land productivity improvement, strongly constrained global trade, and weak international institutions (O’Neill et al. 2015).

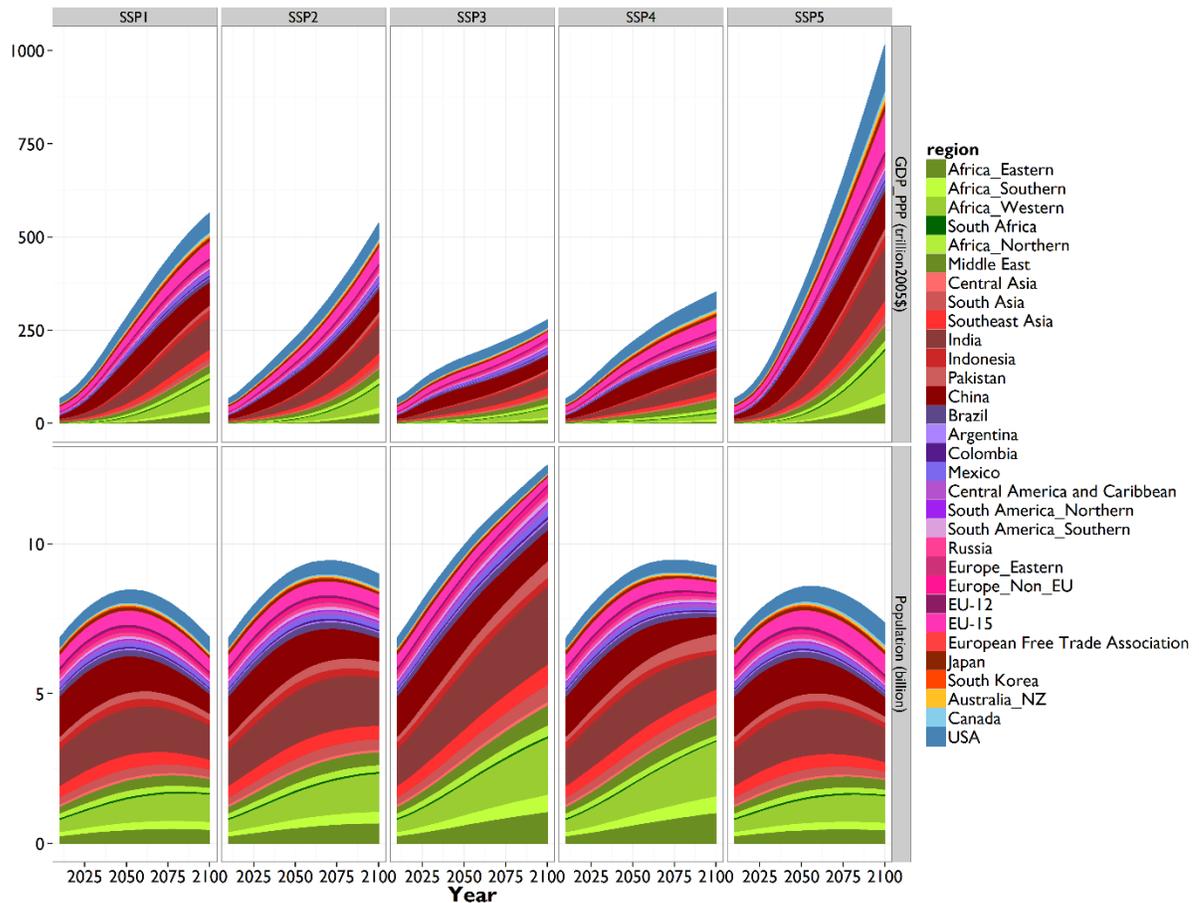


Figure 3.1 GDP and Population by SSP grouped into the 32 regions defined in GCAM

When implementing these development pathways in GCAM, I only employ the two quantitative components – GDP and population – all other assumptions remain at the core model settings with no adjustment for the qualitative SSP storylines. I use this design to explore the direct effects of population and economic growth on FAA, although this method does not capture the likely correlations between socioeconomic change and technological and institutional changes (for instance crop yield rates would likely improve more rapidly under high, rather than low, economic growth scenarios). Many of the other parameters in the SSP narratives have the potential to affect food prices that can be explored in further research.

3.1.2. Uncertainty of future consumer prices

The uncertainty with respect to how regional consumer prices may evolve to 2050 is explored by using the two empirical models developed in section 2.3.4 with different assumptions about regional consumer prices as a function of global market prices and other factors. Both models are applied with each population and GDP trajectory from individual SSPs, and the underlying assumptions about global market framework is not designed to be reconciled with the qualitative SSP storyline.

3.1.3. The higher global prices scenarios

The set of scenarios that only look at the first two dimensions – different population and GDP trajectories, and different ways that consumer prices may change – is defined as the reference scenarios. The final dimension of the analysis is to explore FAA under set of scenarios that are illustrative of factors, other than population and GDP growth, which may cause higher global prices, such as changes in regional crop yields under long-term climate change or abrupt production shocks due to drought. I call the set of scenarios that also include the last dimension as the higher global price scenarios.

In the higher global price scenarios, I increase the reference global prices in 2050 of all five staple commodities at the same time by 100 percent, 200 percent, and 300 percent. The same increase rates are applied to all crops so as not to artificially emphasize effects in one region over another due to differences in staple diets across regions. Further, increasing prices for all commodities will limit substitution across staples, which I do not model in this exercise. In reality, however, all staples would not be uniformly impacted. For example, international rice prices tend to be more volatile, due in part to

smaller and more concentrated markets, as well as less substitution with other staples for many major rice consuming regions (Anderson and Martin 2007).

As discussed, the effects of the producer price increases are not result in the same level of increases in consumer prices due to different price margins (section 2.3.4). When transmitting the global price increases to regional consumer prices using either the segmented or integrated market model, the pass-through rates vary across regions and staple commodities, with the highest pass-through rates in lower-income regions. This is consistent with empirical evidence (Belke and Dreger 2014; Dawe 2008; Leibtag 2009; Brown et al. 2012).

3.2. Results and discussion

3.2.1. FAA condition in 2050 under the reference scenarios

Along all SSP population and GDP trajectories⁸, FAA improves for almost all regions from 2010 to 2050 (Figure 3.2 and Figure. A1 in Appendices). However, we do observe differences across population and GDP growth scenarios. Under the high GDP and low population trajectories of SSP1, all regions' consumption adjusted staple expenditures are below 5 percent of the average GDP in 2050. Less improvement is found with the low GDP and high population trajectories under SSP3, especially in the poor regions.

⁸ Focus the discussion of our results on SSPs 1 and 3, as these represent two particularly diverse scenarios. Results for the other SSPs can be found in the Appendices.

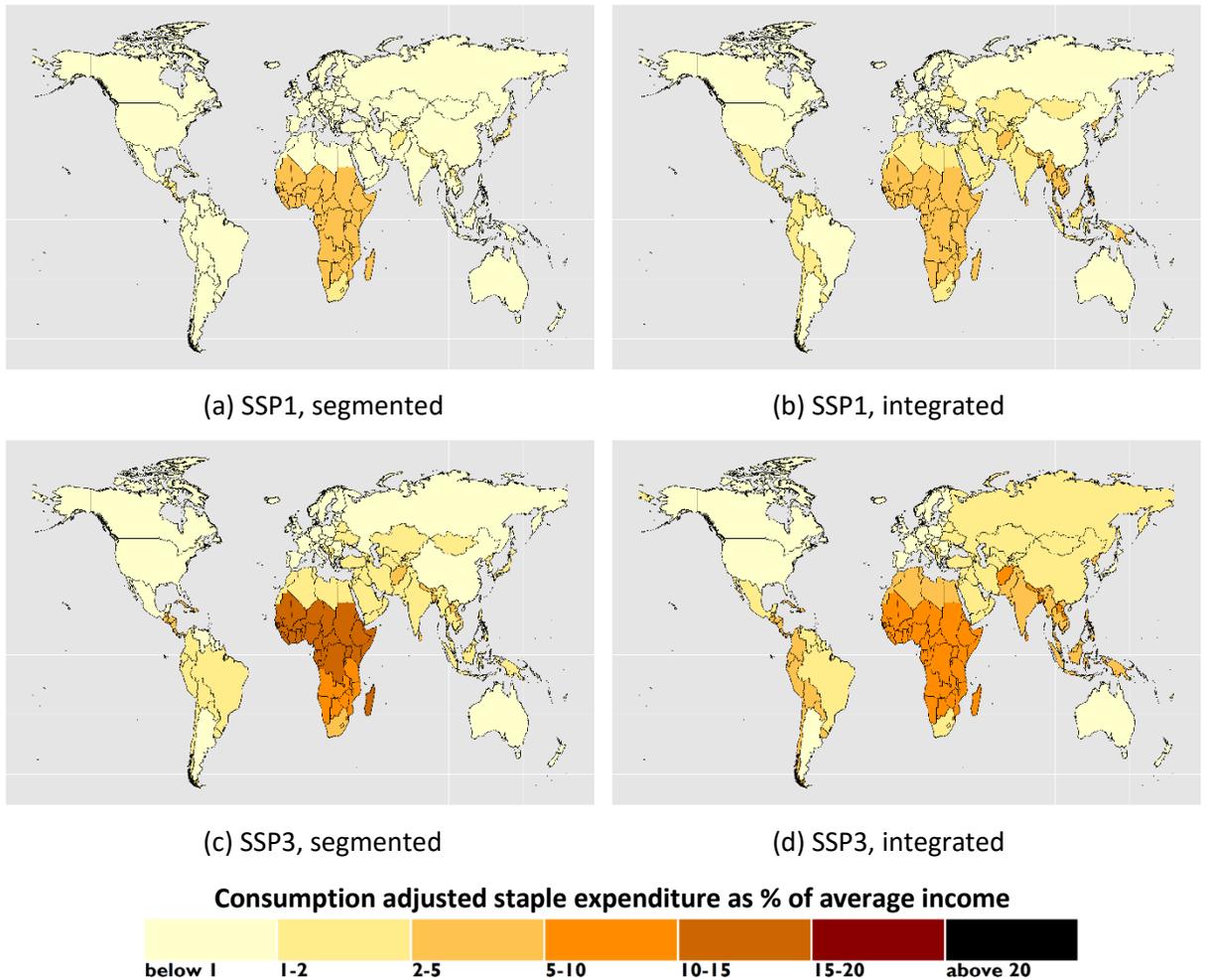


Figure 3.2 FAA conditions in 2050, references

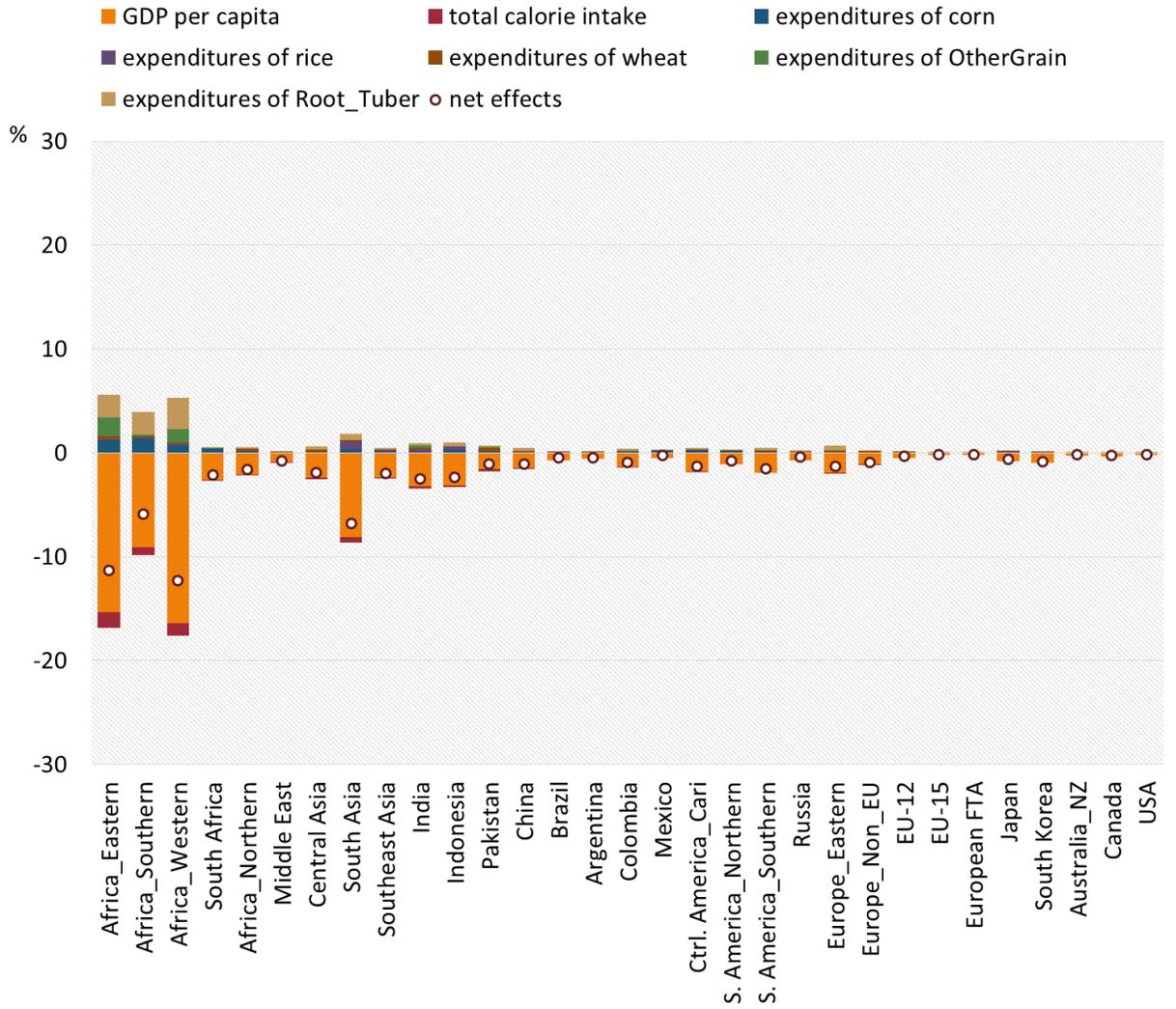
Under alternative population and GDP trajectories and different assumptions of regional consumer price changes: (a) SSP1 and the segmented market model; (b) SSP1 and the integrated market model; (c) SSP3 and the segmented market model; (d) SSP3 and the integrated market model.

The relationship between consumer and producer prices affects both the absolute level of the metric and the distribution of improvement in FAA across regions. For instance, less improvement is seen in South Asia in 2050 with consumer prices derived from the assumption of well-integrated global markets than in one where regional differences in prices persist through mid-century. In the former case, our FAA metric shows South Asia to be comparable to Sub-Saharan Africa in 2050; while in the later,

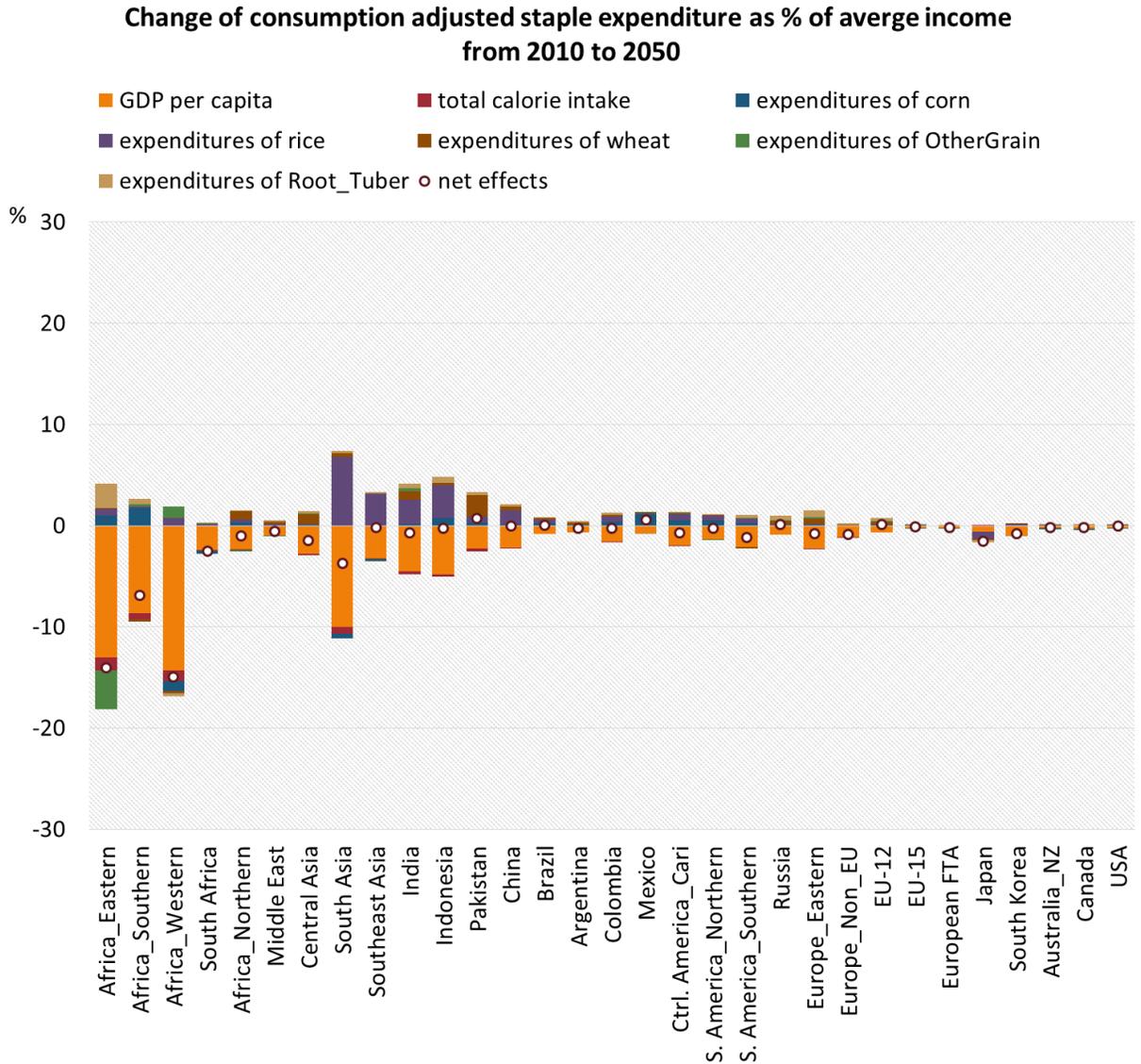
Sub-Saharan Africa remains the worse FAA condition (Figure 3.2). However, in the reference scenarios, improvement in FAA through 2050 is robust across the range of sensitivities that I tested.

The FAA metric derives from several interacting factors. To explore the relative impacts of each factor, I conduct a decomposition analysis. Figure 3.3 shows that the positive effects of income growth have a larger impact on the metric than the negative effects of rising staple expenditures that are mainly caused by rising consumer prices. In all reference scenarios, the GDP per capita increases at a faster pace than consumer prices and contributes the most of the improvements of FAA in almost all regions, even under the low economic growth projections defined in SSP3 (Figure 3.3). The only exceptions are Pakistan and Mexico with the integrated market framework: if the 2010 regional variability of consumer prices does not persist through 2050, staple prices – mainly wheat in Pakistan and corn in Mexico – rise faster than income under SSP3, leading to declines in FAA in these two regions (Figure 3.3b).

Change of consumption adjusted staple expenditure as % of average income from 2010 to 2050



(a) SSP3, segmented market model, reference



(b) SSP3, integrated market model, reference

Figure 3.3 Decomposition of changes in FAA condition by region, SSP3, references
 From the 2010 segmented market model baseline to 2050 under SSP3 population and GDP trajectories with different assumptions of regional consumer price changes: (a) the segmented market model; (b) the integrated market model.

Rising consumer staple food prices are due primarily to factors other than rising producer prices. Food demand increases due to growing population and GDP across all SSP trajectories, which forces agricultural expansion to less productive land. But combined with increasing crop yields, global producer prices in GCAM rise only slightly

from 2010 to 2050 (Figure. A2 in Appendices). However, as incomes increase, there is a corresponding increase in price margins. At the regional level, consumer prices may increase by as much as six times, depending on assumptions of either segmented or integrated global market in 2050 (Figure. A3 in Appendices).

In most cases, consumer prices rise from 2010 to 2050, which worsens FAA. In some other cases, however, the move from a segmented market in 2010 to an integrated market in 2050 will lower regional consumer prices of certain staples, which improves FAA. Under the SSP3 GDP and population trajectories and the assumption of an integrated global market, even with increases in consumption, total expenditures on other grains decline in Eastern Africa, corn expenditures decline in Western Africa and South Asia, and expenditures on rice decline in Japan (Figure 3.3b). Thus, in some regions the elimination of regional price distortions, combined with rising incomes and continued improvement in yields, may reduce the consumer prices of staple foods.

In an analysis of food security using the SSPs in the AIM IA model, Hasegawa, Fujimori, Takahashi, et al. (2015) found decreasing numbers of undernourished people in all but SSP3. Their finding of a rising number of undernourished people in SSP3 demonstrates the key role of population growth in their measure of food access (Hasegawa, Fujimori, Takahashi, et al. 2015). This result emphasizes the need to understand the drivers of a result in any metric. In fact, I also find that in an SSP3 trajectory with a segmented market framework, more people live in regions where consumption adjusted average staple expenditures exceed 10 percent of GDP per cap in 2050 than in 2010 regardless of the improvement in FAA, due to rapid population growth (Figure. A4 in Appendices).

3.2.2. FAA condition in 2050 under higher global prices

The analysis in section 3.2.1 explored long-term trends in global producer prices caused by population and GDP growth. However, larger increases in global producer prices are likely to be observed as a result of drivers beyond population and GDP growth, such as long-term yield impacts from climate change (Nelson et al. 2014), production shocks due to extreme weather events (Porter et al. 2014), and land competition between food and bioenergy (Lotze-Campen et al. 2014). To explore how these may impact FAA, I conducted sensitivity analyses with increases in the 2050 global producer prices of all five staple commodities together by 100, 200 and 300 percent.

I find that higher staple prices may reduce or eliminate the gains in FAA due to economic growth – in some cases, I even observe worsened FAA compared to the 2010 level (Figure 3.4). For example, in the integrated market framework under a 200% increase in global producer prices, rising staple expenditures become larger than income growth under SSP3 in Southern Africa, South Asia, Southeast Asia, India, Indonesia, Pakistan, Mexico, and several others (Figure 3.4). Different magnitudes of global price increase tell a consistent story, with less damage to FAA in the 100 percent increase scenario and worsening compared to 2010 in more regions in the 300 percent increase scenario.

Change of consumption adjusted staple expenditure as % of average income from 2010 to 2050

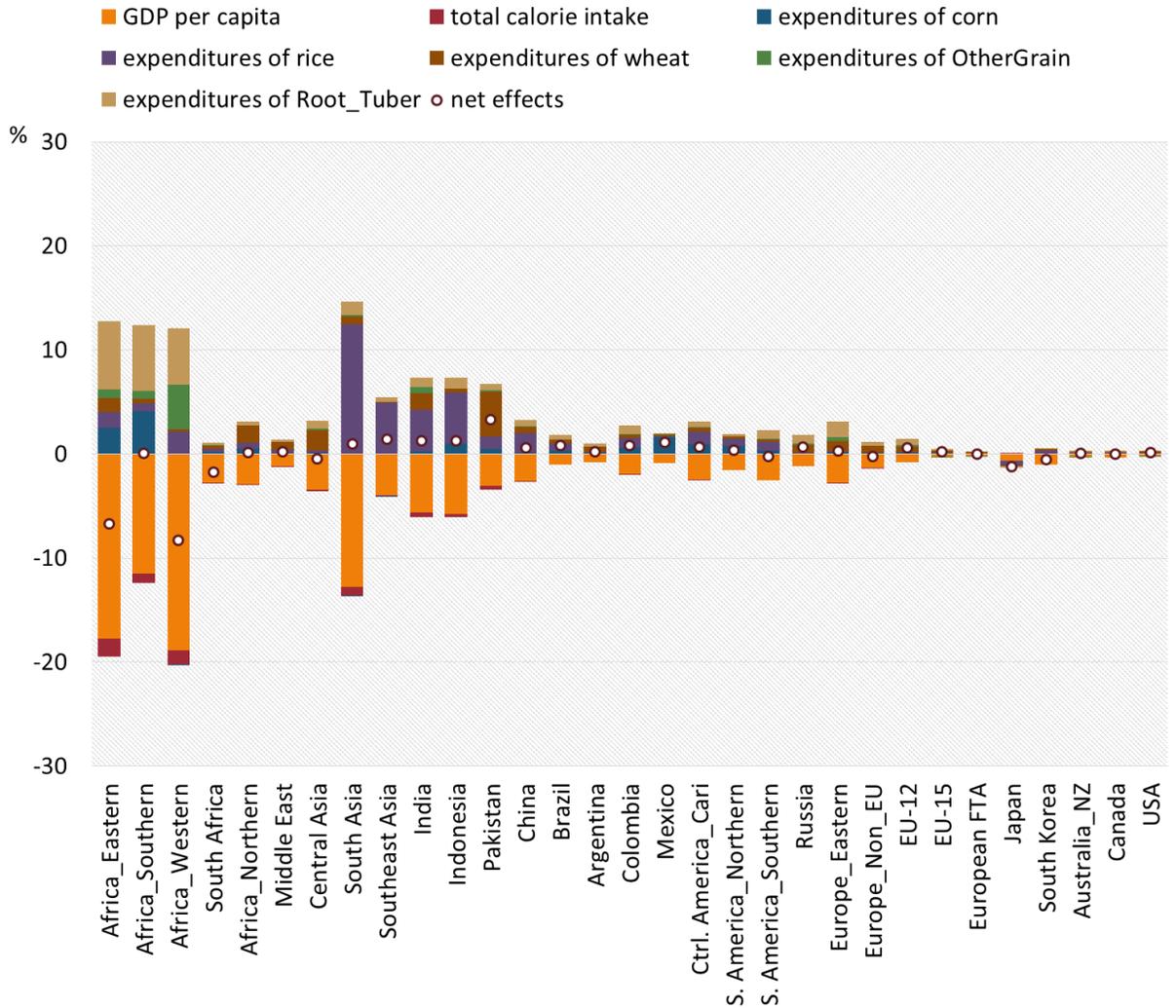


Figure 3.4 Decomposition of changes in FAA condition by region, SSP3, 200% global price shock From the 2010 segmented market model baseline to 2050 under SSP3 population and GDP trajectories and the integrated market assumptions of regional consumer price changes with 200 percent increases of global produce prices.

The negative impacts of larger increases in global producer prices depends on the expectation of future economic conditions. All regions are less impacted under the high GDP and low population growth in SSP1 across the range of global price sensitivities that I tested (Figure 3.5). On the other hand, the high population low GDP growth in SSP3

causes Sub-Saharan Africa to be much more negatively affected by higher global producer prices. The poor are more vulnerable to adverse shocks.

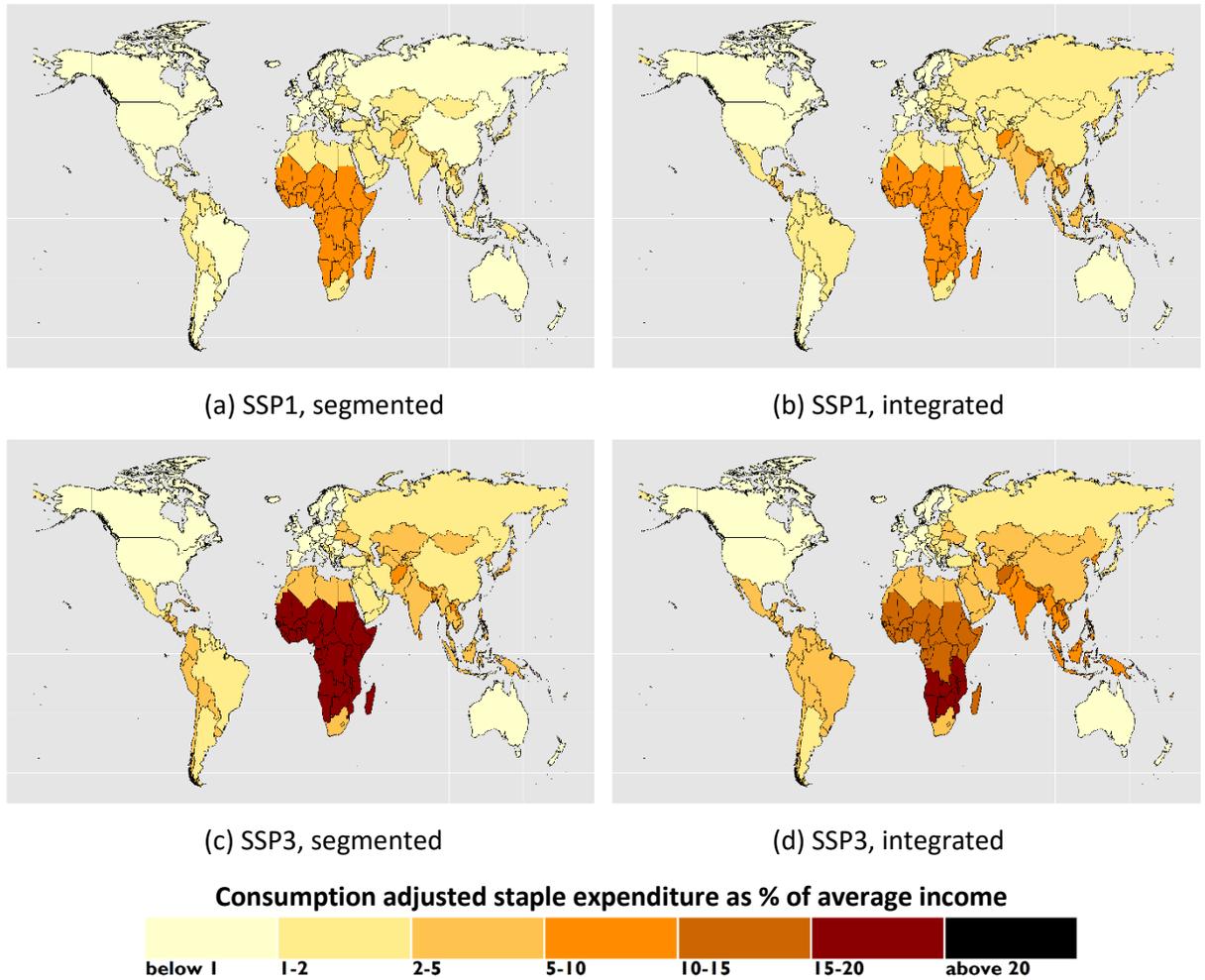


Figure 3.5 FAA conditions in 2050, 200% global price shock
 Under alternative population and GDP trajectories and different assumptions of consumer price changes: (a) SSP1 and the segmented market model; (b) SSP1 and the integrated market model; (c) SSP3 and the segmented market model; (d) SSP3 and the integrated market model.

As in the reference scenarios, assumptions about the development of regional consumer price also affect FAA, and the impacts are different across regions. For instance, several regions in Asia show worsened FAA when consumer prices follow an integrated market pattern, while Sub-Saharan Africa show the opposite (Figure 3.5).

Changing from the segmented to the integrated market framework, converging consumer prices may result from removal of food subsidies, trade restrictions, high inventories, and other policy interventions that have kept domestic consumer prices low historically (Anderson and Martin 2007; Dawe 2008). It suggests that although open trade may help lower staple expenditures for certain regions, open trade may also increase some others' exposure to harmful situation such as international price shocks. However, policies that isolate domestic markets, such as trade restrictions, also tend to intensify price volatilities in the global market, with negative impacts on net importers (Rutten, Shutes, and Meijerink 2013; Abbott 2011).

Finally, regional outcomes also depend on which staple crop experiences high global prices. Given the same percentage increase in global prices of all staple commodities, major consumers of rice tend to experience the largest increase in staple expenditures. Figure 6 shows worsening of the FAA in several Asian regions compared to 2010 when global prices increase by 200 percent in an integrated global market under SSP3. These larger impacts on staple expenditures and FAA of the major rice consumers are mainly because of two reasons. First, major rice consumers are mostly from Asia, who are likely to be poor. Second, rice dominates the staple diet in these regions, and people heavily rely on rice as staple food and have few substitute in their diets.

By contrast, any other crop does not dominate the staple diet of such large poor population as rice does in Asia. For instance, major consumers of wheat, such as those in Western Europe and North America, are relatively wealthy. On the other hand, poor consumers of wheat, such as those in Africa, tend to have a more diverse diet for staples. It is probably unlikely that all staple crops altogether experience the same level of global

price shocks as in our experiment, and thereby having a more diverse staple diet consumers are able to switch to other cereals when wheat price gets high. It suggests that a more diverse staple diet helps ease the price spike impacts. As a result, if global price shocks hit individual crop separately, rice consumers tend to be more negatively impacted. However, I do observe that increases in wheat expenditures in Pakistan and corn expenditures in Mexico cause worsened FAA compared to 2010 in these two regions (Figure 3.4). As discussed in section 4.1, FAA decline in these two regions under the reference scenarios as well due to large increases of consumer prices with the change from a segment market in 2010 to an integrated market in 2050.

Moreover, recent historical observations show global price of rice can increase as twice as much of corn, wheat, and other grains during the same time period (von Braun and Tadesse 2012). In fact, because of smaller and more concentrated global market, as well as smaller substitution effects for major consumers, international prices for rice tend to be much more volatile than for those other cereals (Anderson and Martin 2007). That being said, the associated impacts may be even larger for rice consumers.

3.2.3. Compare the stories with prior studies

This chapter assesses the impacts of changing population, GDP, food prices, and their interactions, on the proposed metric, FAA, of long-term food availability and access. Several key findings are consistent with existing research that demonstrates the robustness of the proposed metric of FAA.

First, continued regional inequality in FAA. Absent changes in policy or governance that are not captured by the model, regions that have the lowest FAA today,

Sub-Saharan Africa and, under certain circumstances, South Asia, are likely to remain worst in 2050. Second, although regional inequality may persist, improved FAA conditions in almost all regions are found in the range of population and GDP pathways defined in the SSPs and different assumptions of the development of regional consumer prices. This is because average income increases in all regions even under the most pessimistic SSP projections, and baseline yield improvements cause staple food prices to increase more slowly than income. Across the scenarios I tested, higher demand due to population and GDP growth do not worsen FAA. This is because: (a) although production is expanded to less productive lands to meet increasing demand, pressure on food prices can be counteracted by improved yields at all agricultural lands; and (b) economic growth improves FAA directly, and in our scenarios, this positive effect almost always outweighs its negative effect on prices and food expenditures.

Third, FAA worsens only when price increases outpace the growth of income. In other words, if regional FAA declines compared to 2010, food prices must increase beyond what is expected in demand under assumptions for yield improvements and total production. For instance, uncertainty in food prices can cause large changes to FAA, in some cases negating the gains due to economic development in poor regions. There are several conditions beyond population and GDP growth that could lead to higher prices on both producer and consumer sides, such as climate change, trade, and institutions.

With respect to climate change, agricultural production and food supply are expected to be negatively impacted by climate change, due to factors such as long-term changes in temperature and precipitation patterns, more frequent and intense extreme weather events, resource competition with bioenergy and land-use based mitigation.

With respect to agriculture trade, climate change has the potential to affect agricultural trade patterns as long-term impacts on crop yields are not expected to be evenly distributed. Low latitude regions, such as Sub-Saharan Africa and South Asia, tend to be the most vulnerable to yield losses (Knox et al. 2012; Rosenzweig et al. 2013; von Lampe et al. 2014; Porter et al. 2014), causing potential changes in agricultural trade flows, switching exporters to importers, or increasing dependence on imports.

With respect to institutional factors, such as price distortions and trade barriers, there tend to be large and uneven impacts on regional consumer prices and FAA across regions. These policy interventions are intended to lower consumer prices and protect consumers' food access in major producing countries, but may also increase food prices for importing countries and intensify global market volatility (Rutten, Shutes, and Meijerink 2013; Headey 2011; Abbott 2011).

Moreover, there may also be interactions between all these factors. For example, changing production and trade patterns may further affect institutions. It may become increasingly expensive to maintain high inventories or provide subsidies to protect domestic consumers' food access. It may also, in the meanwhile, provide stronger incentives to implement export restrictions, which hurts consumers' food access in the importing countries.

In conclude, all of these key stories from this chapter are consistent with existing literature that assess long-term food security along alternate expectations of the future, by using other metrics. It confirms that the conclusions of the other studies are robust under different methods and metrics explored here.

Chapter 4. Impacts on FAA from alternative climate policy designs

One of the key messages from Chapter 3 is that uncertainty in food prices caused by drivers beyond population and GDP growth can largely impact food availability and access. Climate mitigation policies could be one of such drivers, by promoting the expansion of bioenergy and forests, and causing increases of food production costs due to competition of land, water, and other natural resources. Moreover, alternative climate mitigation policy designs may affect FAA by influencing incomes.

This chapter therefore evaluates FAA on a regional level in 2050 for different climate policy designs using the set of metric and methods developed in Chapter 2. Under the end-of-century 450 ppm CO₂ concentration target, three groups of different climate and land-use policy structures are tested, along two alternative population and economic trajectories as envisioned by the SSPs.

4.1. Policy scenarios

I explore four different policy options in energy and land use sectors to meet a string climate target, by comparing the impacts on regional FAA between these policy scenarios. Besides, I also explore the uncertainty of population and GDP growth with two alternative trajectories as defined in the SSP1 and SSP3 (Table 4.1).

Table 4.1 Socioeconomic and policy scenarios

scenario name	sectors subject to carbon price	level of natural land protection	climate target	socioeconomic information
SSP1-Ref-NoCC	NoPolicy	none	NoTarget	
SSP1-450-ffict	energy	none		
SSP1-450-ffict-prot90	energy	90% in each region	450 ppm CO ₂ concentration	SSP1
SSP1-450-ffict-prot99	energy	99% in each region		
SSP1-450-uct	energy and land use	none		
SSP3-Ref-NoCC	NoPolicy	none	NoTarget	
SSP3-450-ffict	energy	none	450 ppm CO ₂ concentration	SSP3
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

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: zero percent, 90 percent or 99 percent of natural land in each of the 32 GCAM regions are protected, or in other words, removed from economic competition in GCAM. The land use policies explored here protect all natural land, instead of only focusing on forest (i.e. REDD), because studies have shown that in addition to loss of biodiversity, agriculture expansion to other types of natural land also accounts for a large portion of emission leakages (Popp et al. 2014). In the fourth policy scenario, the carbon price is equally implemented on terrestrial emissions from the land use sector (UCT), adding an incentive to natural carbon stocks.

These policy instruments are rather illustrative than pragmatic: both are straightforward to implement in the modeling framework, but are subject to many practical challenges in reality, such as the complexity of monitoring, report and validation (MRV) for terrestrial carbon pricing. However, it is valuable of doing the policy experiments, which informs policy making about the worst unintended outcomes to food availability and access when moving towards either direction.

For each of the four different policy designs, both abatement costs and land use patterns will change. All of the four policy scenarios are to meet the 450 ppm CO₂ concentration target by the end of the century. Also, a 550 ppm target is explored as sensitivity analysis, provided in the Appendices.

In addition, I use two alternative population and GDP trajectories as defined in the SSPs to explore the uncertainty, particularly for the poorest regions, of future economic and demographic evolution. Specifically, the SSP1 world has relatively rapid GDP growth, with an increasing equality across regions, and slow population growth; while by contrast, the future world pictured in SSP3 is under low GDP and high population growth with fragmentation and inequality (O'Neill et al. 2013). With different population and GDP growth trajectories, both energy and food demand as well as the global equilibrium prices will change, and so will CO₂ emissions and the amount to mitigate that affect abatement costs. Moreover, I do not reconcile population and GDP growth with other qualitative storylines associated with each SSP that further describe future world along challenges of mitigation and adaptation (O'Neill et al. 2015).

Two reference scenarios are also included as the hypothetical baseline. None of the scenarios include potential climate change impacts. In other words, my analysis focus on the costs of specific mitigation strategy, without discussing the overall benefits of mitigation – the avoided or reduced climate change impacts on crop yields, food production, and other damages.

4.2. Results and discussions

In this section, I first show and compare regional FAA in 2050 under alternative socioeconomic and policy scenarios to identify the policy conditions that generate unintended outcomes to regional FAA; and then I explain what is the main driver of FAA change under each policy scenario to understand why certain policies tend to have larger impacts on FAA than others, by conducting the LMDI decomposition analysis.

4.2.1. Impacts on regional FAA between policy instruments

Although the same end-of-century climate target can be met by implementing a number of different policy instruments, regional FAA may look very different between these policy options that I tested. Policy either strictly restricts land use (FFICT-Prot99) or prices terrestrial carbon emissions (UCT) tends to have larger impacts on FAA in 2050, especially under rapid population and slow GDP growth (Figure 4.1). By contrast, compared to the reference scenario without climate change (Figure A17 in Appendices), the impact on FAA by pricing fossil fuel and industrial emissions alone (FFICT) is minimal, followed by the moderate land use restriction policy (FFICT-Prot90). The set of regional FAA maps under the 550 ppm target tells a consistent story and is provided in the supplementary material (Figure A18 in Appendices).

When comparing across regions, Sub-Saharan Africa tends to remain at the worst FAA condition in 2050 across all tested scenarios; however, if combined with rapid population and slow GDP growth, stress on FAA will increase for South Asia, India, Pakistan, and Indonesia when terrestrial emissions are priced (UCT), and is further extended to several other regions in Central Asia, Northern Africa, and South America only when 99% of natural land are protected (FFICT-Prot99). Overall, poor regions are more sensitive to both the socioeconomic development uncertainty and the choice of policy tool to reach the stringent climate target; while developed countries' FAA tend not to be impacted by mitigation policies and are robust to the range of sensitivities that I explored (Figure 4.1).

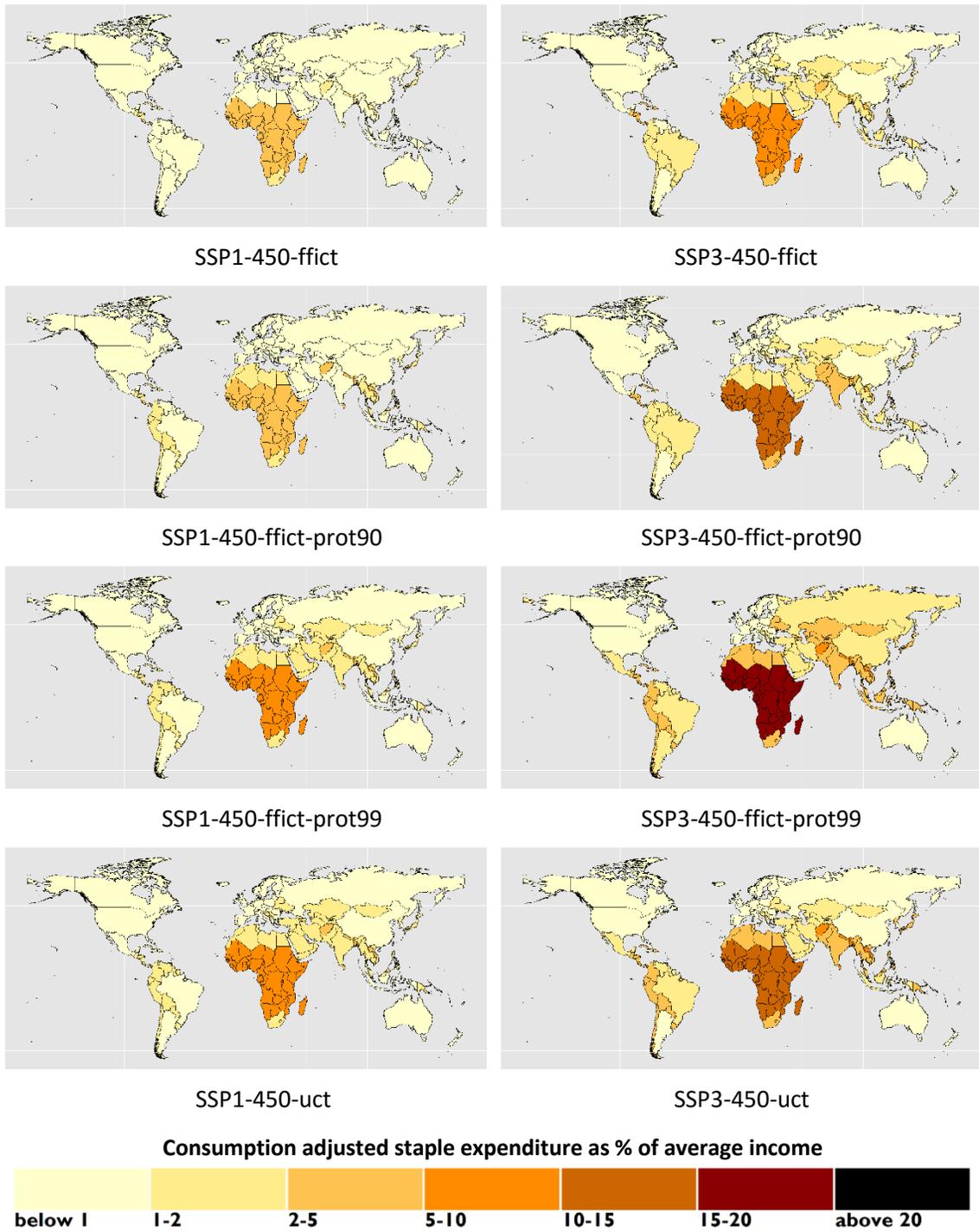


Figure 4.1 FAA conditions in 2050 with climate target, by SSP and policy

4.2.2. Land use patterns drive differences in FAA between policies

To explain why certain policies tend to have larger impacts on FAA and why certain regions' FAA are more affected, I first look at the contribution of each driver to the FAA change, by conducting a LMDI decomposition analysis. I focus on the poorest regions whose FAA in 2050 are most affected by mitigation.

Figure 4.2 shows that increases in these regions' consumption-adjusted staple expenditure as a percentage of average GDP (FAA) from the reference scenario are almost all driven by increased staple expenditures, while the change in FAA caused by decreased GDP per capita and total caloric intake is negligible. Further comparing the second run of each policy scenario with the first run, the combined effects of several other factors associated with reduced GDP per capita – including average staple food demand, global market prices and the transmission to regional consumer prices – tend to be minimal as well.

It suggests that between the two main channels of changing income due to abatement costs and changing food prices due to land use competition, impacts on the poor regions' FAA by mitigation are mainly caused by the latter. In other words, to explain the between-policy difference of impacts on the poor's FAA, I will focus on the variation of land use patterns between alternative policy tools and the associated changes in global market prices of staple food.

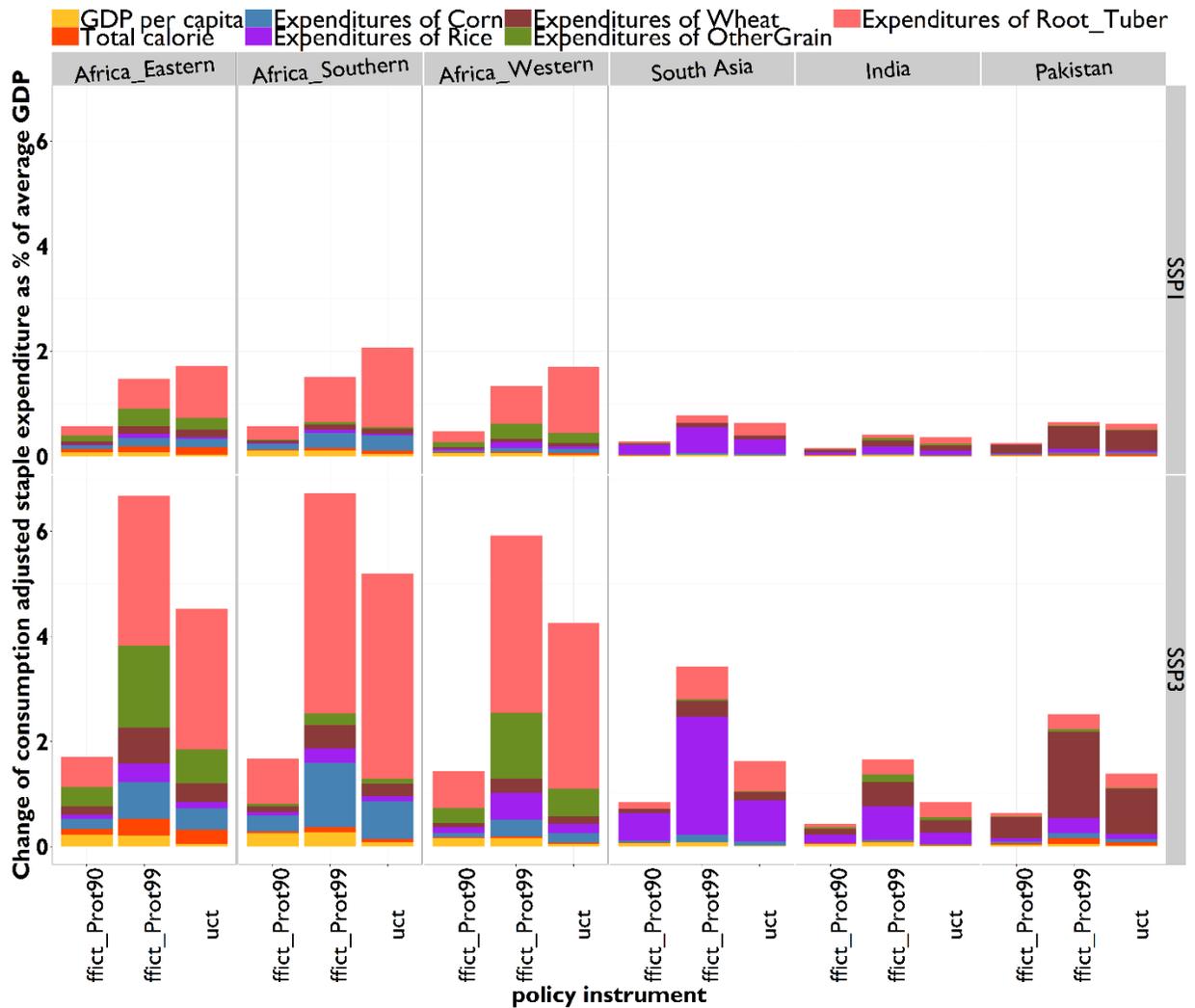


Figure 4.2 Decomposition of changes in FAA, by selected region and policy
 Increased consumption-adjusted staple expenditures as % of GDP per capita in 2050 caused by
 the change in each variable

Between the policy instruments tested, I first look at the effect of pricing carbon emissions in different sectors. This largely alters the relative profitability of each competing use of land between agriculture, biomass and forest (Calvin et al. 2013). For example, the UCT equally values terrestrial carbon emissions and thus increases the profitability of afforestation. Therefore, substantial forest area expansion is observed worldwide from 2010 to 2050 (Figure A20 in Appendices). In contrast, the FFICT only

prices the energy system CO₂ emissions, making biomass production more profitable than forest. When natural land are not protected, deforestation and biomass area expansion are observed to reach the same climate target (Figure A20 in Appendices). However, the competition between bioenergy and forest has different implications on agriculture: the global market prices of staple food largely increase under the UCT but stay nearly unchanged from the reference scenario under the FFICT (Figure A19 in Appendices). It suggests that there is enough arable land to meet both the bioenergy demand for stringent climate target and the increasing food demand to feed more people (Calvin et al. 2013) even with the rapid population growth under SSP3. By contrast, the UCT tends to bring a more intense land use competition between forest and food production.

Next, I look at the effect of land use restriction with different stringencies. Land use restrictions, on one hand, further reduce the total area available for economic competition between agricultural and mitigation activities (either afforestation or biomass production); however, on the other hand, by sustaining natural forest, reduce bioenergy demand and thus the land for biomass production to reach the climate target (Figure A20 in Appendices). The combined effect on agriculture is that global market prices of staple food are driven up from the price level under FFICT alone (Figure A19 in Appendices). Moreover, when keeping 90% of natural land from economic competition, the associated increases in global market prices are not sensitive to food demand driven by alternative population and GDP growth trajectories between SSP1 and SSP3. However, when enlarging the protected natural area to 99%, price increases are substantially higher under SSP3 than under SSP1, indicating that the remaining arable land is approaching its

capacity limit to accommodate the food demand in 2050 driven by rapid population growth. In other words, it becomes much more sensitive to socioeconomic development uncertainties when supply constraint is high.

4.2.3. Economic and diet factors drive regional differences in FAA

In addition to food prices, the impacts of each policy on regional FAA depend on regional economic conditions and diet preferences. First, with regards to economic conditions, when increases in global market prices due to land use competition are further transmitted to regional consumer prices, the poor regions, Sub-Saharan Africa, for example, tend to experience higher percentage change in consumer prices (Figure 4.3). Such inequality of consumer price increases is further enlarged under higher global producer prices (FFICT-Prot99) accompanied with rapid population growth under SSP3. Moreover, with already higher percentage consumer price increase, the lowest economic condition in Sub-Sahara Africa further leads to the largest increase in consumption adjusted staple expenditure as % of average income – worsened FAA (Figure 4.2).

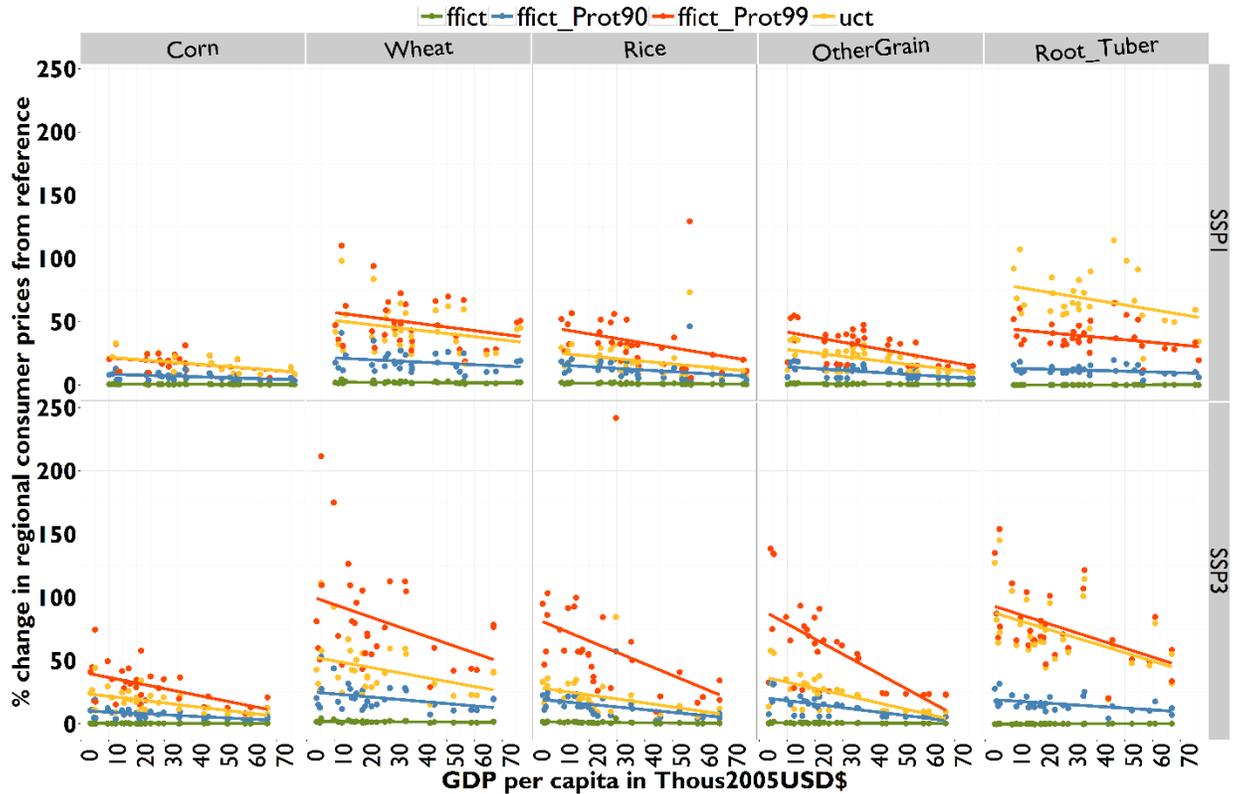


Figure 4.3 Change in regional consumer prices of staple commodities in 2050
From the reference scenario without climate change or mitigation, by policy instrument and SSP

Second, with regards to diet preference, there is a large regional variation in terms of the composition of the increased staple expenditures (Figure 4.2): all of the three Sub-Saharan African regions are most affected by the largest increase in roots and tubers expenditures, but also by other grain and corn expenditures, while the increased rice expenditures account for most of the FAA change in South Asia and India, and the increased wheat expenditures drive the FAA change in Pakistan. Moreover, diet variation explains why the risk of valuing terrestrial emissions (UCT) is more concentrated on the poor in Sub-Saharan Africa, who are the main consumers of roots and tubers. The percentage change in regional consumer prices of roots and tubers are substantially higher than other staple commodities in 2050 only when pricing terrestrial emissions

(UCT). Therefore, under the UCT, main consumers of roots and tubers tend to be more hurt than consumers of other staples. By contrast, price increases are comparable across staple commodities under strict land-use restriction policies, affecting a broader range of regions.

The reason that UCT tends to affect roots and tubers more than other staple crops is that afforestation will mainly occur in the tropics (i.e. Sub-Sahara Africa and Brazil), which has unique implication to the production of roots and tubers. Specifically, UCT encourage afforestation and reforestation mainly in the tropics where forests generate higher profits compared to agricultural products, or in other words, crop yields are relatively low. Accordingly, crop lands are shifted from low (i.e. Sub-Sahara Africa and Brazil) to moderate and high latitude regions (i.e. China and the United States) (Figure A21 in Appendices) where in general agricultural production tends to be more profitable than afforestation. However, this shift of crop lands from tropical to temperate regions under UCT considerably reduce the production of roots and tubers in Sub-Saharan Africa. By contrast, the rest staple commodities are mainly produced in other regions and thus are less affected.

Given these unique features of the production and consumption of roots and tubers, the risk of valuing terrestrial emissions (UCT) is more concentrated on the poor in Sub-Saharan Africa, while strict land-use restriction policy (FFICT-Prot99) affects a broader range of regions. From a global perspective, it tends to be most cost-effective when carbon stocks locate in tropical regions and food production in temperate regions (Johnson et al. 2014; West et al. 2010; Foley et al. 2011), which can be achieved under the UCT, assuming effective global trade of agricultural products. This global-wide

competing use of land may help ease the pressure on staple food prices, except for roots and tubers, compared to the strict regional-wide land use restriction policy. It should be noticed global market prices under the UCT tend to have a quick jump when policy starts in 2020 but will be taken over by the strict land conservation policy (FFICT-Prot99) around 2030 to 2040 in most cases. That being said, I may observe worse FAA condition under the UCT in the first one or two decades of policy implementation, but after that, regional FAA condition are worse under the strict land conservation policy (FFICT-Prot99).

From a regional perspective, however, the UCT tends to be particularly problematic to Sub-Saharan Africa's FAA in 2050. Sub-Saharan Africa lost the majority of their crop land compared to the reference (Figure A21 in Appendices) and imports almost all its production of roots and tubers from China (Figure A24 in Appendices), substantially lowering average yield and driving up global market price of roots and tubers. Under GCAM's assumption of free agriculture trade, this shift means dramatic change in trade flows, and the main consumer of roots and tubers – who are in Sub-Saharan Africa and poor – will heavily rely on imports for staples. This, in reality, may not happen because arguably roots and tubers dominate people's staple diet in Sub-Saharan Africa due to self-supply and local production; with increasing reliance on imports, particularly with costs of trade, it is more likely to substitute with other staples, which is not modeled here.

Finally, one issue that influences land use and therefore FAA is bioenergy when implemented with carbon capture and storage (BioCCS). Studies have shown that, on one hand, BioCCS, as a negative emission technology, is critical to meet stringent climate

targets; however, on the other hand, the reliance on wide-spread deployment of BioCCS is highly uncertain in terms of economic, environmental and technological constraints (Edmonds et al. 2013; Humpenöder et al. 2014; van Vuuren et al. 2013; Smith et al. 2015). Therefore, to make sure our results are robust even in absence of BioCCS, I turn off this mitigation technology option in GCAM for each policy scenario as a sensitivity test. I find that global market prices slightly increase without BioCCS compared to the full technology scenarios, because more forests are needed to meet the same climate target (Figure A25 in Appendices). However, this change has minimal impacts on regional FAA.

4.2.4. Results compared with prior studies

This chapter examines the additional risks to regional FAA associated with alternative mitigation strategies, given the overall benefits of reducing climate change impacts. Building on previous work that unpacks multiple channels through which mitigation may affect food availability and access, I find that between the two channels of changing GDP per capita due to abatement costs and changing food prices due to competing use of land, impacts on the poor's FAA are almost all driven by the latter.

This result is opposite to prior finding that reduced caloric consumption more strongly depends on changing income due to mitigation costs (Hasegawa, Fujimori, Shin, et al. 2015). Variations with respect to the modeling tool, design of policy scenarios, and the metric of food availability access are the main reasons that lead to contrary findings. First, GCAM has exogenously determined GDP, and the income change is taken into account by adjusting GDP with abatement costs that are calculated as the area below

marginal abatement cost curves. By contrast, the modeling tool employed by Hasegawa, Fujimori, Shin, et al. (2015) takes into account all consumption losses through the economy associated with abatement costs. Second, Hasegawa, Fujimori, Shin, et al. (2015) only look at one policy design that induces the competing use of land between biomass and agriculture, which has only moderate impacts on food prices. By contrast, I also examine policies that protect or value natural carbon stocks, raising food prices to much higher levels. Third, the adopted metric in Hasegawa, Fujimori, Shin, et al. (2015) based on total caloric intake is very irresponsive to price change, while staple food budget share, one component of the metric of FAA, directly reflects the impacts of increased food prices on consumers' food expenditures.

Moreover, my analysis extends previous analyses by focusing on the comparison between alternative climate policy instruments. I find that: (1) with alternative policy instruments to achieve the same stringent climate target, policies that either encourage bioenergy expansion while strictly restricting land-use or encourage large-scale afforestation by pricing terrestrial carbon emissions tend to have larger impacts on the poor's FAA; (2) while the variation of impacts on FAA between policy instruments are mainly affected by the variation of land use patterns, the regional variation of FAA impacts tends to be driven by regional economic condition and diet preference of staple food; and (3) strict land-use restriction policies affects a broader range of developing countries; whereas the risk of valuing terrestrial emissions (UCT) 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.

Chapter 5. Lessons for land use policy making

Chapter 4 finds that there should be concerns with the unintended outcomes to long-term food availability and access for the poor associated with ambitious climate mitigation, especially under two policy conditions – policies that strictly limit bioenergy, agricultural or other commercial activities from any existing natural land or policies that value terrestrial emissions at the same price as energy system emissions. Both types of policies have the potential to largely raise food prices by intensifying land use competitions.

The land use sector is a critical component of any pathway to avoiding dangerous climate change. It has large potentials to reduce GHG emissions at low costs mainly through the prevention of land use change emissions and carbon sequestration (Smith et al. 2014). Results from Chapter 4 are highly relevant for making effective policies to mitigate terrestrial emissions. Many policy recommendations have recognized the potential pressure on forests from measures to improve food security (FAO 2016), few considered the other side of the story that aggressive land policies under ambitious climate mitigation may also risk food availability and access for the poor. Therefore, in this chapter, I discuss how my research, by taking into account the potential risks to food availability and access, is relevant to climate policy making specifically in the land use sector. This chapter answers the last research question: *How should we design climate policies so that the side-effects on food availability and access can be minimized or avoided?* It draws policy implications both for the international mechanism and for selected individual regions and countries.

5.1. Trade-offs of policies in the complex land use system

The land system is important and complex. It provides food, fibre and fuel, as well as many ecosystem services (Foley et al. 2005). All these different purposes have to be met with the finite land on our planet. Global landscape have been transformed substantially by human activities, driven by socioeconomic and institutional changes (Lambin and Meyfroidt 2011; Turner, Lambin, and Reenberg 2007; Foley et al. 2005; Reenberg and Seto 2014). Furthermore, competition for land is expected to be exemplified for meeting increasing demand of food, energy, and terrestrial carbon storage in the 21st century (Johnson et al. 2014; Foley et al. 2011; Thomson et al. 2010; Smith et al. 2013).

The multi-function and complexity of land use system determines that policy measures targeting one objective are likely to have feedbacks to other purposes (Bustamante et al. 2014). This is demonstrated, for example, by the results from Chapter 4: climate policies that target on reducing terrestrial emissions generate unintended consequences to long-term food availability and access for the poor through the complex land system. Besides, there are trade-offs of different policy instruments with respect to affecting other functions of the land system, such as natural carbon storage and ecosystem services (i.e. biodiversity and soil-water conservation).

Table 5.1 provides several examples of the impacts on multiple functions of the land system between alternate climate policy designs in the land use, land-use change and forestry (LULUCF) sector while pricing carbon emissions from the energy system. A good outcome is indicated by the color of green, a bad outcome is indicated by red, and the median case is indicated by yellow.

Table 5.1 Trade-offs of alternate policies for meeting multiple objectives

Objectives Policy Instruments in LULUCF	Food availability and access	Carbon storage	Ecosystem services (i.e. biodiversity, watershed protection)
None	No additional impact	Reduced with deforestation	Diminished
Full natural land protection	Large impacts over long-term and increasing total demand	Sustained in natural forests	Conserve current natural ecosystem
Pricing terrestrial carbon	Large impacts depending on initial implementation	Increased with afforestation	Uncertain with new plantation

First, with respect to food availability and access, without any land policy, there is little impact on FAA (green). But when combined with full natural land protection, preventing any agriculture or biomass land expansion beyond existing commercial land, impacts on FAA are large and affect a larger group of developing countries, especially under high food demand driven by rapid population growth (red). Instead, pricing terrestrial carbon has more flexibility to shift land use around the globe to meet increasing food demand. However, pricing terrestrial carbon tends to abruptly impact FAA as soon as the policy is implemented and more focus on the most food-insecure Sub-Saharan Africa (red). Because of the timing differences, from a development perspective, it is unclear which policy imposes higher risk to the poor’s FAA.

Second, with respect to carbon storage, mitigating land use change emissions is competitive from an economic stand point of view and play a key role for meeting ambitious climate goals. Pricing the energy system emissions without any land policy

tends to decrease forest coverage and thus put a lot of pressures on the energy system to mitigate (red). When combined with full natural land protection, carbon stocks are sustained in existing natural system, and thus lower the pressures to mitigate through the energy system (yellow). Equally pricing terrestrial emissions encourages large-scale afforestation, and thus stringent climate targets can be achieved with much less pressures on the energy system (green).

Third, with respect to protecting the ecosystem services, without explicit policy interventions with land use, expansions of cropland and biomass production cause deforestation around the globe and lose the associated ecosystem services (red). Full land conservation sustains all the current landscapes and ecosystems (yellow), while the price mechanism in the LULUCF sector further encourage large-scale afforestation/reforestation in the tropics, but the impacts on biodiversity depends on how the policy will be implemented in local contexts (yellow). For example, if the price mechanism only values carbon stocks, it may negatively impact forest structure and composition creates conflicts with biodiversity (Putz and Redford 2009).

Although mitigating terrestrial emissions is essential for meeting ambitious climate goals, specific policy instrument for achieving the climate goal may have disadvantages for meeting some other societal goals. Trade-offs of alternative policy tools in the LULUCF sector needs to be evaluated against the multifunctional of this sector in providing food, energy, and ecological services. Successful mitigation policies need to consider how to address these multiple competing goals (Smith et al. 2014). The next sections in this chapter will review and inform existing climate policies in the LULUCF sector.

5.2. Reducing Emissions from Deforestation and Forest Degradation (REDD)

5.2.1. Review REDD and REDD+

The United Nations Reducing Emissions from Deforestation and Forest Degradation (REDD) Programme has been adopted since 2008 as the main international policy mechanism focusing on land use, land-use change and forestry (LULUCF) activities in developing countries. The main objective is to incentivize a large amount of low-cost emissions reductions in the land use sector (Strassburg et al. 2009). The enhanced version, referred as the REDD+, also supports foster conservation, sustainable management of forests, the enhancement of carbon stocks as well as other forestry activities at national levels (UNFCCC 2014).

REDD is designed as a results-based financing mechanism, by certifying carbon credits and receiving payments for each ton of carbon dioxide saved or removed from the atmosphere (Brown 2013). It builds upon and tries to improve the design of Clean Development Mechanism afforestation or reforestation (CDM A/R) projects, which has been unsuccessful due to financial, administrative and governance constraints (Thomas et al. 2010). There have been a number of uncertainties and challenges in terms of designing and implementing the REDD (and REDD+ as well), such as difficulties of monitoring, report and verification (MRV) (Herold and Skutsch 2011), potential carbon leakage (Golub et al. 2009; Harvey, Dickson, and Kormos 2010), financing constraints without ambitious international climate goals (Lubowski and Rose 2013; Angelsen et al. 2012), and so forth.

The advanced version, REDD+, has learned lessons from both the CDM and REDD (Lederer 2011; Angelsen and Rudel 2013; Angelsen et al. 2012). One of the key advanced feature of REDD+ is to extend the main objective of REDD from mitigating carbon emissions only to other social and development benefits, providing payments for the multiple services that forests can provide (Angelsen et al. 2012). For example, although there are large potentials to achieve both the climate and biodiversity goals through REDD (Harvey, Dickson, and Kormos 2010; Strassburg et al. 2009), if increasing carbon stocks were singled out as the main incentive, certain activities may impact forest structure and composition as well as biodiversity (Putz and Redford 2009; Obersteiner, Böttcher, and Yamagata 2010).

This improvement is highly relevant to address the potential conflict of interests between achieving a global climate goal and goals for local communities, such as poverty alleviation (Sunderlin et al. 2008), livelihood benefits (Chhatre and Agrawal 2009), and agriculture production (Angelsen 2010). With policy targets beyond terrestrial emission reductions, a number of REDD+ initiatives involve capacity building, establishing and securing community forest rights, as well as engaging relevant stakeholders such as indigenous peoples, as parts of the whole strategy (UNFCCC 2016). Many empirical evidences suggest that secure property rights to local communities are in general associated with both lower deforestation rates and better livelihood outcomes (Stevens et al. 2014; Sunderlin et al. 2014; Pagdee, Kim, and Daugherty 2006; Duchelle et al. 2014; Resosudarmo et al. 2014; Naughton-Treves and Wendland 2014).

5.2.2. Implications to REDD+ design and implementation

To date, the scope of REDD+ is far from realizing large amount of emission reductions, and thus the potential impacts on food availability and access from land-use based mitigation as observed in Chapter 4 are unlikely to occur yet. Although the successful implementation and full realization of REDD+'s potential in emission reductions depends on many technical, institutional, and political challenges, the absence of an ambitious international climate agreement is critical (Angelsen et al. 2012).

Therefore, as the international ambition for climate mitigation enhances and funding sources for REDD+ increase with carbon financing, whether the REDD+ will generate unintended outcomes to food availability and access for the poor becomes uncertain. To minimize the potential side-effects, I make two policy recommendations: first, land policy making at the national level should evaluate specific contexts and stages and adopt a combination of different instruments; and second, emissions from the land system should continue to be managed through a separate mechanism from the energy system emissions.

Although the results-based financing mechanism is established at the international level, the participated developing countries of REDD+ are responsible for developing national strategies or action plans to implement the REDD+ initiatives, by fully taking into account national and subnational circumstances (UNFCCC 2016). Existing national strategies often combine several policy approaches, including forest conservation, livelihood support, results-based economic incentives, and so forth (Sunderlin and Sills 2012).

Based on the results from Chapter 4, two of the policy approaches – natural land conservation and terrestrial carbon pricing, if implemented across wide ranging of countries and very strictly, we have to be concerned with the food availability and access issue for the poor. Given the multi-function of the land system, full natural land protection will leave little space for any increasing demand of food and energy crops to be met beyond existing commercial land, and thus the potential to enhance total production solely depends on the improvement of productivity. One advantage of terrestrial carbon pricing over full land protection, as observed in Chapter 4, is the flexibility to find the most productive land for agricultural activities, which helps moderate the rise in production costs and food prices to meet increasing food demand from larger and wealthier population.

More importantly, choice of policy instruments may largely depend on specific contexts and stages. Currently, most REDD+ initiatives are designed to stop and avoid deforestation in developing countries compared to the “business-as-usual”, which can be achieved domestically through either land conservation policy or terrestrial carbon pricing, or the combination of the two. In practice, remote forests can be passively protected with the help of conservation policies; while pricing terrestrial emissions, or the results-based payment mechanism, is more effective in preventing deforestation in the frontier areas as communities are more likely to receive assistances (Angelsen and Rudel 2013).

With respect to minimizing the unexpected consequences to food availability and access, it is also favorable to take the combined approach to avoid deforestation according to specific contexts. In frontier forests, flexibility of the economic incentive

prevents the least productive land from agricultural expansion, increasing the food production gain to carbon losses. On the other hand, large and remote areas, such as many tropical forests with rich biodiversity, have much higher opportunity costs for agricultural expansion, and thus the economic selection of the most productive land tends to have little contribution to lower food prices due to low accessibility. Instead, providing economic incentives may lead to higher clearing rates for remote forests with newly developed infrastructures (Pfaff et al. 2014; Angelsen and Rudel 2013).

Although terrestrial carbon pricing has more flexibility in providing multiple services through the land system, when terrestrial emissions are valued equally to the energy system emissions, large-scale afforestation will be achieved by replacing existing cropland, particularly in the tropical developing countries. Loss of crop land, especially for the poor regions, will also create food availability and access concerns.

This suggests that the carbon price of terrestrial emissions should not be linked to the price of energy system emissions, but at a lower level where deforestation is prevented without sacrificing food availability and access for the poor. That said, although emission reductions in the LULUCF sector are cost-effective, due to the multi-function of the land system, the energy sector will have to take on a larger share of emission reductions than what would have been determined solely based on marginal abatement costs. As an increasing number of national and regional carbon markets have emerged or been proposed, emission reductions from the LULUCF sector are usually not directly covered but instead used as an offset mechanism. Moving forward, although it is cost-effective to fully link the LULUCF sector and the energy system via a single carbon price, given the critical role of the land system in providing food, emissions from the

LULUCF sector should continue to be managed through a separate mechanism, like the REDD+. Emissions from the energy system are controlled separately through carbon taxes or carbon markets, which simply provides the financial sources to avoid deforestation and increase natural carbon stocks. The scale of afforestation should be evaluated against national contexts and priorities, including food security concerns, but rather not based on the cost-effective global mitigation.

5.3. Country-case analyses

Section 5.2.2 discussed in general how to select different land policy instruments based on specific national and subnational circumstances. This section applies the recommendation to several country cases in the tropics, by discussing the key drivers of deforestation, their LULUCF targets, activities, and policies. One of the most important features that has emerged in recent international climate policy regime is to take the form of national approach, including the already discussed REDD+ and the Intended Nationally Determined Contributions (INDCs) under the Paris agreement. This national approach provides an opportunity at the early stage to understand different national contexts as well as policy tools.

With respect to specific national contexts, many research efforts have been made trying to understand the key drivers of tropical deforestation, with increasing number of case studies completed in various local contexts (Clements and Milner-Gulland 2015; Hosonuma et al. 2012; Kaimowitz and Angelsen 2008; Pagdee, Kim, and Daugherty 2006). In particular, conversion to agricultural land has been one of the key drivers of deforestation in developing countries since the 1990s, either dominated by large-scale

commercial agriculture in South America or by subsistence agriculture in Sub-Saharan Africa (FAO 2016). I thus look at Brazil and countries in the Congo Basin and West Africa as a comparison in the following country case analysis.

The first country case that I look at is Brazil, where LULUCF has been its largest GHG emission source. During the last decade, Brazil has achieved significant reduction of deforestation in the Amazon (Escobar 2015), which was previously driven by cropland for soy and cattle pastures (Nepstad et al. 2009). The launches of several critical conservation policies, the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) in 2004 and a series of Presidential decrees and resolutions during 2007-2008, have contributed to the slowdown of deforestation rate in addition to the effect of decreasing agricultural products in international markets (Assunção, e Gandour, and Rocha 2012). Also, Brazil has performed as a pioneer player in the REDD/REDD+ initiatives through a number of national strategies and pilot REDD+ projects (Moutinho et al. 2014). Given these progresses, Brazil's INDC that pledges to eliminate unlawful deforestation by 2030 and restore 12 million hectares of forest, seems less ambitious and redundant with previous targets (Escobar 2015).

By pursuing aggressive land protection programs, Brazil's land policy portfolio depends more strongly on the conservation approach. This is arguably an effective tool in protecting large tropical forests under the pressure from large-scale commercial agriculture, taking into account the impacts on food availability and access. On the one hand, tropical forests are rich reservoirs of biodiversity, and thus full protection generate other benefits beyond natural carbon stocks. On the other hand, deforestation has been mainly driven by the large soy and cattle industries for exports, which does not directly

link to food availability and access concerns for the poor. More importantly, given the large industry's high access to markets and assets as well as capacity to adjust, preventing the expansion of large-scale commercial agriculture into tropical forest is likely to encourage new investments in technology to improve productivity, and thus benefits rather than damage the business.

Given the successful story in Brazil, whether it can be copied to countries in the Sub-Saharan Africa (SSA) is, however, uncertain. This is because of the critical distinctions in terms of forest features, deforestation patterns and drivers, as well as food security concerns. With respect to forests, the Congo Basin in the SSA is the world's second largest rainforests area, after the Amazon, while forests in East and West Africa are dry and more scattered (Mayaux et al. 2013). Therefore, forests protection can be more effective in countries around the Congo Basin, such as the Democratic Republic of the Congo (DRC), where forests are large and isolated.

With respect to deforestation, the SSA forests overall have experienced distinctive deforestation pattern compared to other tropical forests, with lower clearing rates and mainly caused by subsistence agriculture (Rudel et al. 2013). However, because of the small and more densely populated forests, West Africa and Madagascar exhibit a much higher deforestation rate than the Congo Basin (Mayaux et al. 2013). Compared to remote forests, frontier forests with more dense population face greater pressure from increasing food demand and economic development, both of which have been mainly supported by small-scale agriculture in many SSA countries (Rudel et al. 2013). Therefore, land policies with economic incentives tend to be more favorable than the

traditional conservation approach, which has the potential to provide another option for the livelihoods to these rural people.

With respect to food security, unlike Brazil, many SSA countries are among the world's most food insecure, and face greater challenges to feed their fast growing population and have stronger tendency towards urbanization. Therefore, price of terrestrial carbon is particularly sensitive for SSA countries, given their high priority in achieving food security for anticipated rapid population growth. Because of low economic conditions and the vulnerability in global agriculture trade, SSA countries cannot heavily depend on imports for staple food, and thus cannot risk losing existing cropland. Under modest terrestrial carbon pricing, policies with economic incentives not only enhance small-scale farmers' capacity to increase productivity on existing crop land through various measures, but also helps find the most productive land for agriculture while sustaining or even restoring forests.

Chapter 6. Conclusions

Through the above chapters of my dissertation, I explored how different designs of climate policies might generate unintended consequences to regional food availability and access (FAA) to 2050. Chapter 2 introduced my modeling tool – GCAM, and the development and modeling methods of a new metric of FAA. Chapter 3 tested FAA against a series of alternate expectations of the future to better understand the metric and its robustness. Chapter 4 presented and discussed the core results of the research regarding the impacts on FAA from alternate climate policy designs. Chapter 5 applied the key results to existing policy making in the LULUCF sector, by reviewing both the international mechanism of REDD+ and selected country cases.

In this concluding chapter, I first summarize the key findings by answering the set of research questions asked in Chapter 1; then I discuss the more general policy implications, research contributions, and caveats; and finally, this chapter finalizes with future research potentials.

6.1. Answers to my research questions

To answer the series of questions asked in Chapter 1, I extended the use of IA models to assess long-term food availability and access by developing a new metric of FAA that consists of both consumers' staple food budget share and total caloric intake.

First, I find that under specific policy designs, we need to be concerned about the adverse side-effects on FAA from ambitious climate mitigation. Moreover, the impacts on FAA will likely be concentrated in already fragile low income countries. Chapter 3 also tells us increasing food demand due to population and economic growth alone does

not worsen FAA throughout 2050, because economic growth dominates FAA improvements in all regions. FAA only worsens if price increase outpace economic growth. Such conditions include uncertain price changes caused by factors such as change in market framework and extreme weather events under climate change. However, another potential cause that is not texted with the scenarios is little or negative economic growth, where food prices are likely to rise with increasing demand from larger population, faster than economic growth.

Second, we should be concerned with the unintended outcomes to FAA under two policy conditions from meeting stringent climate target. One is the policies that encourage bioenergy expansion on existing commercial land through very strict land use restrictions, and the other is the policies that encourage large-scale afforestation by pricing terrestrial emissions equally to the energy system emissions. Both policies impact FAA by changing food prices due to competing use of land. In other words, impacts on FAA largely depend on the policy instrument to mitigate terrestrial emissions. The two policies impact FAA by altering land use patterns between competing uses. The former imposes the highest FAA risks to a broader range of developing regions in 2050, especially when remaining commercial land approaches the capacity limits to meet high food demand under rapid population growth. The latter, with the flexibility to shift land use activities around the globe, has lower pressure on staple food prices than the regional allocated land conservation policies. Therefore, sound climate policies can address the potential risks on FAA by planning land conservation to maximize global benefits rather than allocate the restrictions equally by region. However, terrestrial carbon pricing

substantially affects the production of roots and tubers, which is particularly problematic to Sub-Saharan Africa, the main consumer of roots and tubers.

Third, to minimize or avoid the side-effects on FAA for the poor, developing countries can achieve domestic deforestation reduction through either land conservation policy or economic incentives, or the combination of both, depending on specific contexts and stages. In particular, in frontier forests, flexibility of economic incentives help find the most productive land for agricultural activities, increasing the food production gain to carbon or biodiversity losses. By contrast, large and remote forests can be passively protected with the help of conservation policies, because the economic selection of the most productive land has little contribution to lower food prices due to little accessibility. Moreover, to avoid large-scale loss of cropland, the carbon price of terrestrial emissions should not be linked to the price of energy system emissions, but at a lower level where deforestation is prevented without sacrificing food availability and access for the poor. Although it is cost-effective to fully link the LULUCF sector and the energy system via a single carbon price, given the critical role of the land system in providing food, emissions from the LULUCF sector should be managed through a separate mechanism.

A more general policy discussion, not limited to the land-based mitigation policies, is provided in the following section.

6.2. Policy implications in the agriculture sector

Given complexity of the land system, both the land conservation policy and results-based payments with terrestrial carbon pricing are likely generated unintended

outcomes to food availability and access. Chapter 5 discusses in details that a carefully designed land-based mitigation policy, likely a combination of the two approaches, depending on specific contexts, can help minimize the side-effects.

However, a broader range of measures are also important in terms of alleviating the pressures on land between competing use for carbon stocks and agricultural production. In general, this section will discuss from four perspective: adaptation, agricultural productivity, trade liberalization, and demand-side management.

First, adaptation is particularly important in the agriculture sector and through the entire value chain of the food system, due to their high sensitivity to small changes in the climate (Porter et al. 2014). Many adaptation measures are not only effective near-term responses to climate change but also to a broad scope of pressures. In particular, through risk management, technology transfer and adaptive capacity building to poor farmers, adaptation practices can generate multiple benefits on food production, livelihood and rural development (Cooper et al. 2008; Twomlow et al. 2008; Howden et al. 2007). For instance, because more than 70 percent of agriculture is rain fed (Porter et al. 2014), many adaptation practices target on water management, such as increasing access to irrigation, more efficient rainfall harvest, employing water conservation technologies, and so on (Twomlow et al. 2008). Adaptation is not only about to reduce negative effects of climate change but also to exploit possible positive effects (Olesen et al. 2011). For example, introducing new crops that are more suitable to changing local climate, increasing diversification of production, and adjusting planting and sowing dates all lead to crop yield benefits (Porter et al. 2014).

Second, with respect to agriculture productivity, on one hand, it is necessary to meet future higher food demand on existing rather than expanded agricultural areas; on the other hand, however, increase in crop yields alone does not reduce cultivated area expansion (Phalan et al. 2011; EWERS et al. 2009; Rudel et al. 2009; MATSON and VITOUSEK 2006), but more than often encourages forest clearing because of higher profits from the agricultural activities (Angelsen 2010; Kaimowitz and Angelsen 2008). Therefore, approaches known as sustainable intensification are increasingly proposed. It refers to a process that increases agricultural products with a reduction in emission intensity or resource intensity to address the potential trade-offs between intensification and environmental goals, like GHG emission reductions in the agriculture sector (Tilman et al. 2011; Garnett et al. 2013; Smith 2013; Godfray et al. 2010).

Sustainable intensification may be carried out in different ways, such as using advanced technologies or improved resource management practices, and the best practices are highly dependent on national or local contexts (Garnett et al. 2013; Godfray et al. 2010). For example, irrigation technologies may have large potentials to improve productivity in Sub-Saharan Africa (Svendsen, Ewing, and Msangi 2009); however, increasing water scarcity may constrain the ability of Africa to switch their rain-fed farming system to the irrigated farming system (Cooper et al. 2008). As a result, other options that increase water use efficiency with improved resource management tend to have better performance in Sub-Saharan Africa, such as soil-water conservation at the rain-fed systems (Barron et al. 2015; Love et al. 2006), and private irrigation system and small reservoirs for communal irrigation (Samakande, Senzanje, and Manzungu 2004; Barron et al. 2015; Inocencio et al. 2007).

Third, in the context of an increasingly globalized world, food insecurity in one place can be either resolved or exaggerated by global market actions (Godfray et al. 2010). Policy interventions, such as price distortions and trade barriers, are intended to lower consumer prices and protect consumers' food access in major exporting countries; however, these policies intensify price volatilities in the global market, and negatively impact the net importers (Rutten, Shutes, and Meijerink 2013; Abbott 2011). Agriculture trade liberalization removes domestic food subsidies, trade restrictions, and other policy interventions that have tried to isolate domestic consumer prices from the fluctuations in global market prices (Anderson and Martin 2007; Dawe 2008). Although open trade may help lower staple expenditures for certain regions, open trade may also increase some others' exposure to harmful situation such as international price shocks.

Agriculture trade liberalization also transforms global landscape unevenly across regions. Increased agricultural trade have shown opposite outcomes in different developing countries. It has triggered substantial deforestation and other environment costs in the tropics due to strong growth in agricultural exports (Schmitz et al. 2014). Transportation infrastructures increase market access, but during the early stage of road development may incentivize deforestation. In contrast, by shifting from net exporters to net importers of agricultural products, several other developing countries in Asia and South America have recently achieved a simultaneous increase in food production and forest cover, (Lambin and Meyfroidt 2011).

Fourth, demand-side policies have large potentials to reduce food insecurity. About one-third of agricultural production is currently wasted along the food chain (FAO, IFAD, and WFP 2015). Reducing food waste therefore has large potentials to

benefit both mitigation and food security (Smith et al. 2013; Foley et al. 2011); however, quantitative estimates are few and tend to be highly uncertain (Smith et al. 2014).

Besides, changing consumption preference and consuming less of the energy intensive products help enhance resource and emission efficiency (Licker et al. 2010).

6.3. Research contributions

The significance of my dissertation is illustrated from both the literature and policy perspectives. In regard to the literature of long-term assessment of food availability and access, my dissertation make an important methodological contribution by developing a set of new metrics and methods to advance the understanding of long-term FAA with its many diverse, uncertain and interacting drivers. In particular, the metric of FAA identifies the potential trade-offs between caloric energy adequacy and poverty reduction for the poor, using the proxies of consumer's staple food budget share and total caloric intake.

My dissertation also contributes to the literature of integrated assessment of climate mitigation and multiple dimensions of food security, by evaluating and comparing the impacts between changing food prices and changing income. By incorporating a measure of consumers' food budget share, it finds larger impacts associated with changing food prices due to competing land use than previous analysis.

With respect to policy discussion, my dissertation informs effective climate policy-making about the co-impacts on other development goals, which provides another criterion for evaluating and designing climate policies. Avoiding dangerous climate change has featured as one of the Sustainable Development Goals (SDGs) on the newly

adopted global development agenda towards 2030 (United Nations General Assembly 2015). Meeting the long-term climate goal is intimately connected with many of the other non-climate SDGs that address various dimensions of human wellbeing, such as ending poverty and hunger, improving human health, ensuring universal access to modern energy, and so forth (United Nations General Assembly 2015). In particular, my dissertation provides additional information to policy makers, by evaluating the unintended consequences of alternative climate policy designs to food availability and access that are closely related to the hunger eradicating SDG.

Moreover, my dissertation explores the critical role of the land system in both achieving the climate target and providing food, energy and other products and services. It informs policy making that how we manage our finite land to fulfill multiple objectives efficiently is fundamental. Both the land conservation and terrestrial carbon pricing policies contribute to meeting ambitious climate goals, but tend to generate unintended social consequences through the complex land use system. Therefore, policies to mitigate terrestrial emissions need to be accompanied with measures that enhance poverty reduction, agricultural productivity and food system resilience to moderate the side-effects on food availability and access.

6.4. Caveats

There are several important issues or interactions that are not modeled in my research, which in general does not compromise the key conclusions of my dissertation, but requires some additional explanation when interpreting the results.

First of all, I have emphasized several times throughout my dissertation that climate change impacts on crop yields are not modeled. Modeling climate change impacts involves large uncertainty and is beyond the scope of my dissertation. Instead, I focus on comparing the unintended consequences of alternative mitigation policies, acknowledging their overall benefits of avoiding dangerous climate change impacts.

Second, when employing alternative population and GDP trajectories as defined in the SSPs, I did not adjust other parameters or assumptions in the SSP narratives that are potentially correlated with alternative economic growth. For example, the rate of agricultural productivity improvement, especially for the poor regions, is more rapid under the high (SSP1) than the low GDP growth scenario (SSP3). As a result, FAA variations between the SSPs tend to be underestimated.

Third, the current version of GCAM assumes no demand response to price change for crops (Kyle et al. 2011). It does not claim zero price elasticity in reality, but rather creates a bonding case, where food price increases would not be moderated by a reduction in food demand (Wise et al. 2014), and people will meet their income-driven total calorie level no matter what. Such a strong assumption is more likely to be true for those that consume inadequate energy, who would rather spend more than decrease consumption. These people would end up with less available income for other goods, corresponding to increased poverty for sustained caloric intake. As observed and interpreted in essay three, increased food prices move regions, the poor in particular, in opposite directions along these two dimensions of FAA, indicating trade-offs. In regard to food demand, GCAM also assumes that the shares of individual food crops or animal commodities are fixed at the 2010 levels to reflect regional preferences (Kyle et al. 2011).

Therefore, the increased diet diversity along with economic growth is not captured, which tends to overestimate future demand of staple food for today's low income but fast developing countries.

Fourth, GCAM assumes free global trade of agricultural commodities. This assumption may have strong implications to global and local food prices, particularly with changing land use patterns. For instance, the universal carbon tax might replace the majority of cropland in the tropics with forests, indicating that people there will have to heavily rely on imports in 2050. However, for those poor land-locked countries, such as in Sub-Saharan Africa, transportation costs may generate large uncertainty to their ability to access to global market and benefit from global trade.

Fifth, compared to the general equilibrium (GE) model, GCAM does capture the feedbacks to agricultural income with increased food prices for farm household. At the individual level, households that are net sellers of food tend to benefit from the rising food prices (Ivanic and Martin 2008). Similarly at the aggregate level, higher food prices tend to benefit the net food exporting countries while hurt the net food importers. Also, over the long-run, increased food prices may encourage investment in agricultural productivity, which moderates price increase (Angelsen 2010). On average, however, these positive feedbacks are unlikely to offset the negative effects of increases in food expenditures (Cororaton and Timilsina 2012; Golub et al. 2013). Without taking into account these feedbacks, my analysis explores the worst case scenarios for those net food buyers.

6.5. Future research

For future research, there are a number of subjects or directions that could be pursued to further advance the understanding of these complex interactions between climate policies and multiple dimensions of food security.

First, architecture of international climate policy has shifted from the highly centralized Kyoto regime to the most recent bottom-up Paris approach with the Intended Nationally Determined Contributions (INDCs). Climate policy making has been increasingly focusing on the national and sub-national contexts, motivations and challenges. Therefore, further research may focus on individual countries to evaluate the co-impacts of their INDCs as well as other national policies on national specific development priorities.

Second, food availability and access is estimated at the regional average, and thus overlooks the with-in region/country inequality, which may be particularly important for certain countries. Therefore, further research may take into account within-country/region inequality and develop new methods that incorporate the national/regional distribution of income and food consumption, instead of using the average.

Third, with the improvement of food demand modeling in GCAM to capture price elasticity and the substitution effects, further research may develop new metrics to look at all food expenditures that also take into account change in nutrition quality and diversity. While staple food tend to be most relevant to the poorest, change in diet composition is more relevant to fast developing countries.

Appendices

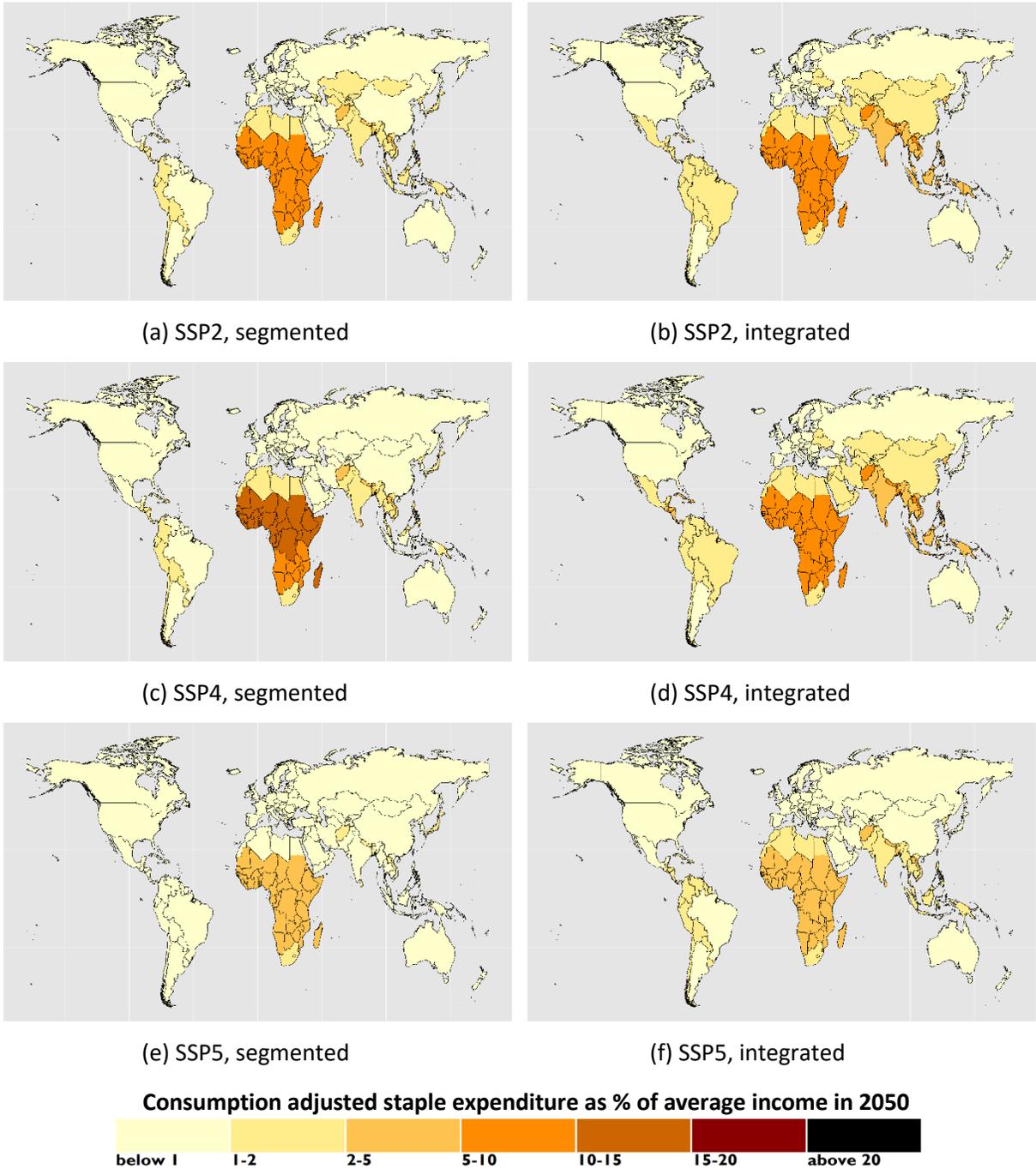


Figure A1 Food availability and access conditions in 2050, references
 Under alternative population and GDP trajectories and different assumptions of regional consumer price changes: (a) SSP2 and the segmented market model; (b) SSP2 and the integrated market model; (c) SSP4 and the segmented market model; (d) SSP4 and the integrated market model; (e) SSP5 and the segmented market model; (f) SSP5 and the integrated market model.

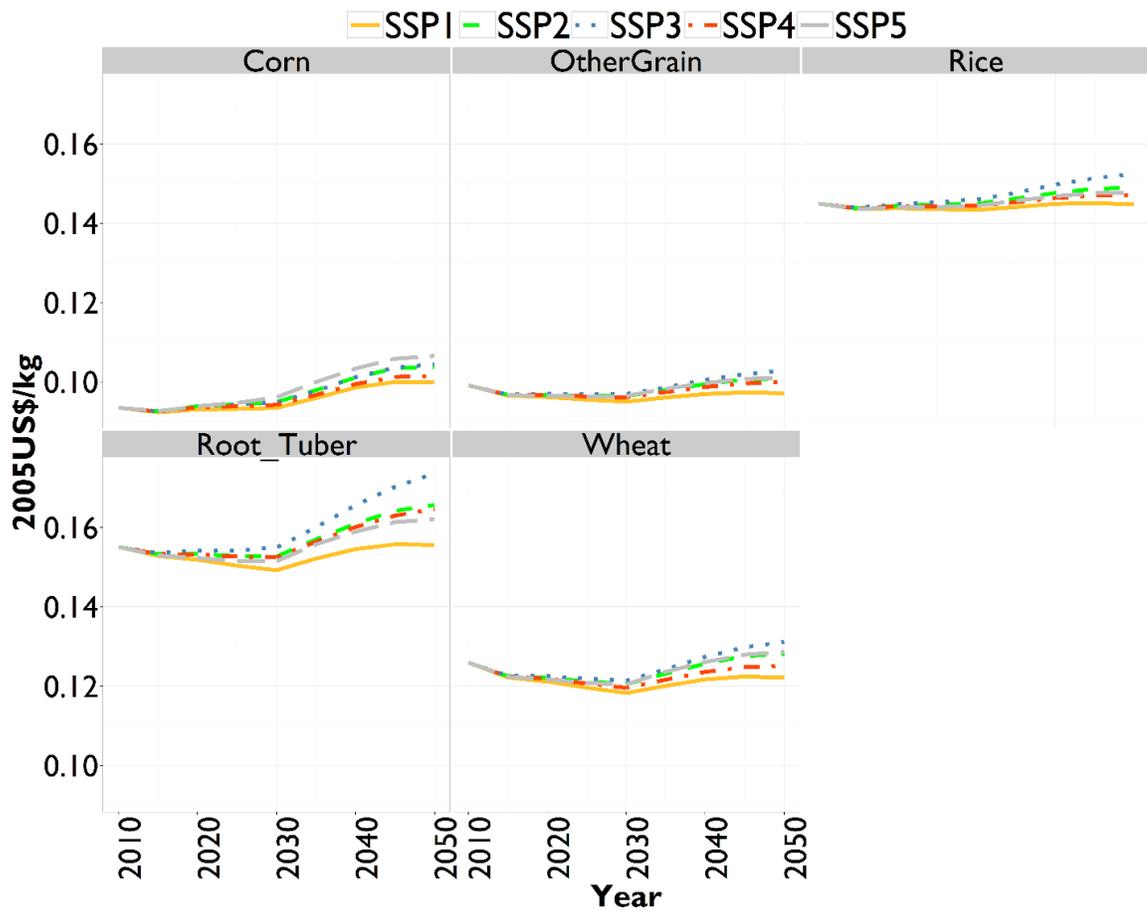
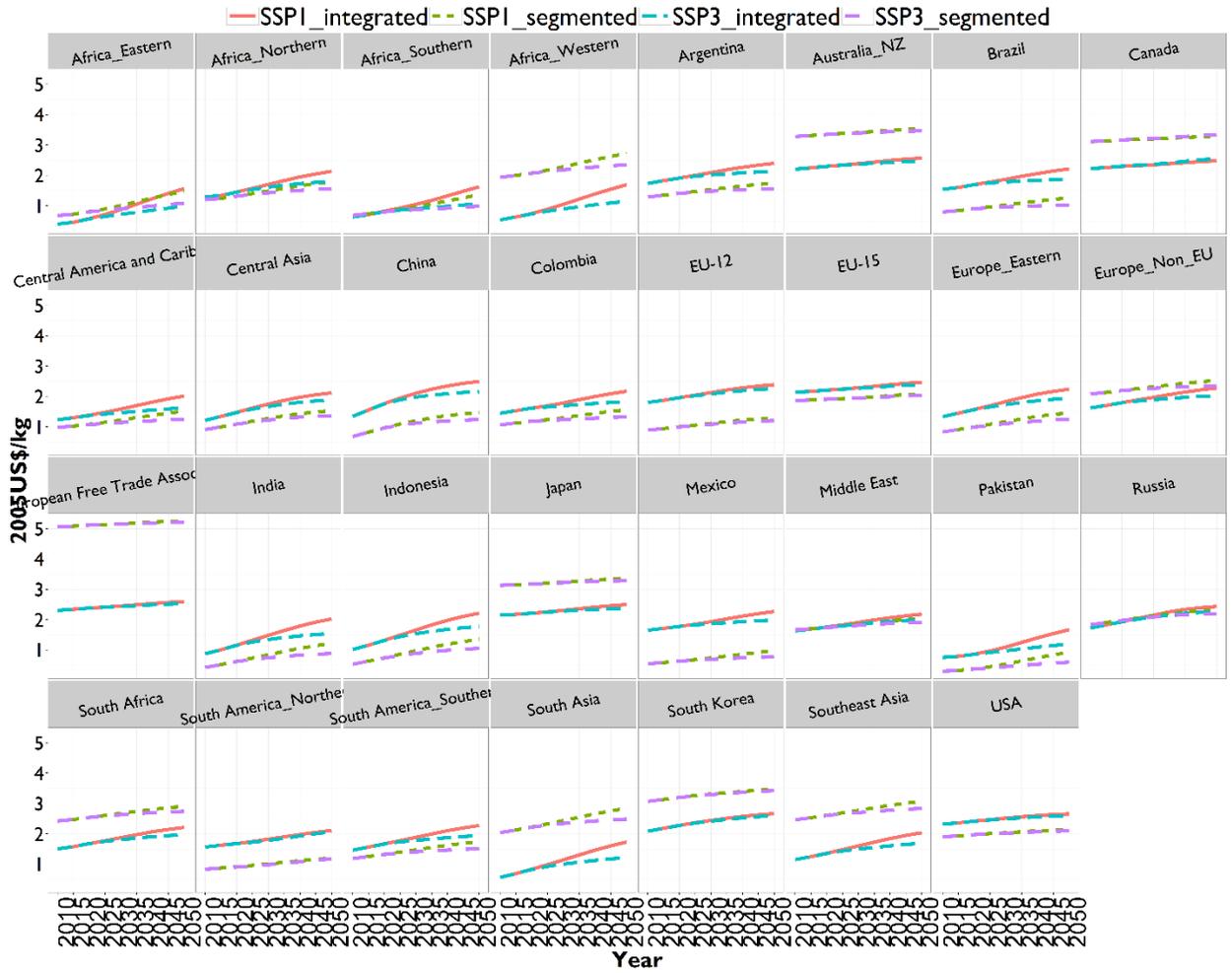
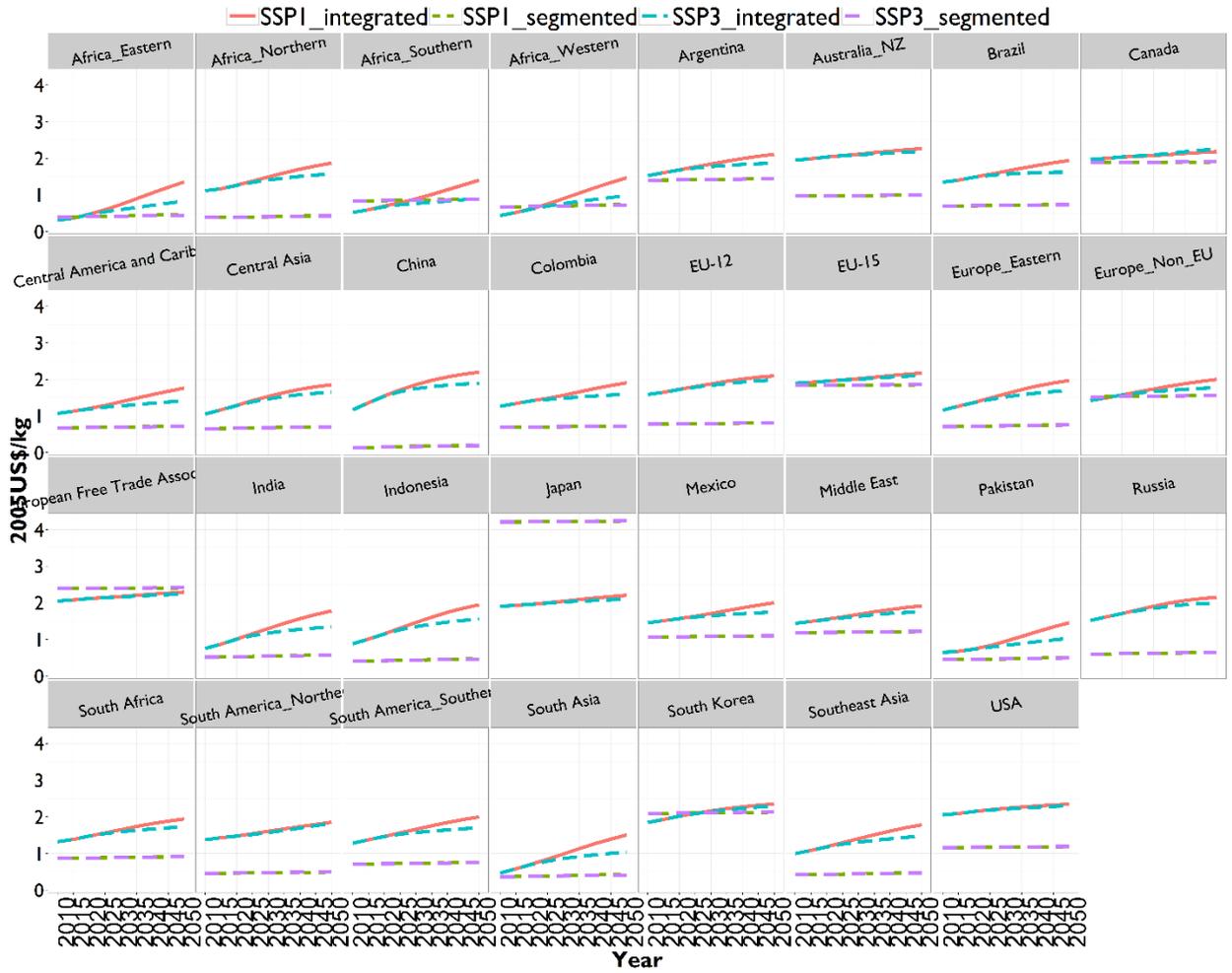


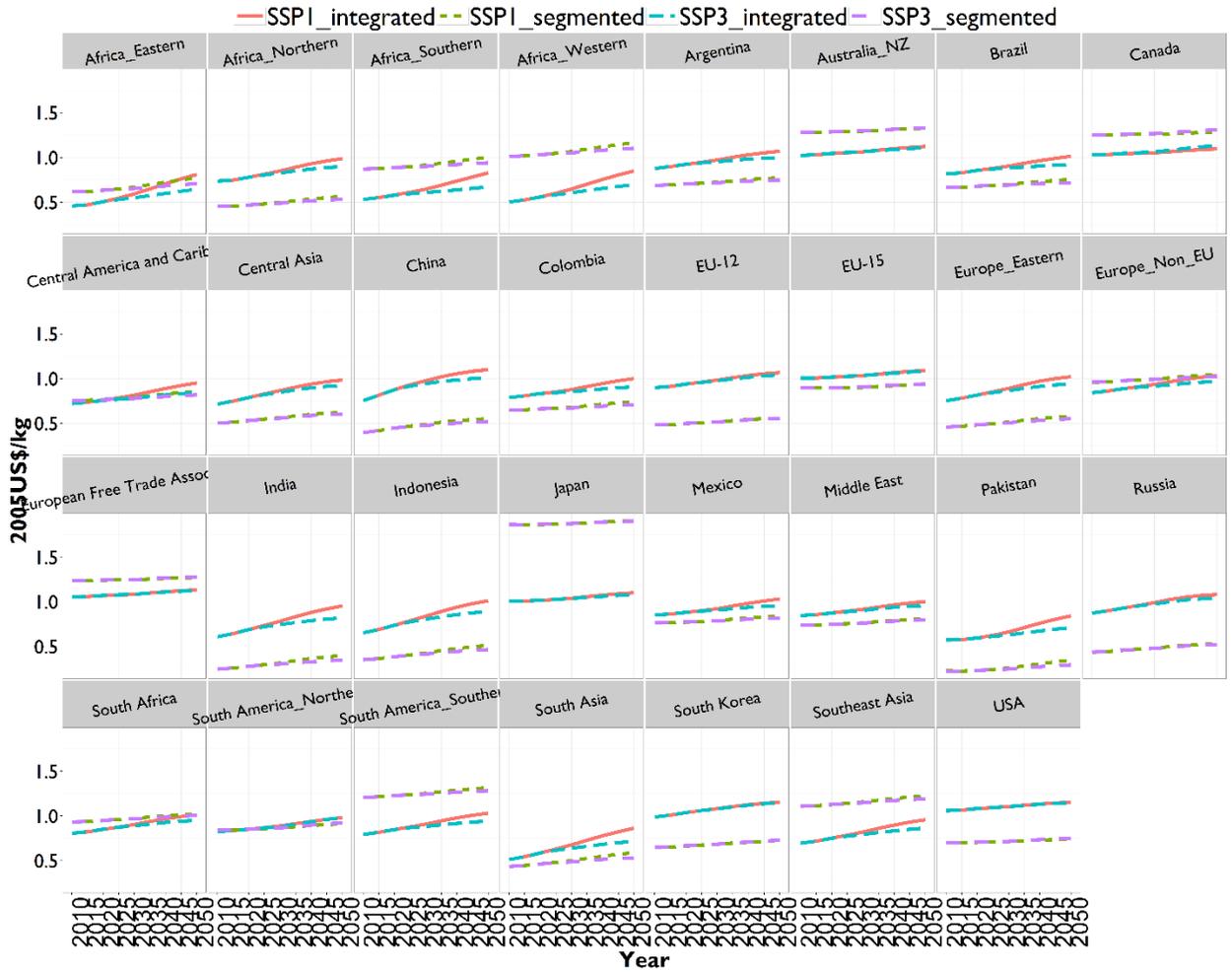
Figure A2 GCAM estimated global producer prices of staple food commodities by SSP, 2010-2050



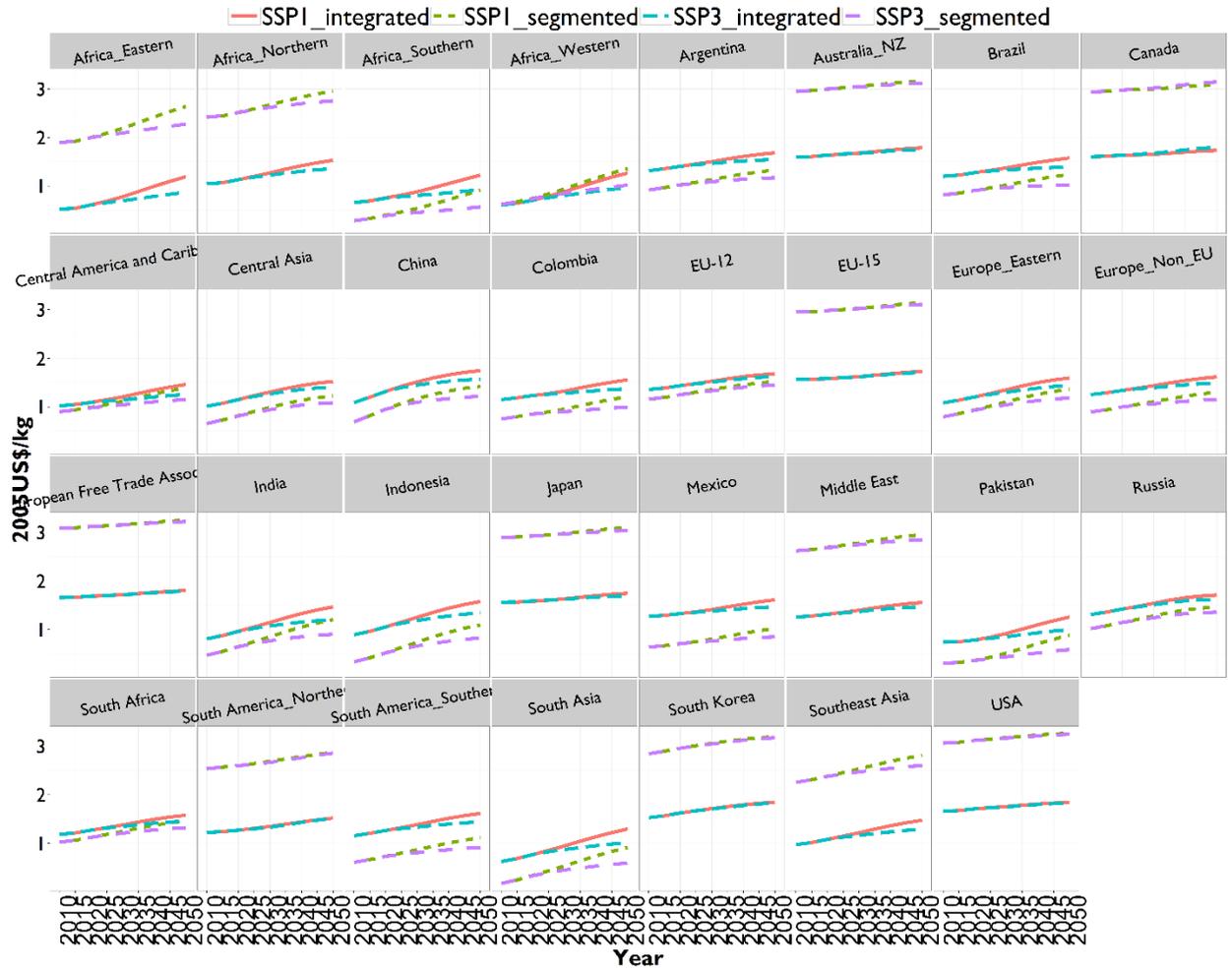
(a) Estimated consumer prices of corn



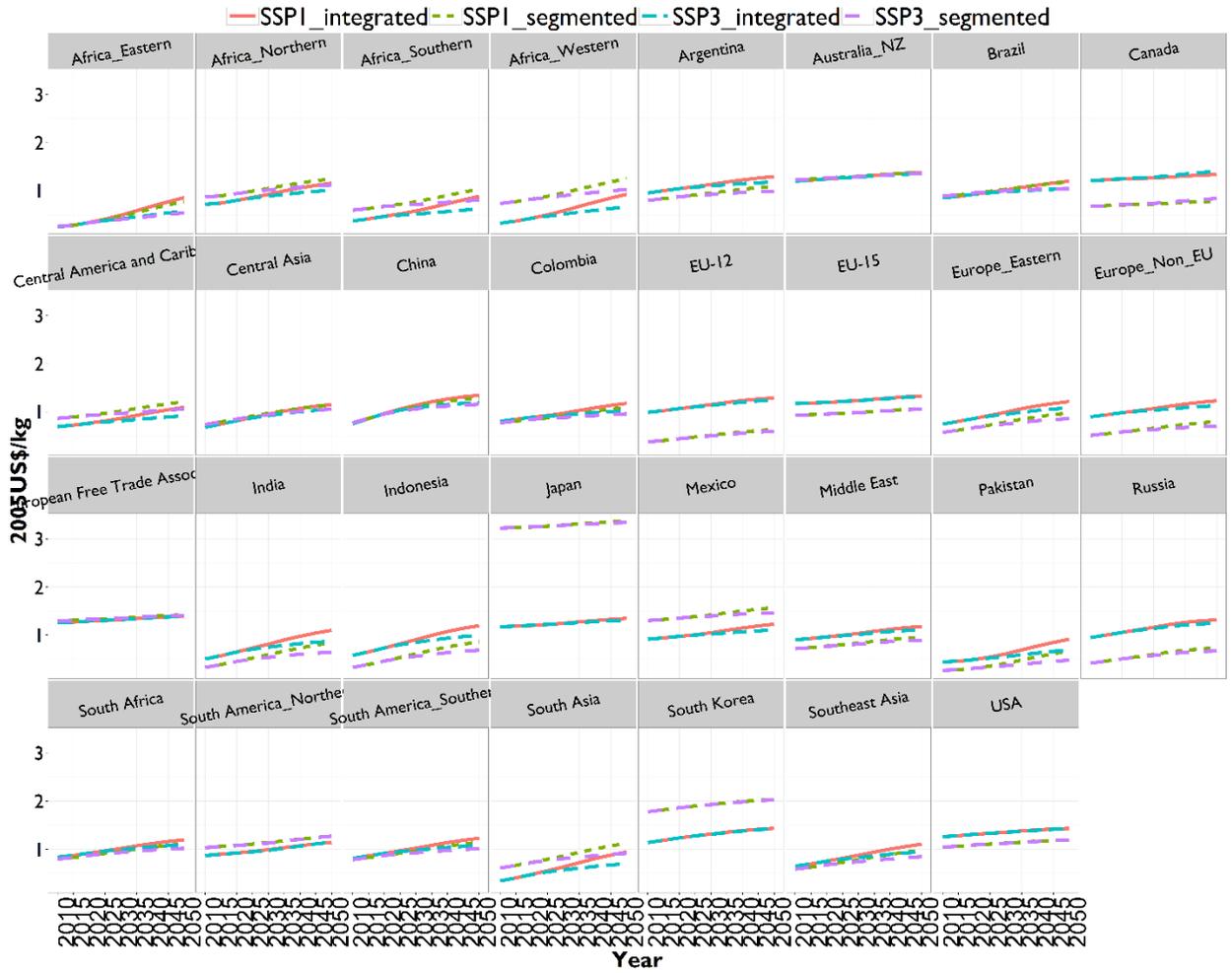
(b) Estimated consumer prices of rice



(c) Estimated consumer prices of wheat



(d) Estimated consumer prices of other grains



(e) Estimated consumer prices of roots and tubers

Figure A3 Estimated consumer prices of: (a) corn, (b) rice, (c) wheat, (d) other grains, and (e) roots and tubers, by region with the segmented and integrated market model, under population and GDP projections of SSP1 and SSP3, 2010-2050

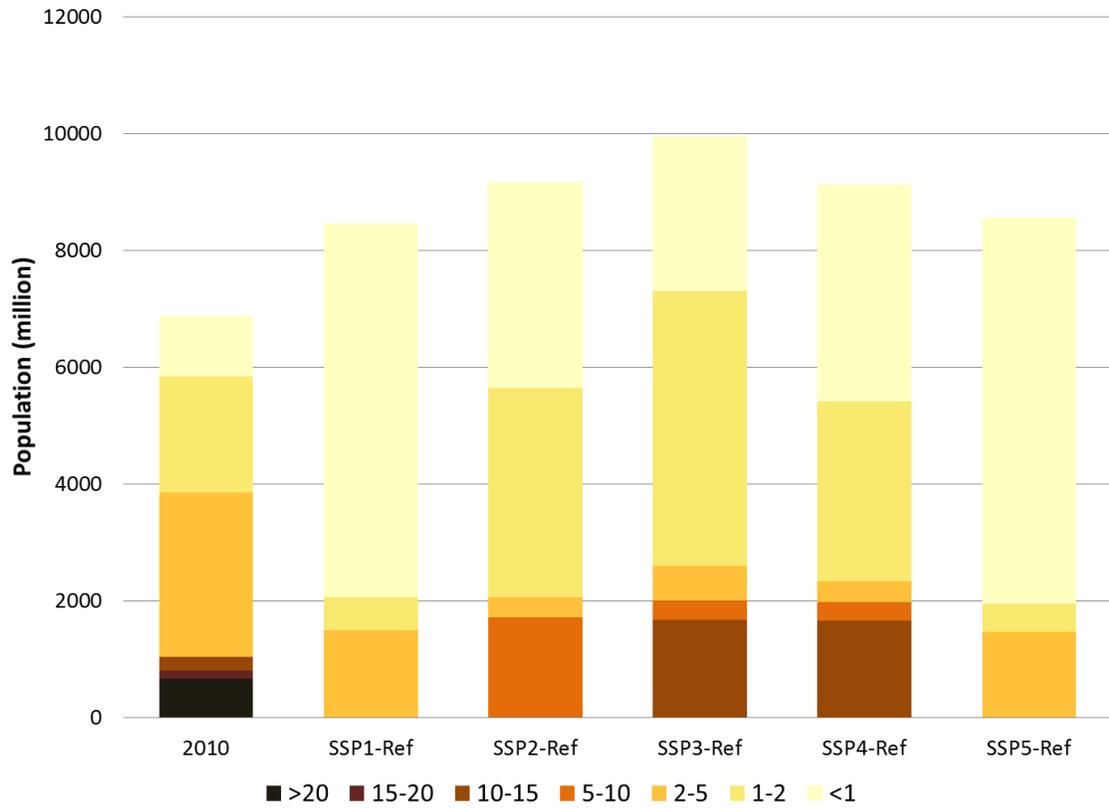


Figure A4 Total regional population in each FAA category in 2010 and 2050, by SSP, segmented market model

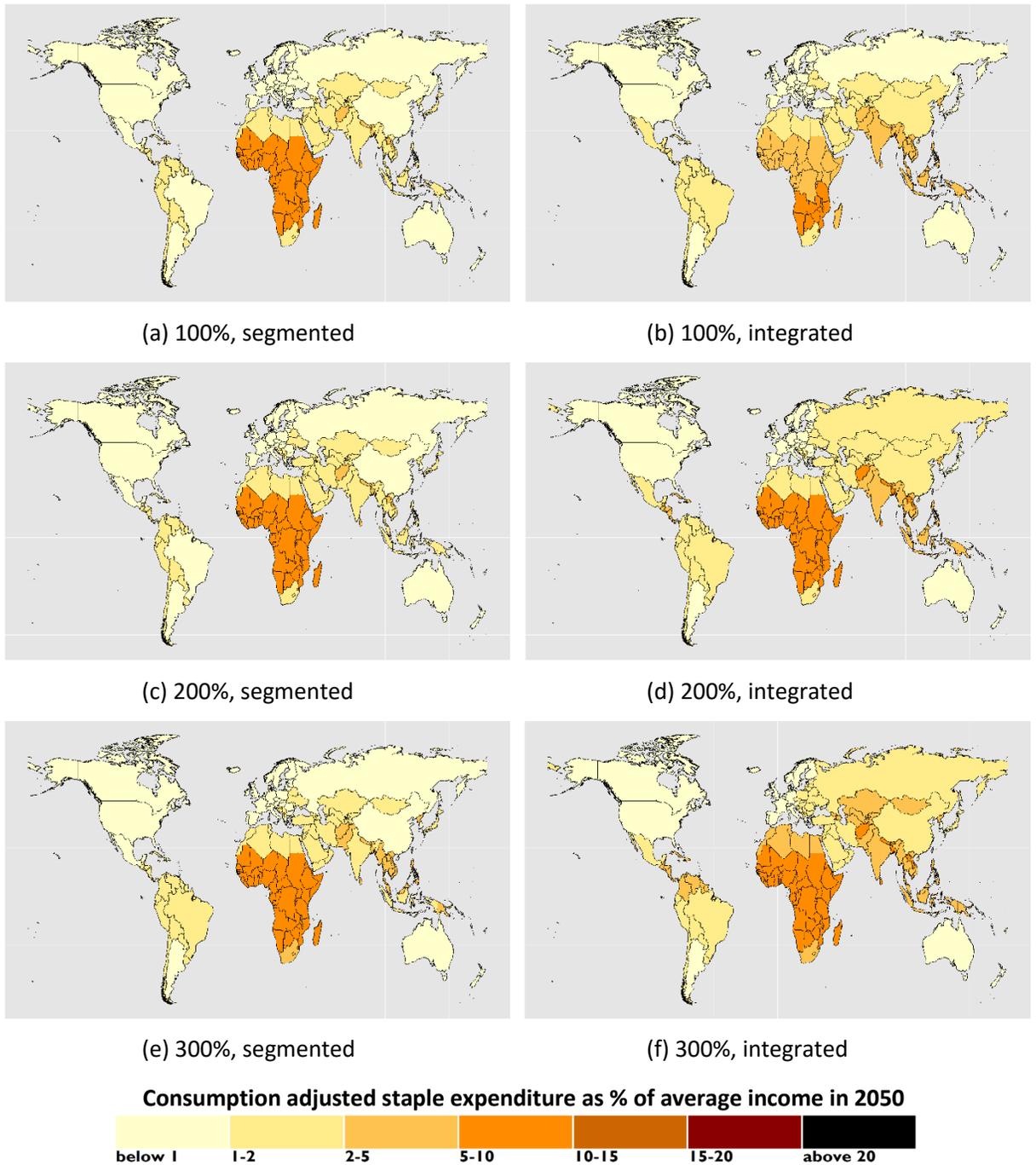


Figure A5 FAA conditions in 2050, SSP1

With different levels of global price increase and different assumptions of regional consumer price changes: (a) 100% increase and the segmented market model; (b) 100% increases and the integrated market model; (c) 200% increases and the segmented market model; (d) 200% increases and the integrated market model; (e) 300% increases and the segmented market model; (f) 300% increases and the integrated market model.

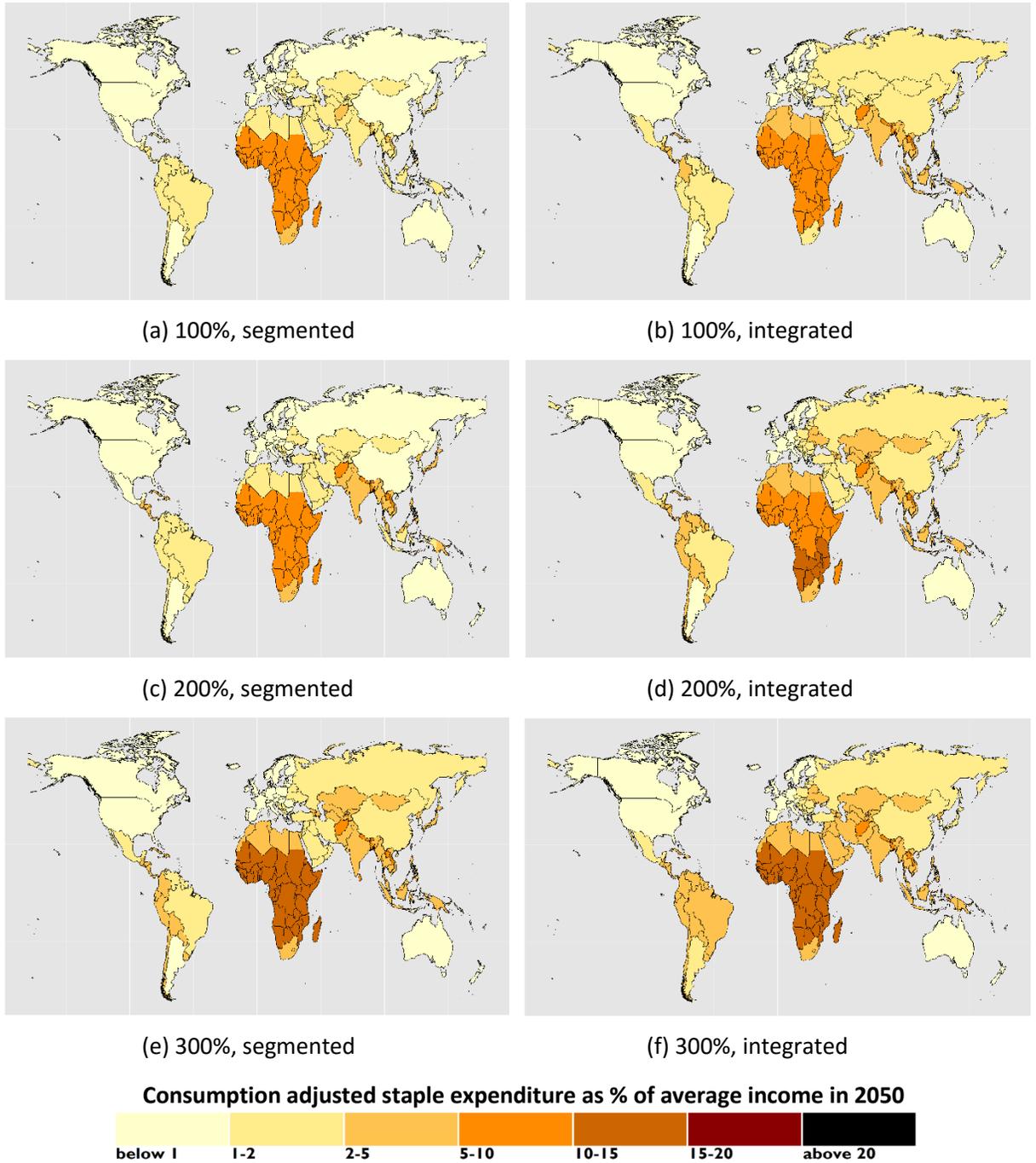


Figure A6 FAA conditions in 2050, SSP2

With different levels of global price increase and different assumptions of regional consumer price changes: (a) 100% increase and the segmented market model; (b) 100% increases and the integrated market model; (c) 200% increases and the segmented market model; (d) 200% increases and the integrated market model; (e) 300% increases and the segmented market model; (f) 300% increases and the integrated market model.

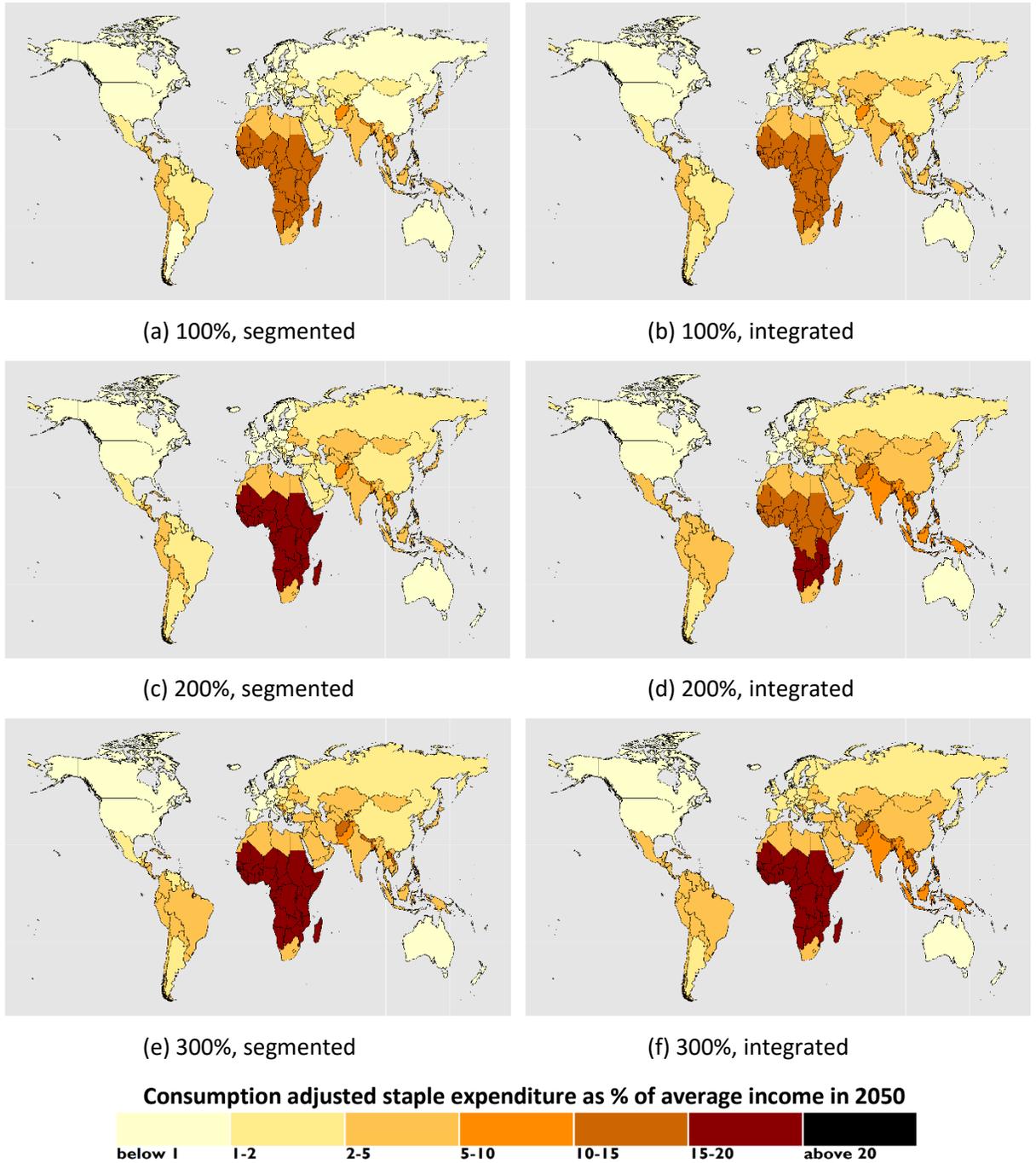


Figure A7 FAA conditions in 2050, SSP3

With different levels of global price increase and different assumptions of regional consumer price changes: (a) 100% increase and the segmented market model; (b) 100% increases and the integrated market model; (c) 200% increases and the segmented market model; (d) 200% increases and the integrated market model; (e) 300% increases and the segmented market model; (f) 300% increases and the integrated market model.

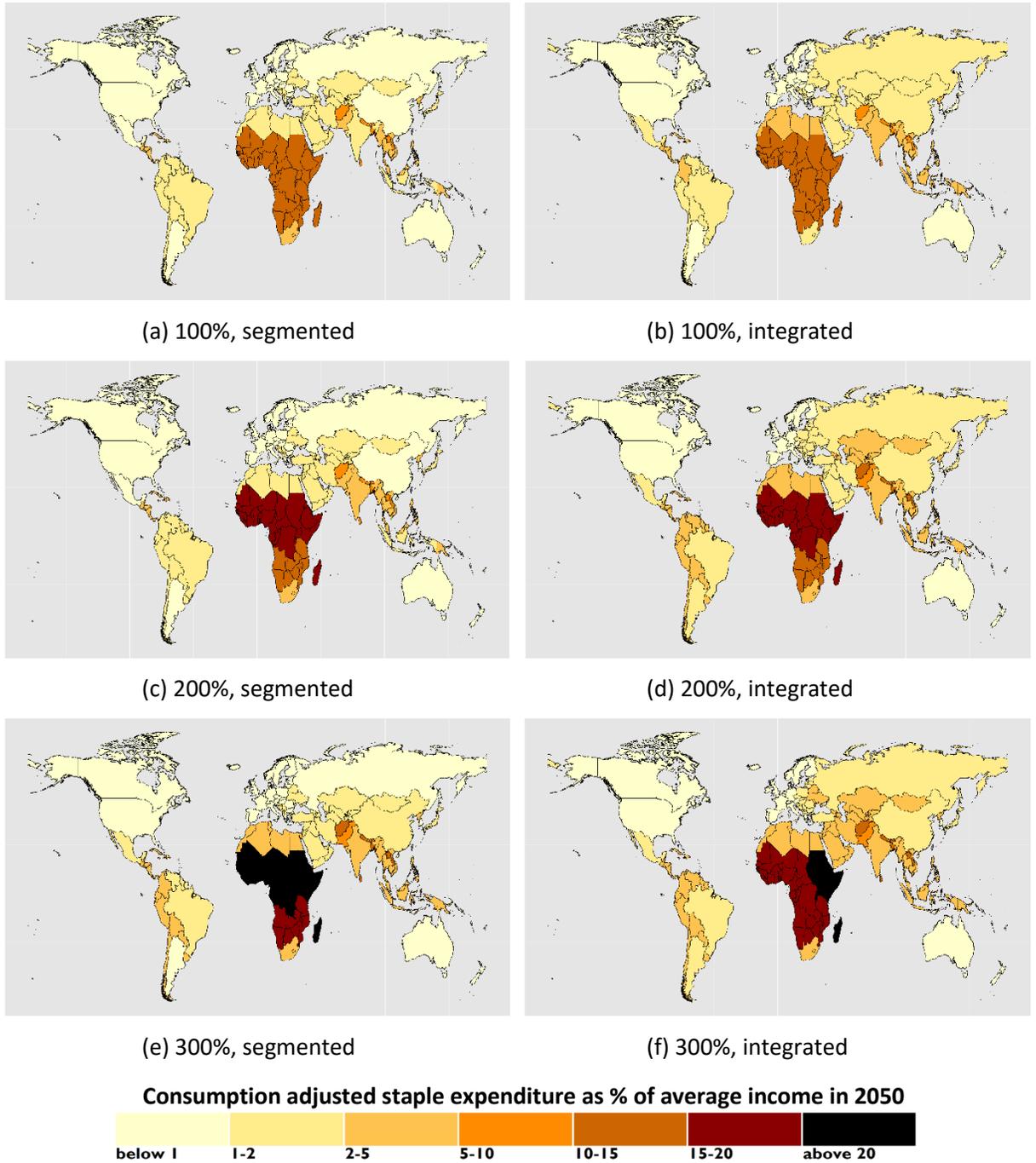


Figure A8 FAA conditions in 2050, SSP4

With different levels of global price increase and different assumptions of regional consumer price changes: (a) 100% increase and the segmented market model; (b) 100% increases and the integrated market model; (c) 200% increases and the segmented market model; (d) 200% increases and the integrated market model; (e) 300% increases and the segmented market model; (f) 300% increases and the integrated market model.

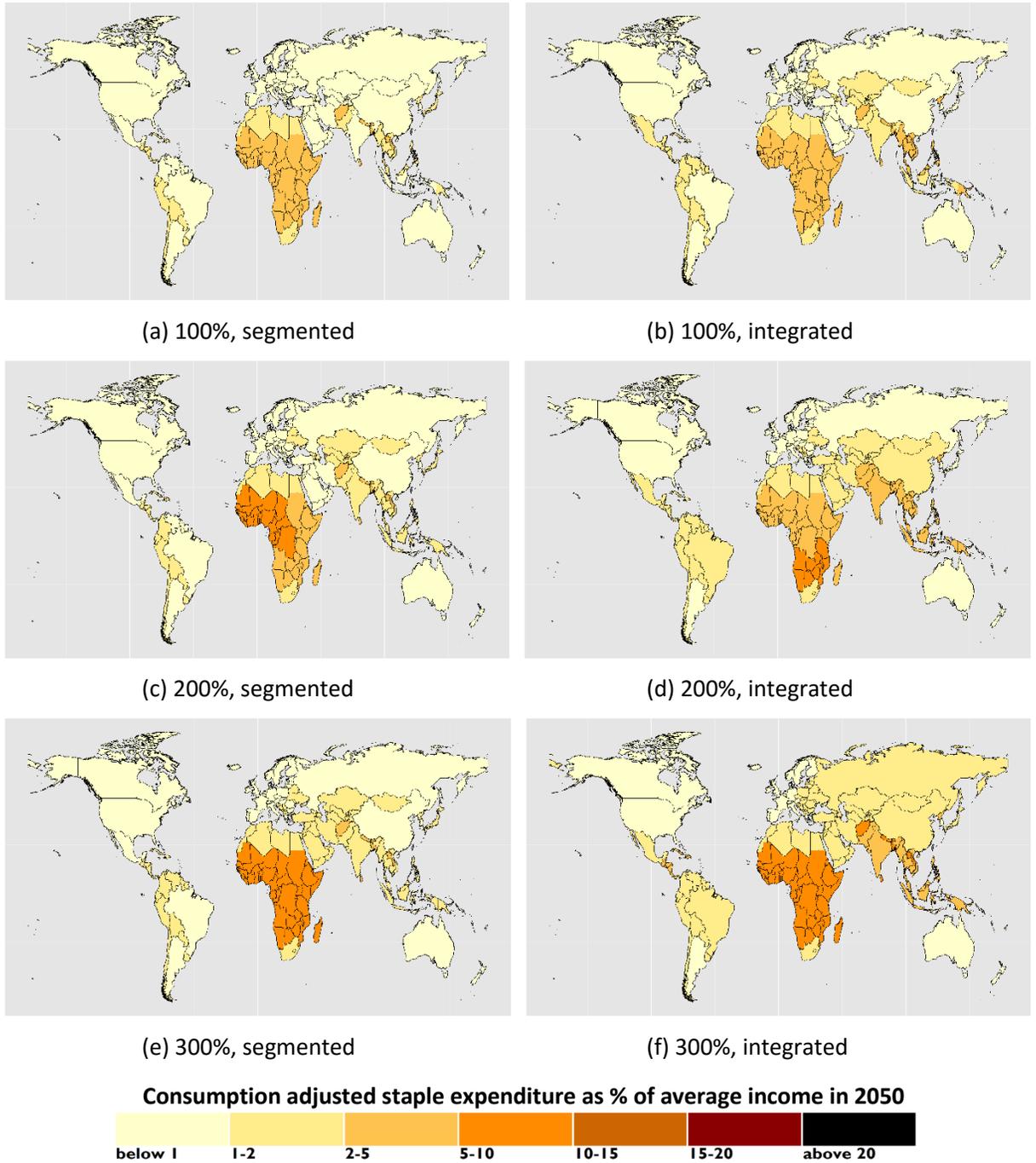
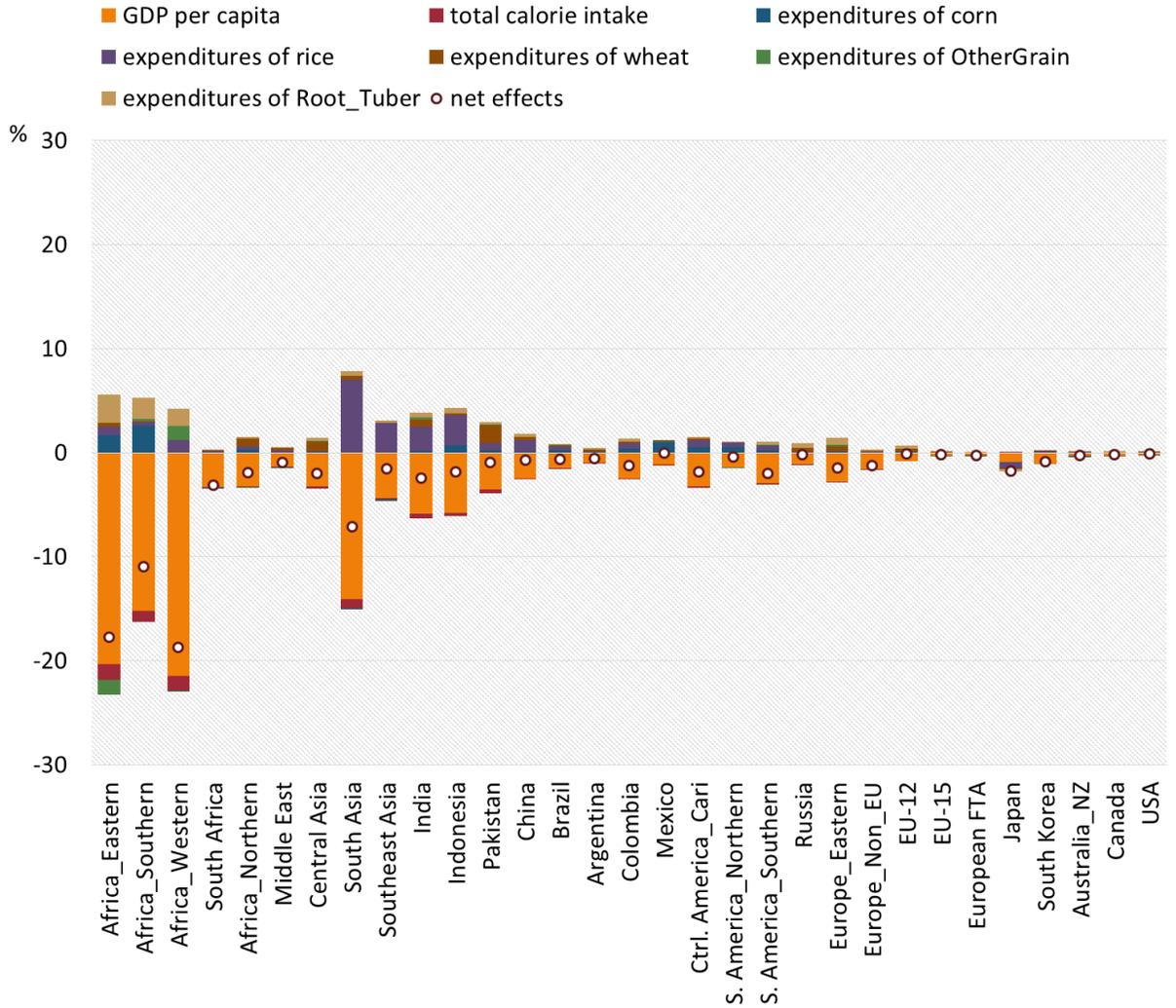


Figure A9 FAA conditions in 2050, SSP5

With different levels of global price increase and different assumptions of regional consumer price changes: (a) 100% increase and the segmented market model; (b) 100% increases and the integrated market model; (c) 200% increases and the segmented market model; (d) 200% increases and the integrated market model; (e) 300% increases and the segmented market model; (f) 300% increases and the integrated market model.

Change of consumption adjusted staple expenditure as % of average income from 2010 to 2050

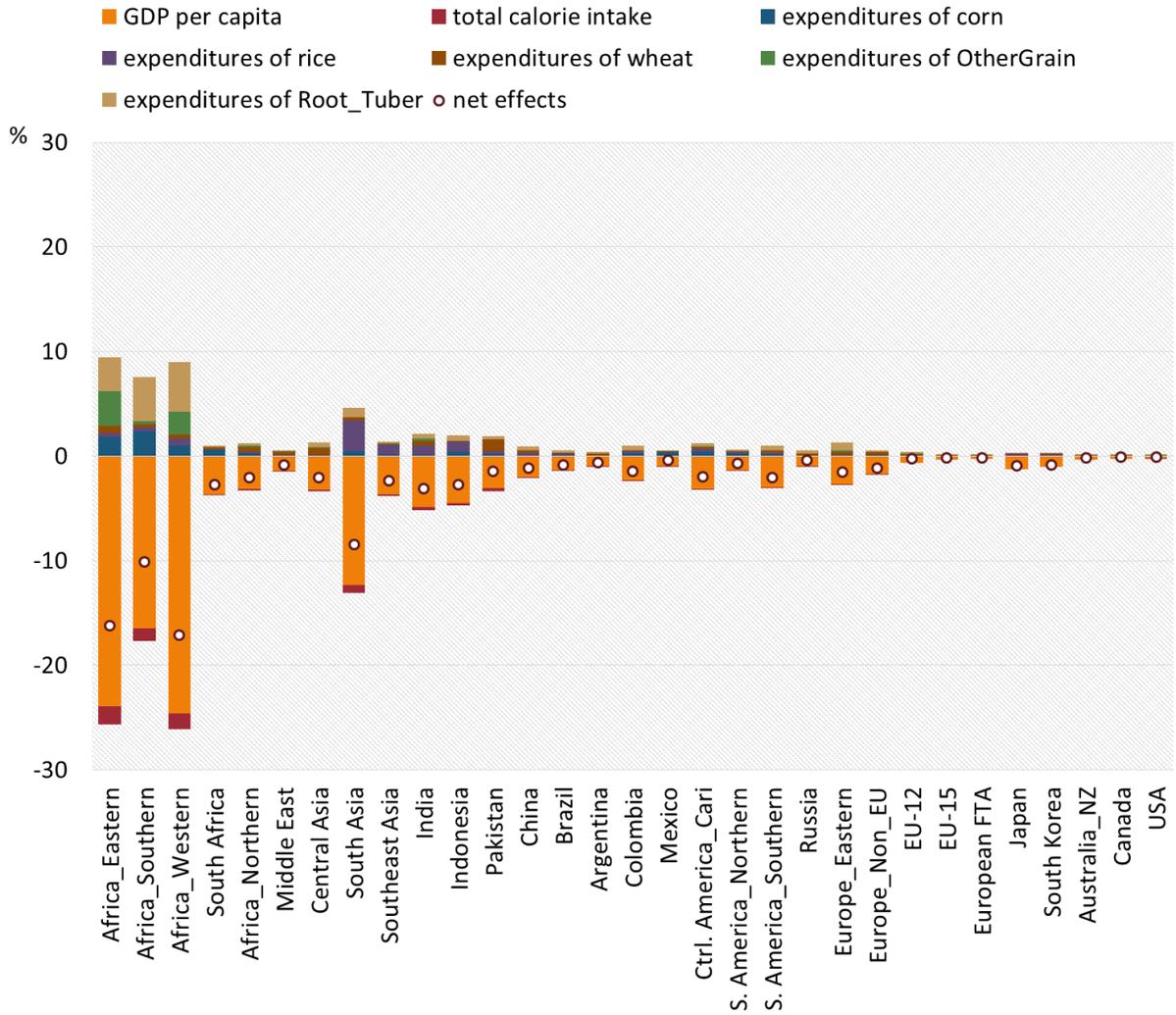


(a) SSP1, segmented, reference

(b) SSP1, integrated, reference

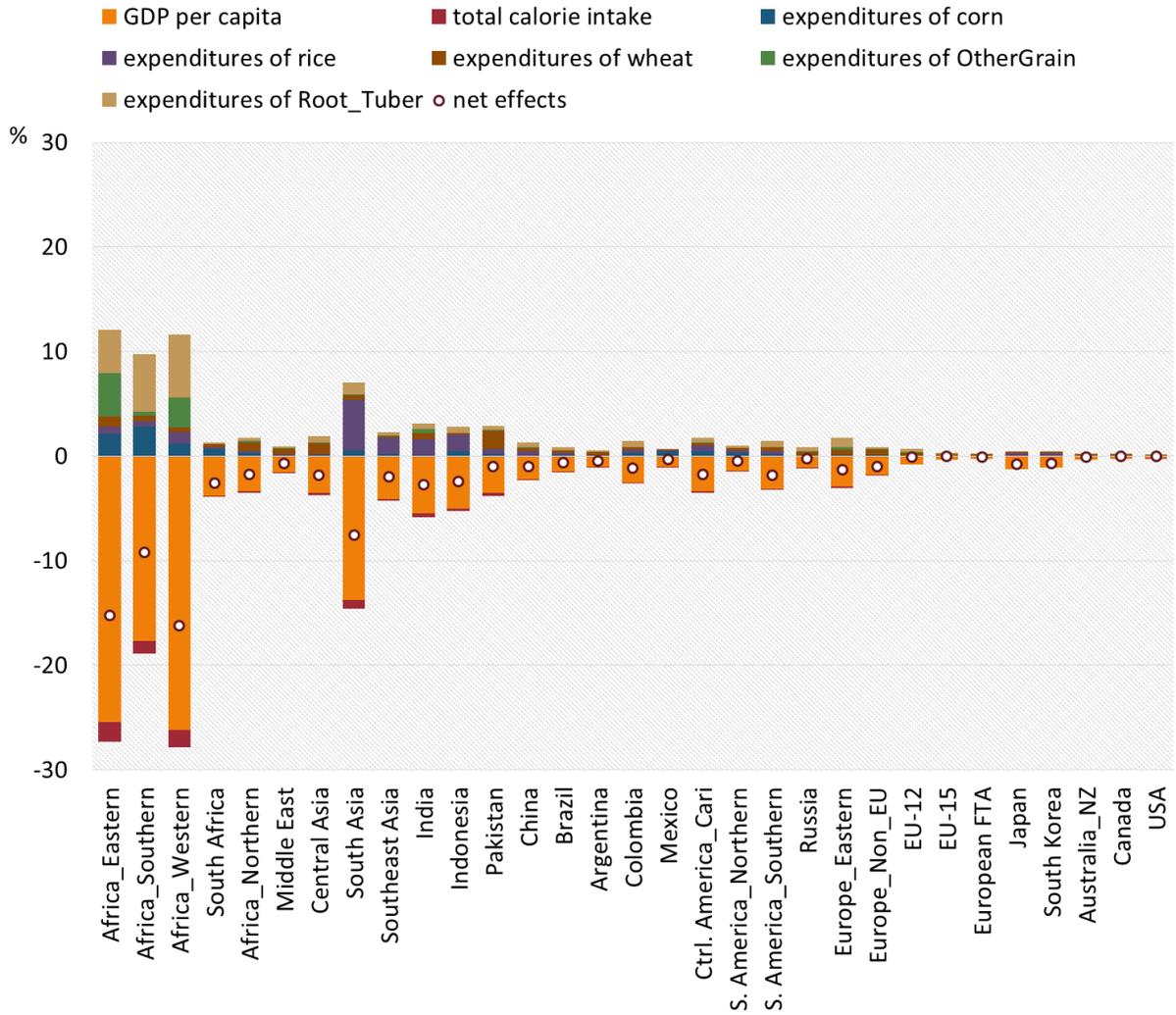
Figure A10 Decomposition of changes in FAA condition by region, reference SSP1
 From the 2010 segmented market model baseline to 2050 under SSP1 population and GDP trajectories with different assumptions of regional consumer price changes: (a) the segmented market model; (b) the integrated market model.

Change of consumption adjusted staple expenditure as % of average income from 2010 to 2050



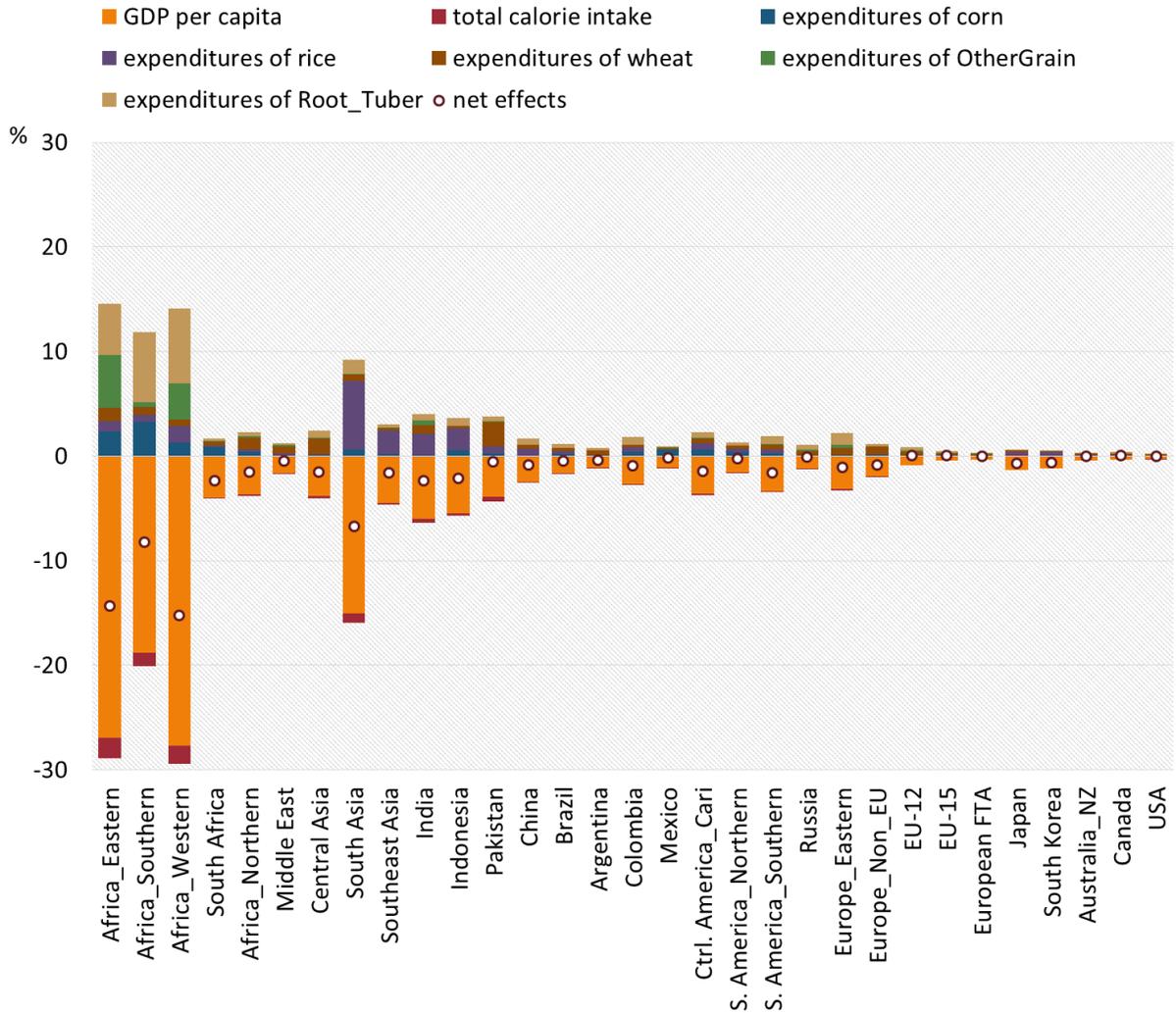
(a) 100%, segmented, SSP1

Change of consumption adjusted staple expenditure as % of average income from 2010 to 2050



(b) 200%, segmented, SSP1

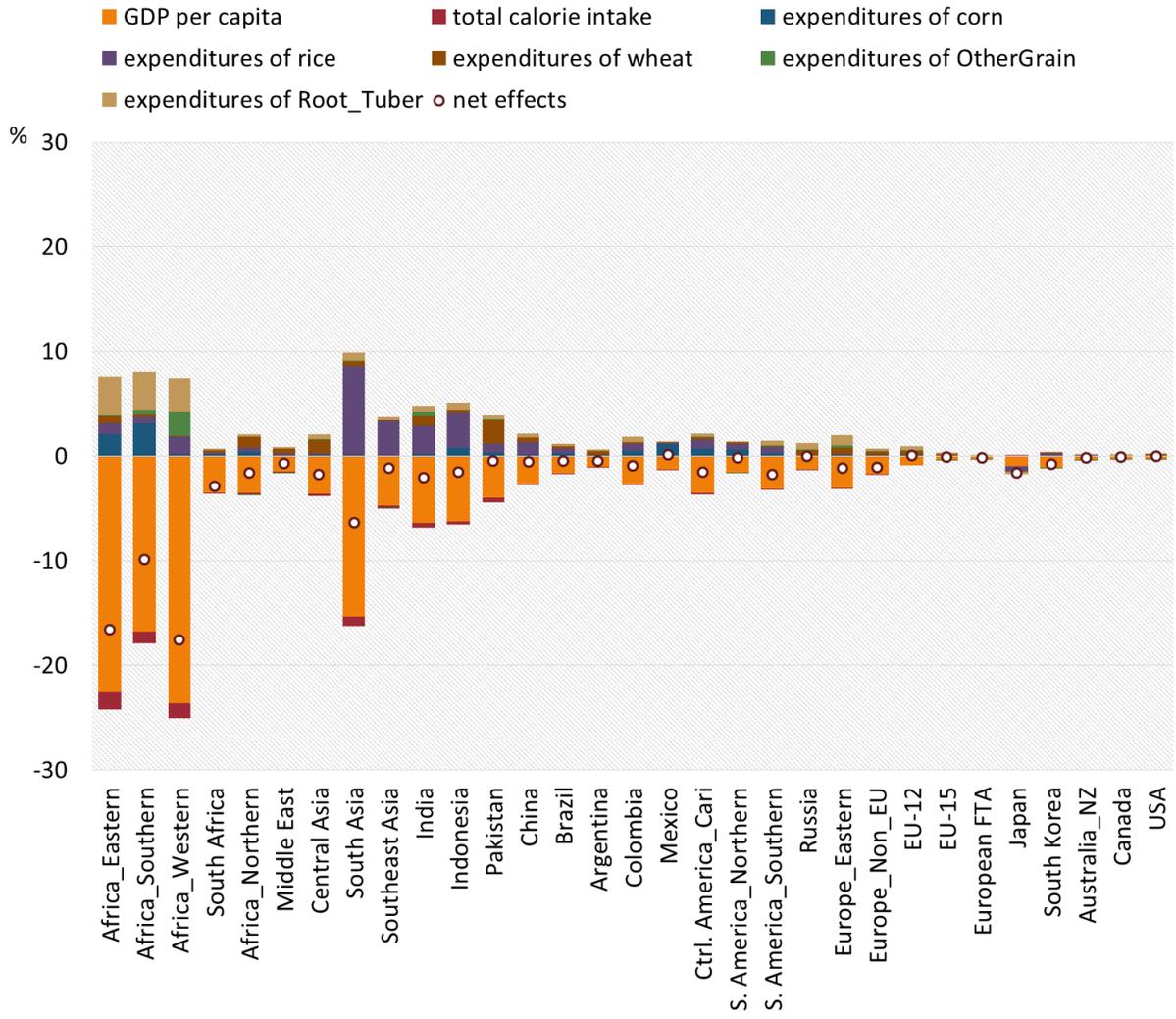
Change of consumption adjusted staple expenditure as % of average income from 2010 to 2050



(c) 300%, segmented, SSP1

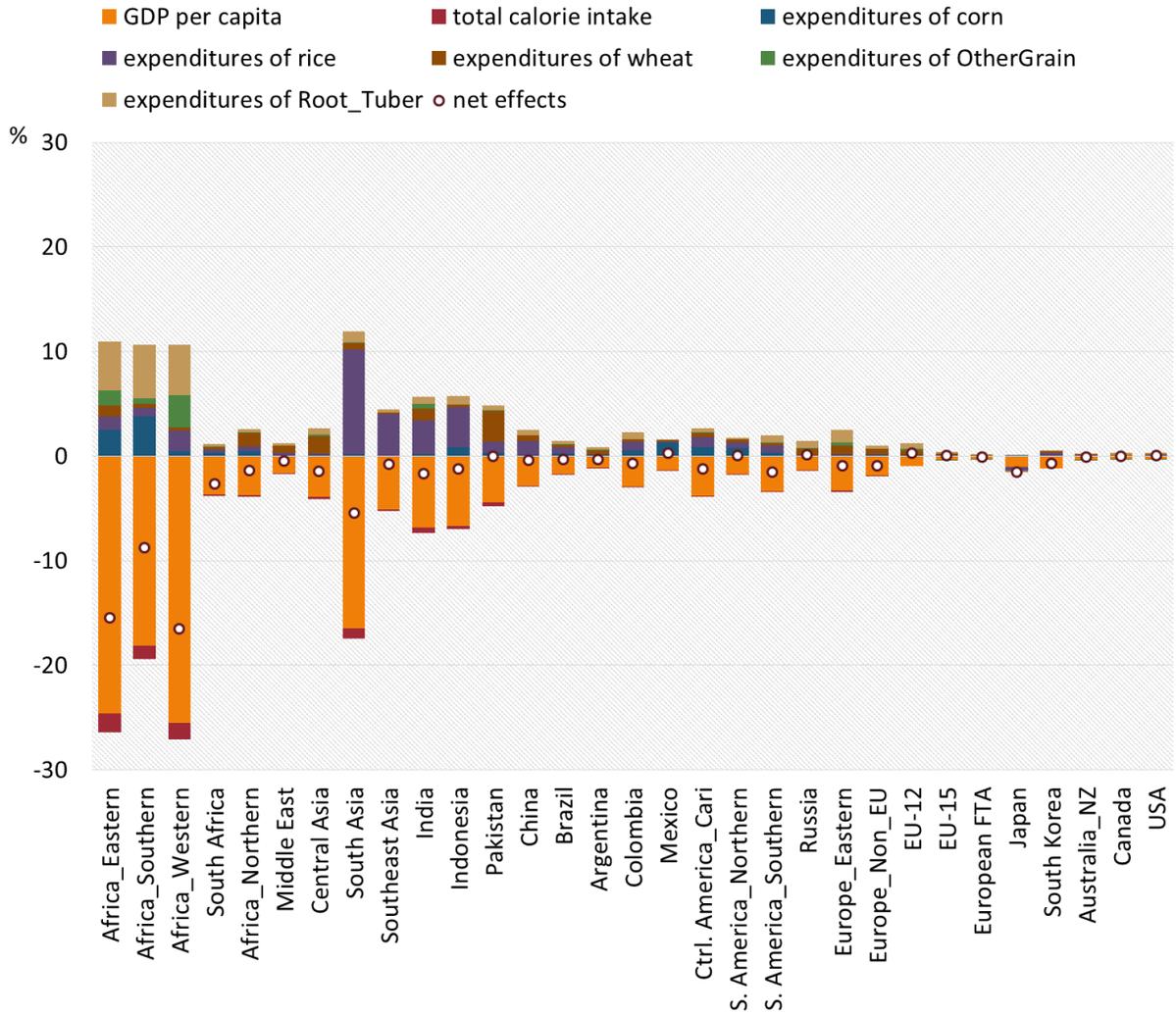
Figure A11 Decomposition of changes in FAA condition by region, global price shocks, SSP1 From the 2010 segmented market model baseline to 2050 SSP1 population and GDP trajectories and the segmented market assumptions of regional consumer price changes with different levels of global price increase: (a) 100%; (b) 200%; and (c) 300%.

Change of consumption adjusted staple expenditure as % of average income from 2010 to 2050



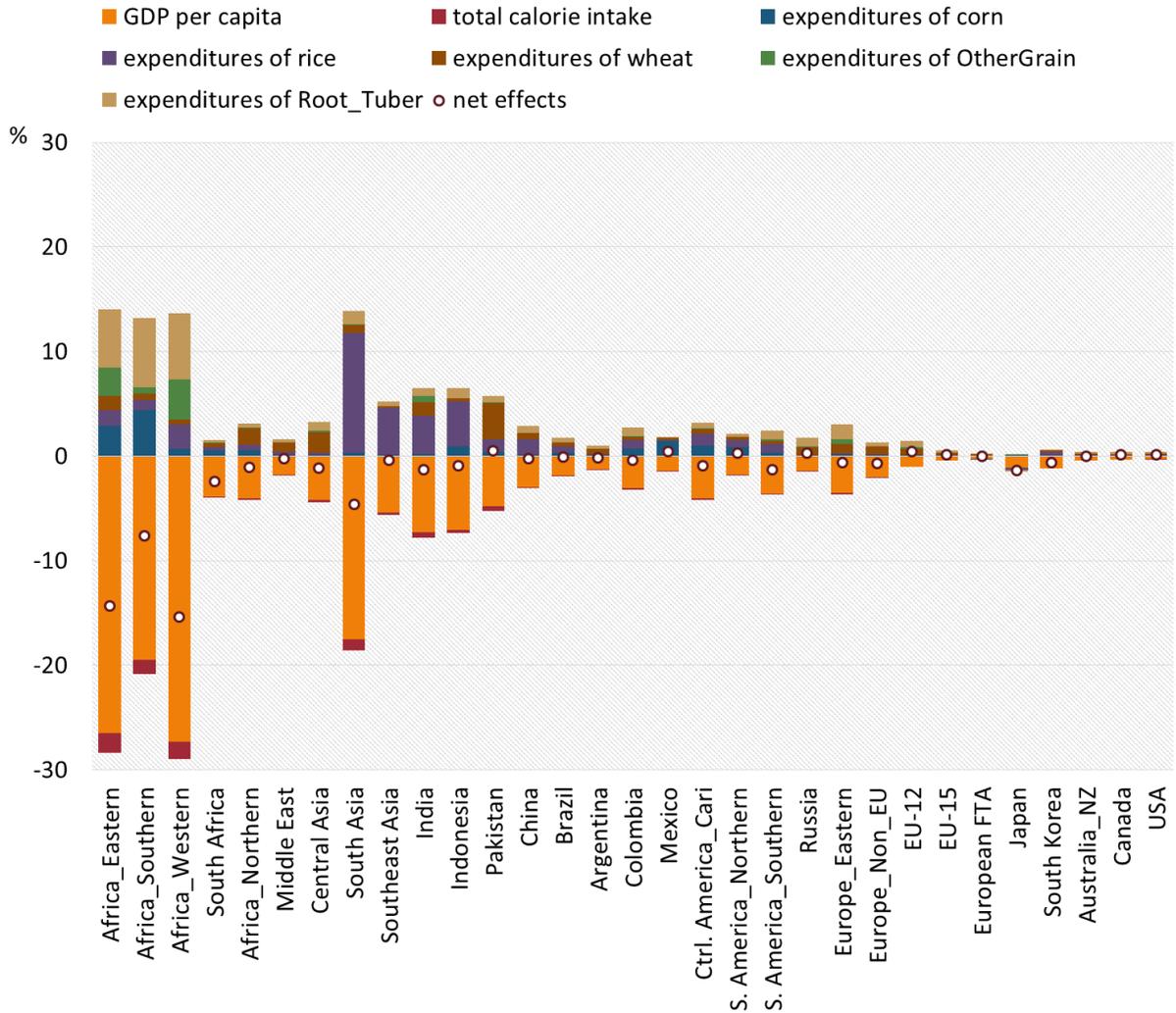
(a) 100%, integrated, SSP1

Change of consumption adjusted staple expenditure as % of average income from 2010 to 2050



(b) 200%, integrated, SSP1

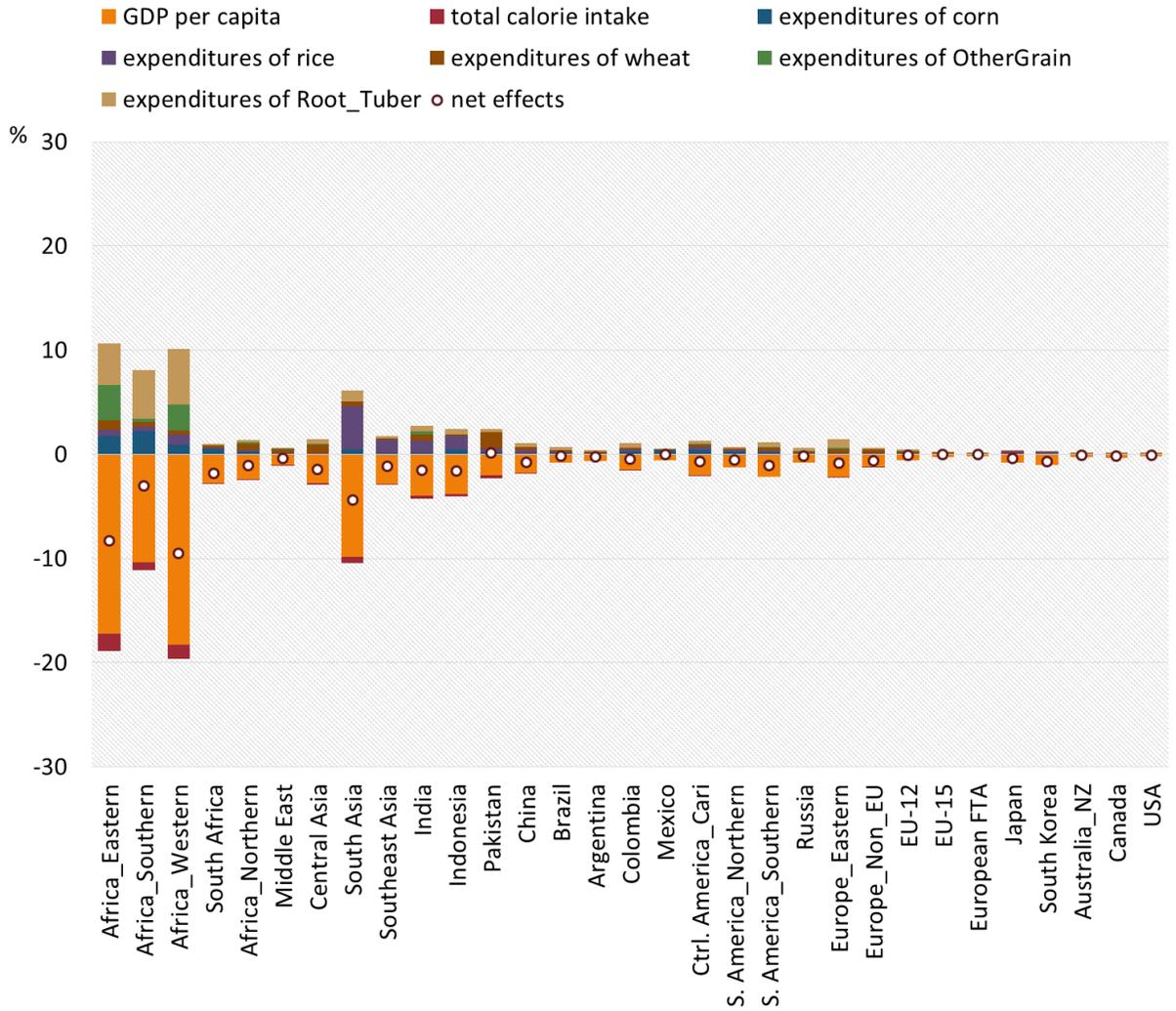
Change of consumption adjusted staple expenditure as % of average income from 2010 to 2050



(c) 300%, integrated, SSP1

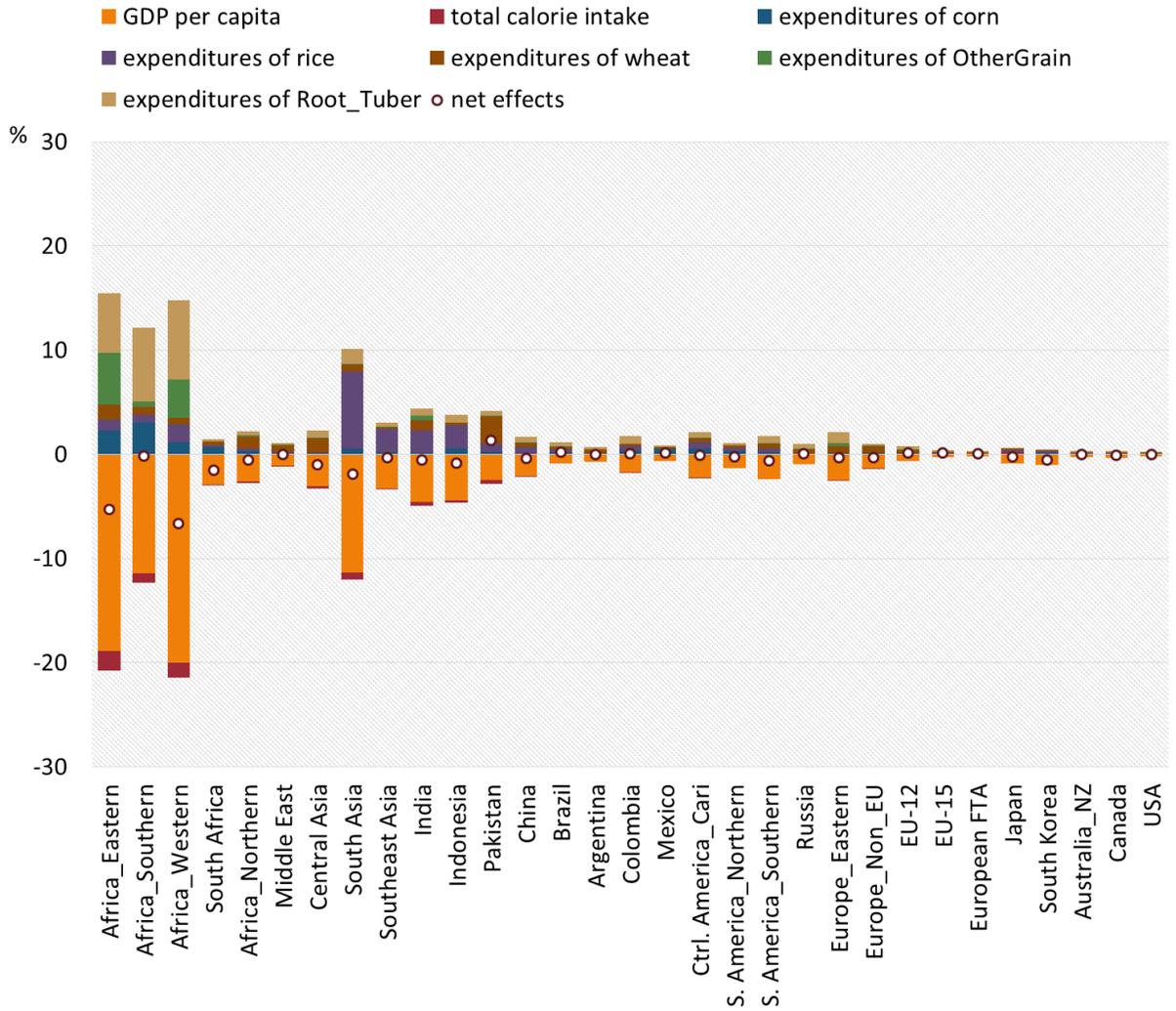
Figure A12 Decomposition of changes in FAA condition by region, global price shocks, SSP1
 From the 2010 segmented market model baseline to 2050 SSP1 population and GDP trajectories and the integrated market assumptions of regional consumer price changes with different levels of global price increase: (a) 100%; (b) 200%; and (c) 300%.

Change of consumption adjusted staple expenditure as % of average income from 2010 to 2050



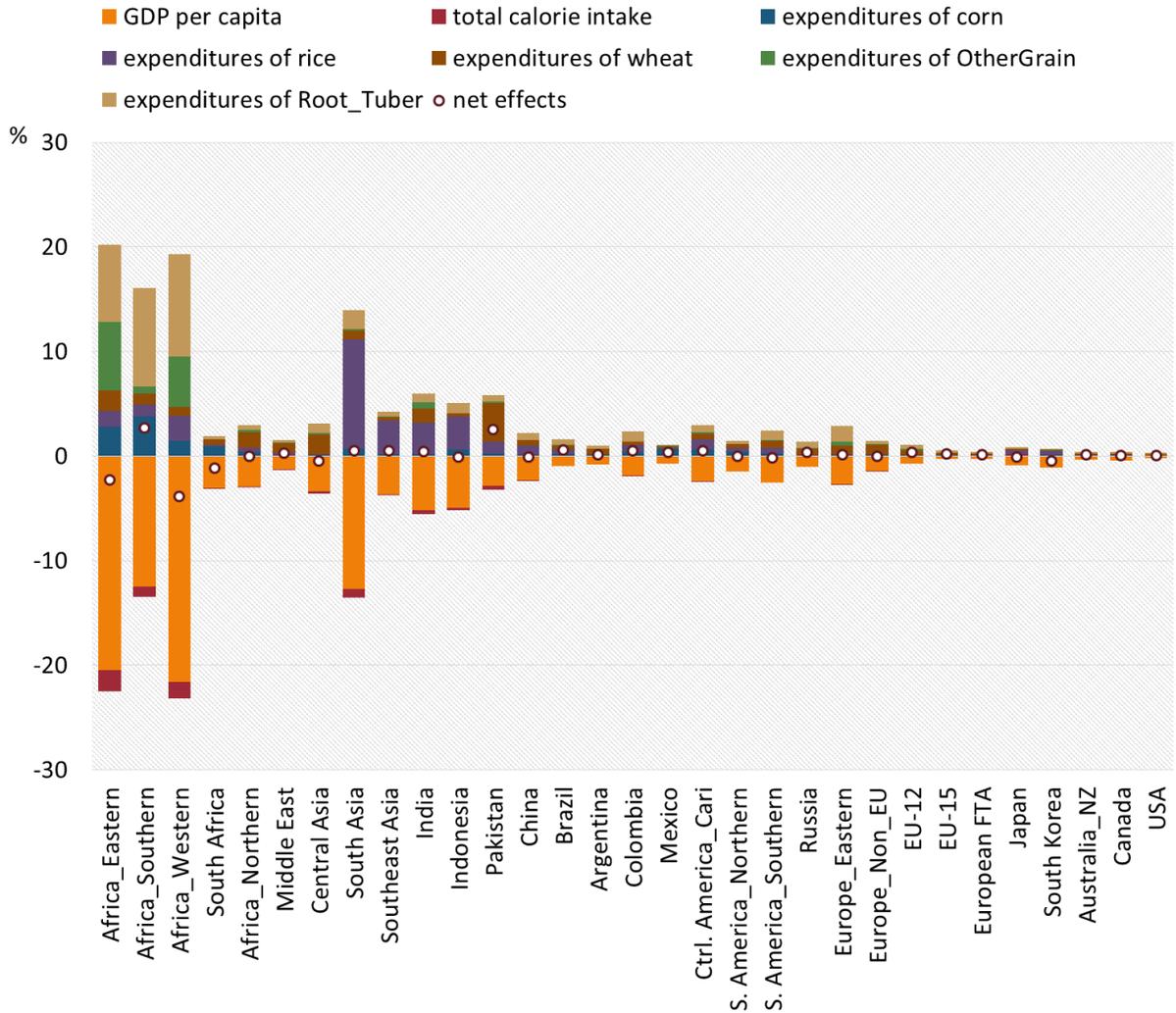
(a) 100%, segmented, SSP3

Change of consumption adjusted staple expenditure as % of average income from 2010 to 2050



(b) 200%, segmented, SSP3

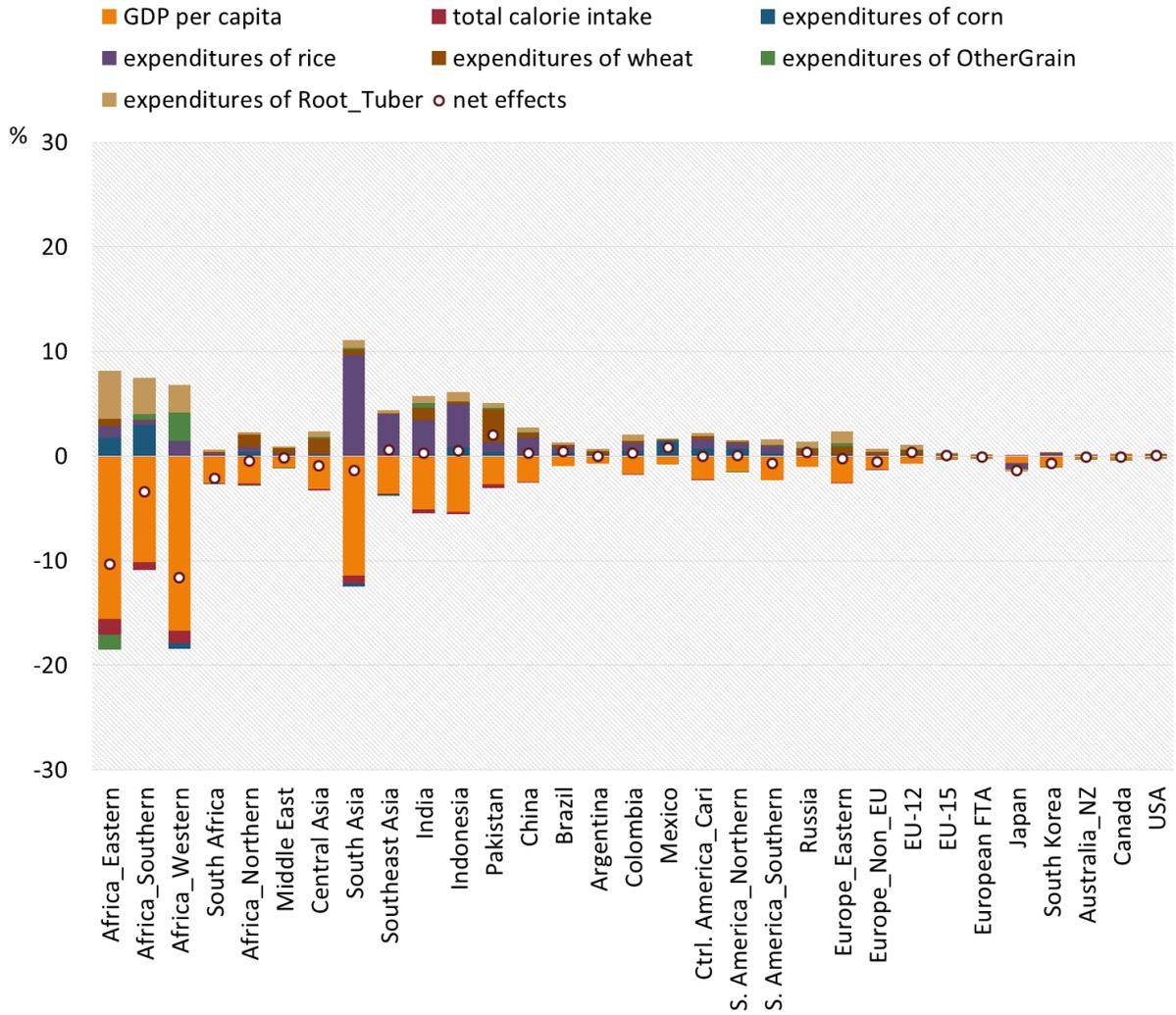
Change of consumption adjusted staple expenditure as % of average income from 2010 to 2050



(c) 300%, segmented, SSP3

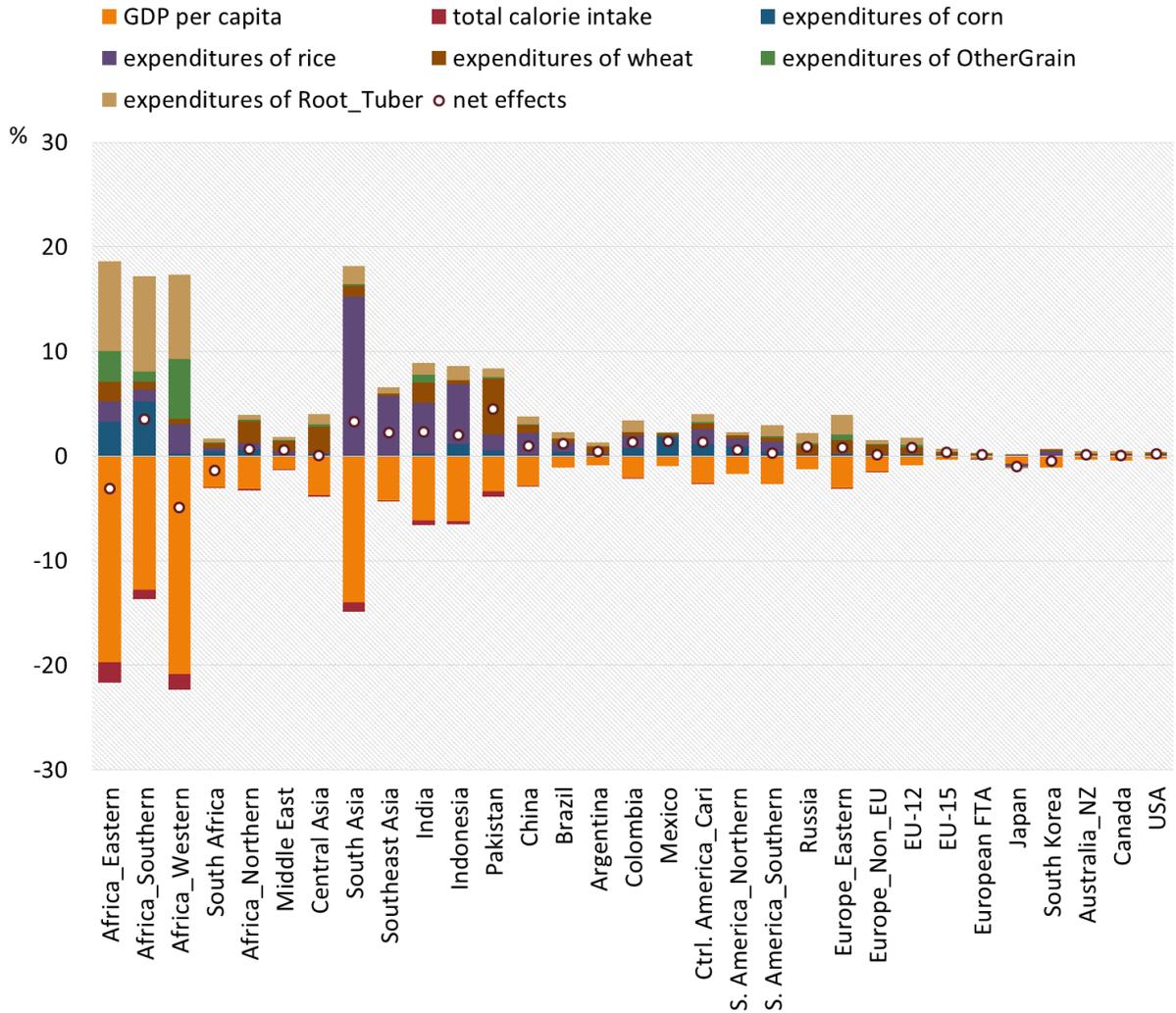
Figure A13 Decomposition of changes in FAA condition by region, global price shocks, SSP3 From the 2010 segmented market model baseline to 2050 SSP3 population and GDP trajectories and the segmented market assumptions of regional consumer price changes with different levels of global price increase: (a) 100%; (b) 200%; and (c) 300%.

Change of consumption adjusted staple expenditure as % of average income from 2010 to 2050



(a) 100%, integrated, SSP3

Change of consumption adjusted staple expenditure as % of average income from 2010 to 2050



(b) 300%, integrated, SSP3

Figure A14 Decomposition of changes in FAA condition by region, global price shocks, SSP1
 From the 2010 segmented market model baseline to 2050 SSP1 population and GDP trajectories and the integrated market assumptions of regional consumer price changes with different levels of global price increase: (a) 100%; and (b) 300%.

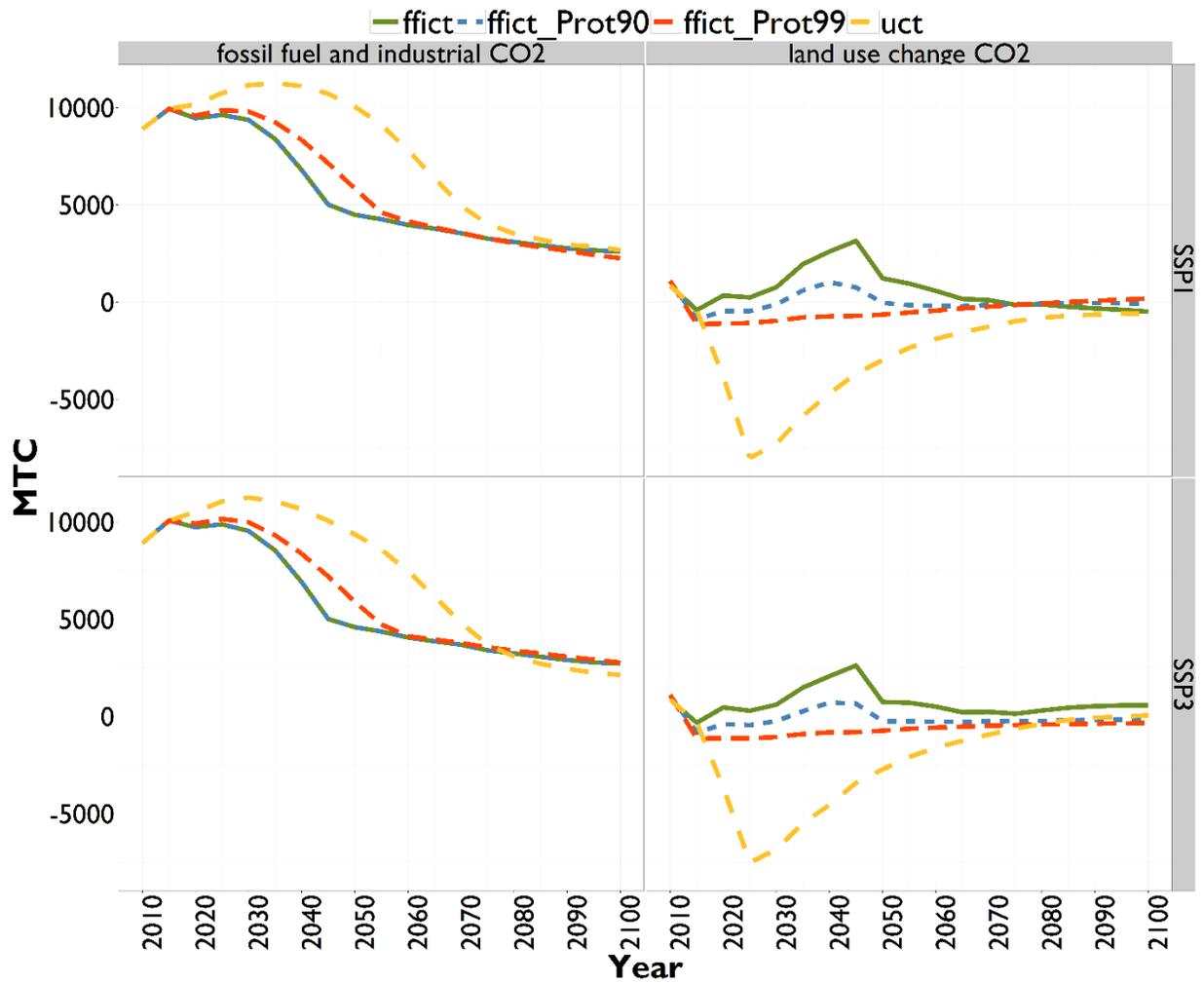


Figure A15 Energy system and land use change CO2 emissions under the end-of-century 450 ppm CO2 concentration target, 2010 – 2100, by SSP and climate policy

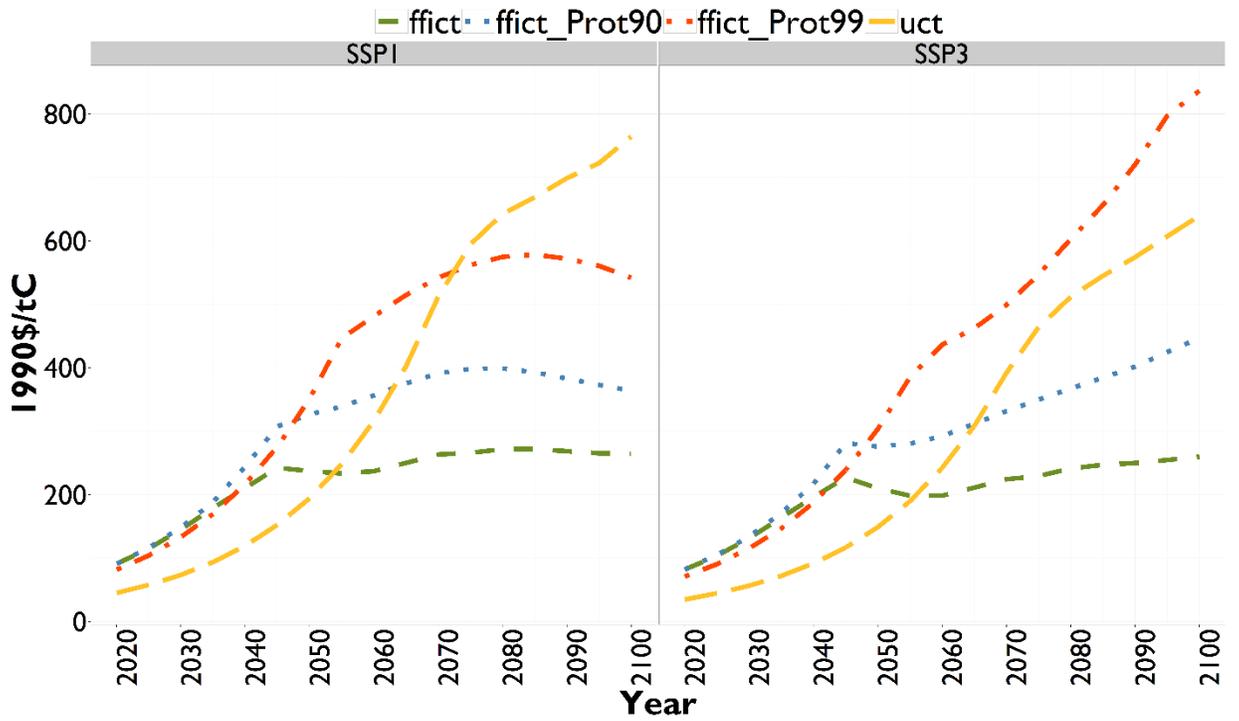


Figure A16 Carbon price under the end-of-century 450 ppm CO2 concentration target, 2010 – 2100, by climate policy and SSP

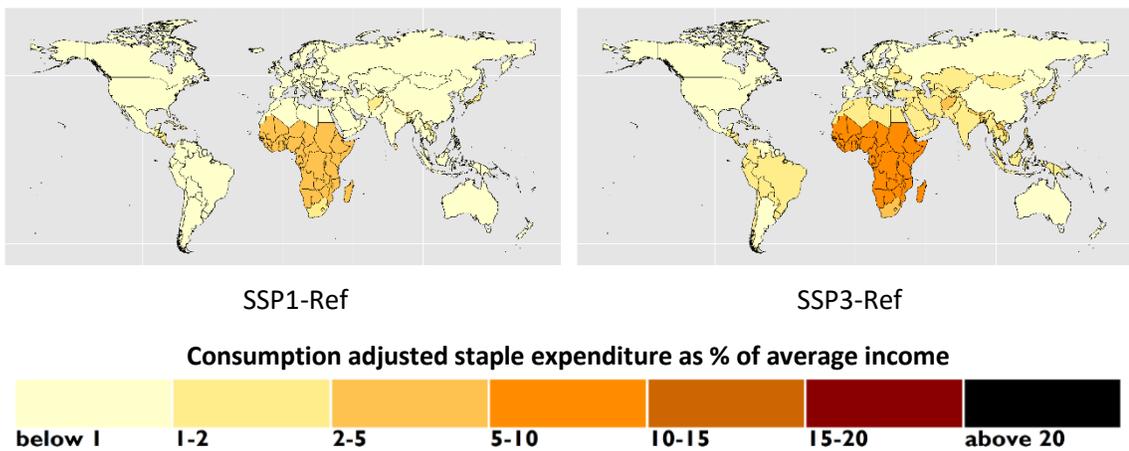


Figure A17 Regional FAA in 2050, reference, no climate impacts, by SSP

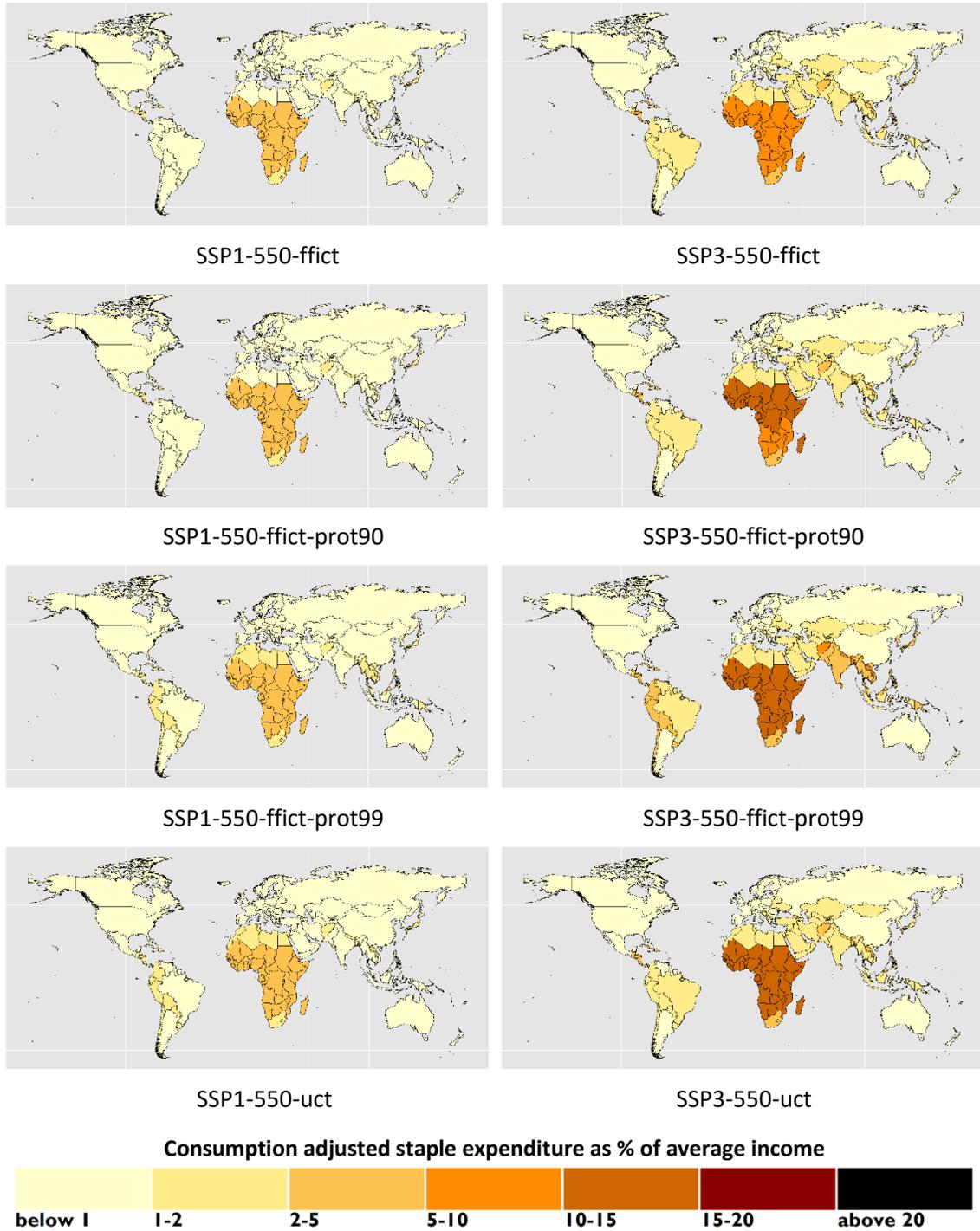


Figure A18 Regional FAA in 2050 under the end-of-century 550 ppm CO₂ concentration target, by climate policy and SSP

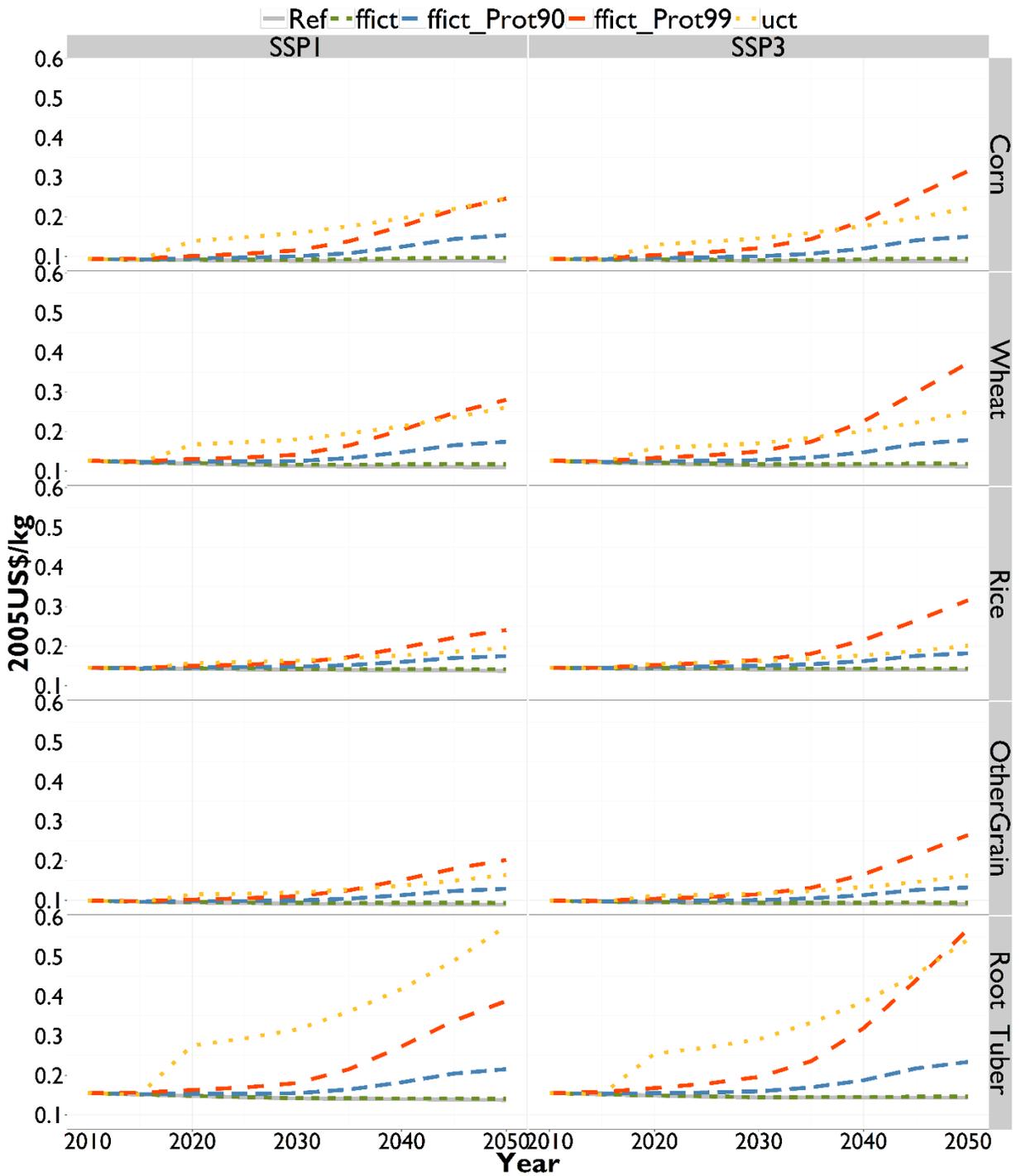


Figure A19 Global market price of staple commodities, 2010 – 2050, by climate policy and SSP

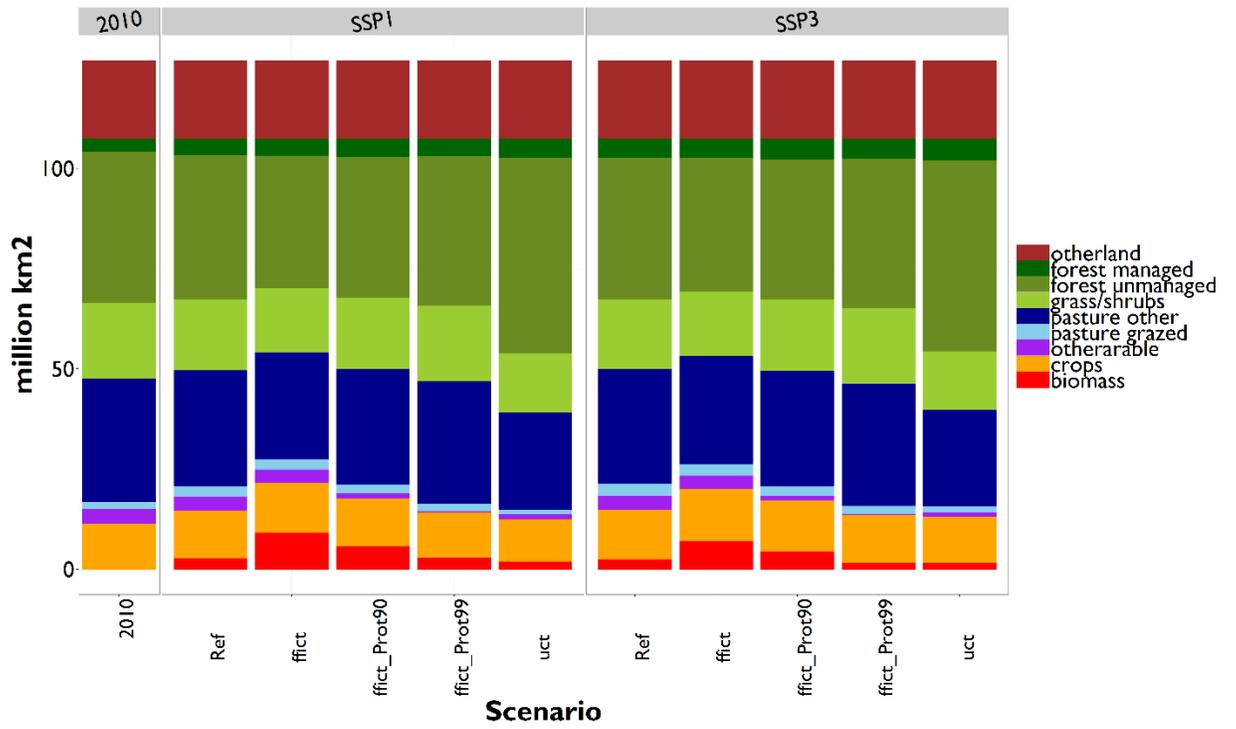
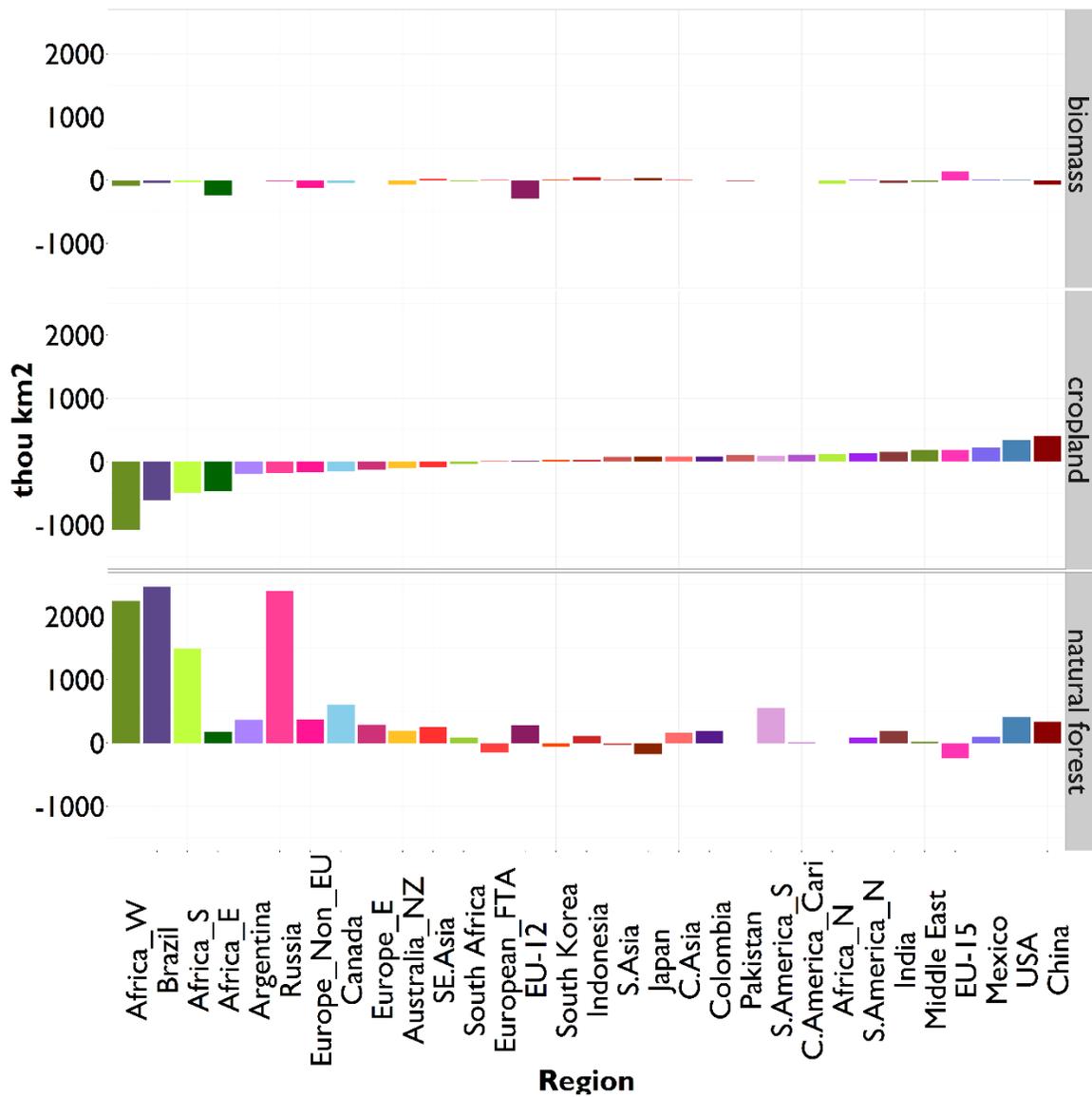
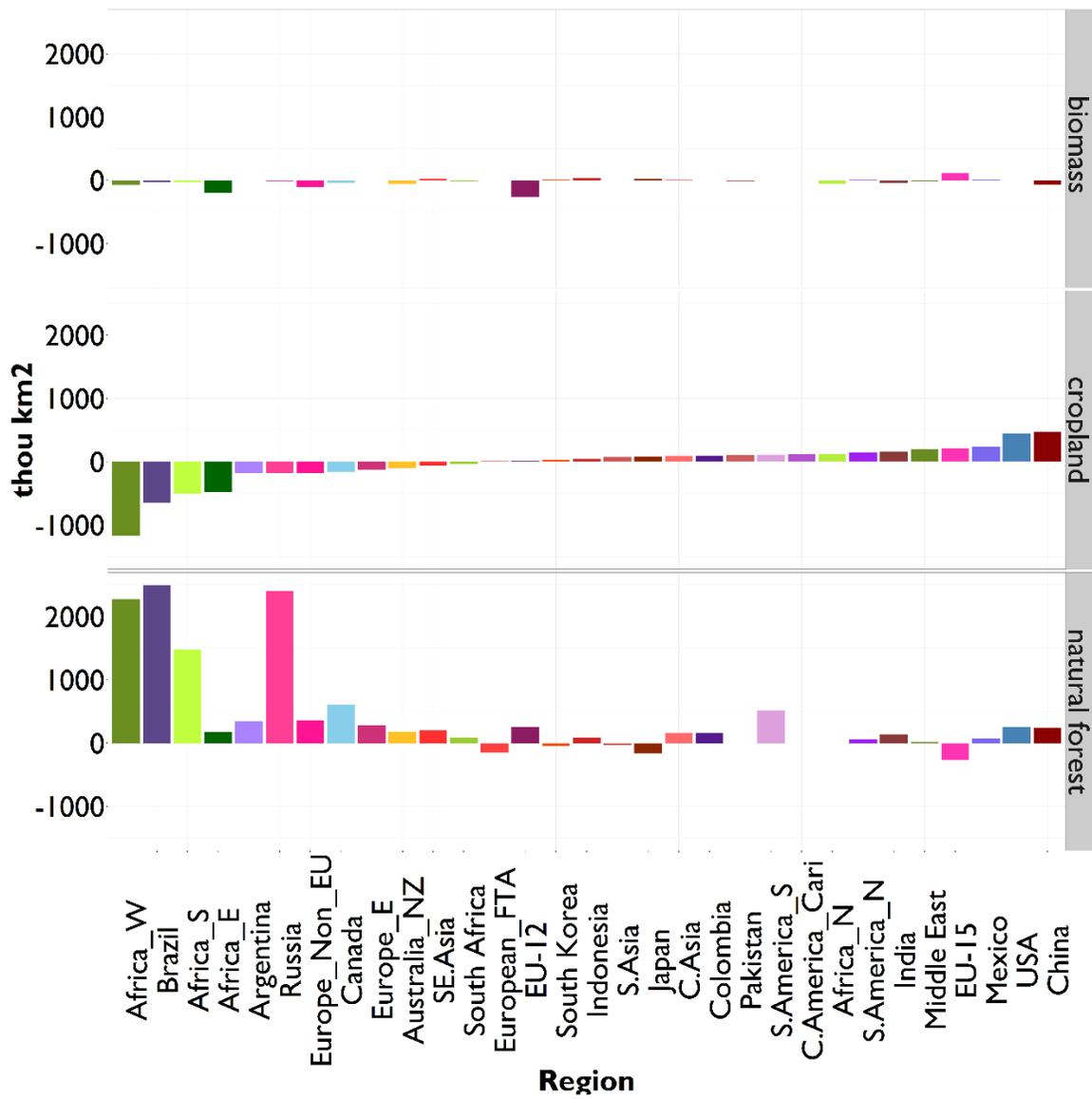


Figure A20 Global land use in 2010 and 2050 under the end-of-century 450 ppm CO₂ concentration target, by climate policy and SSP

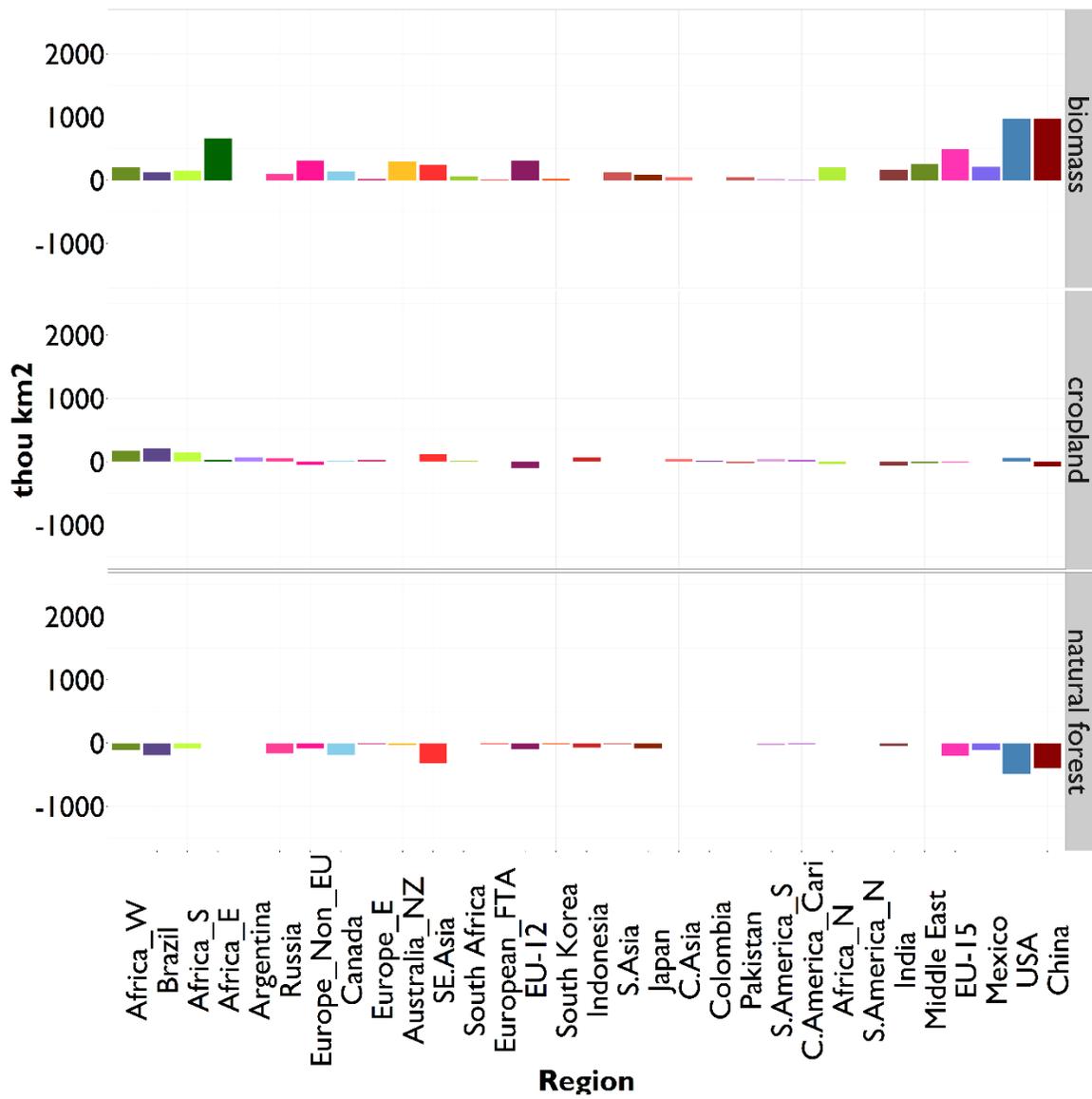


(a) SSP1

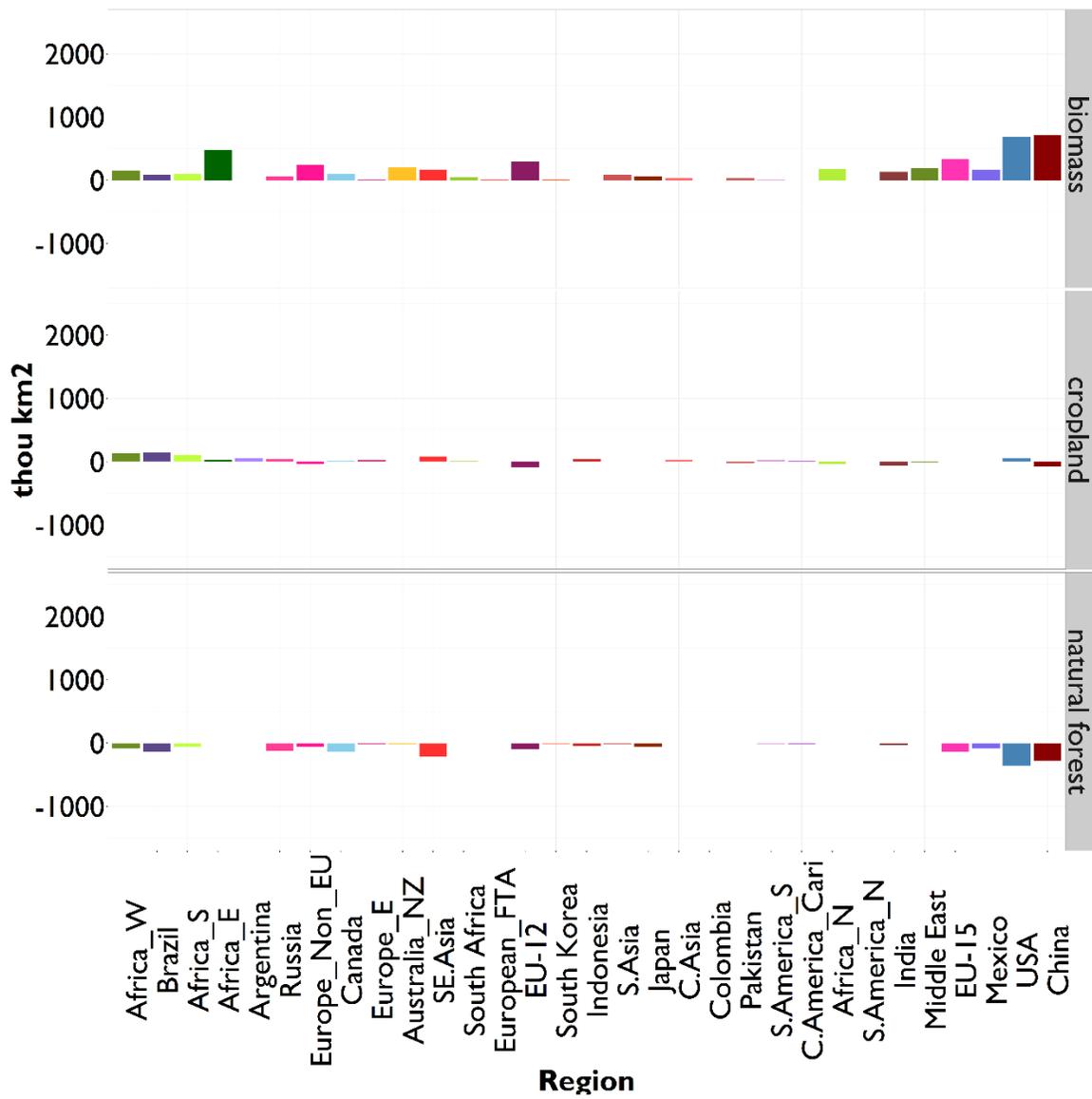


(b) SSP3

Figure A21 Land use change in 2050 from reference to UCT, by region, under: (a) SSP1; and (b) SSP3

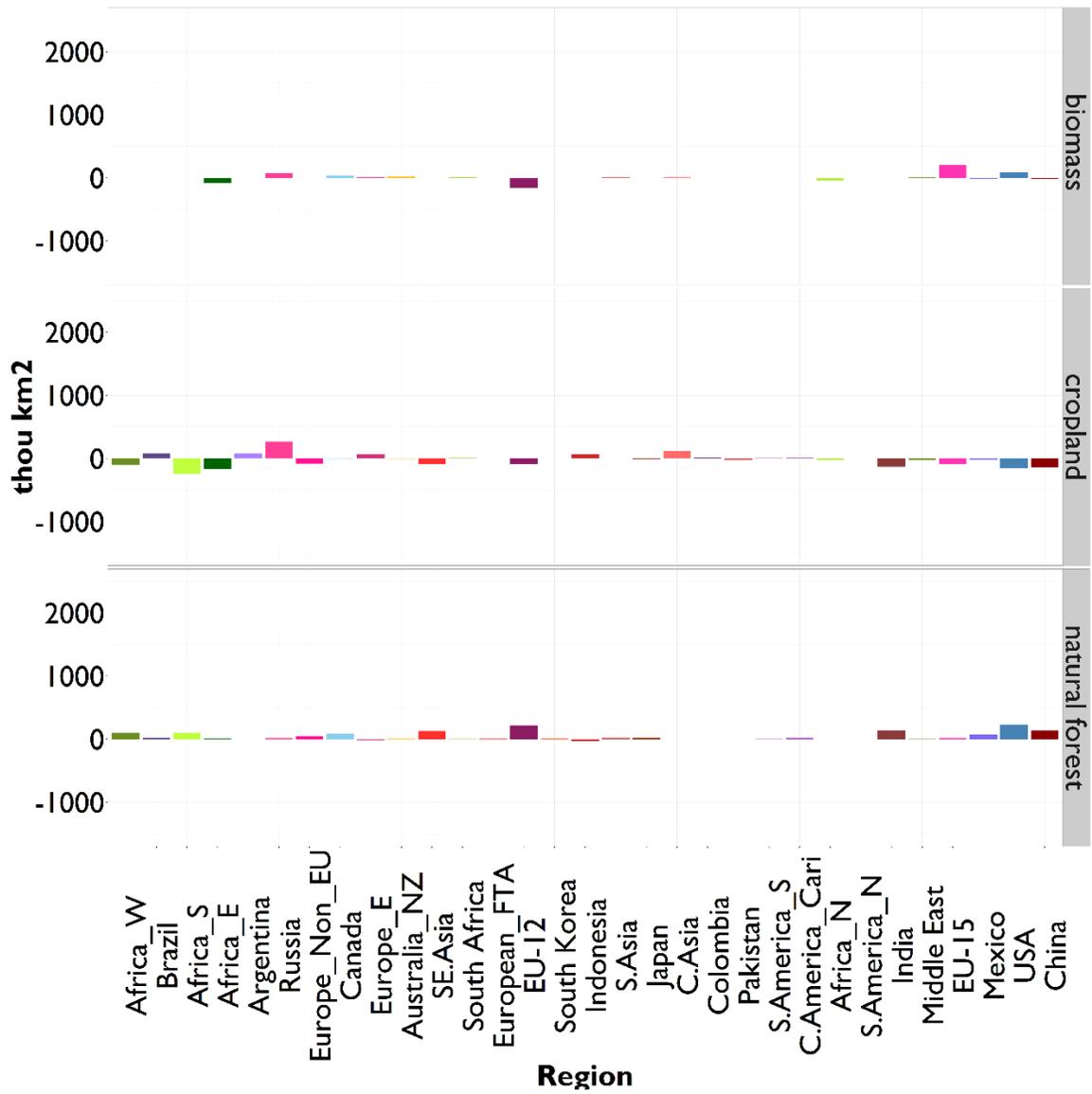


(a) SSP1

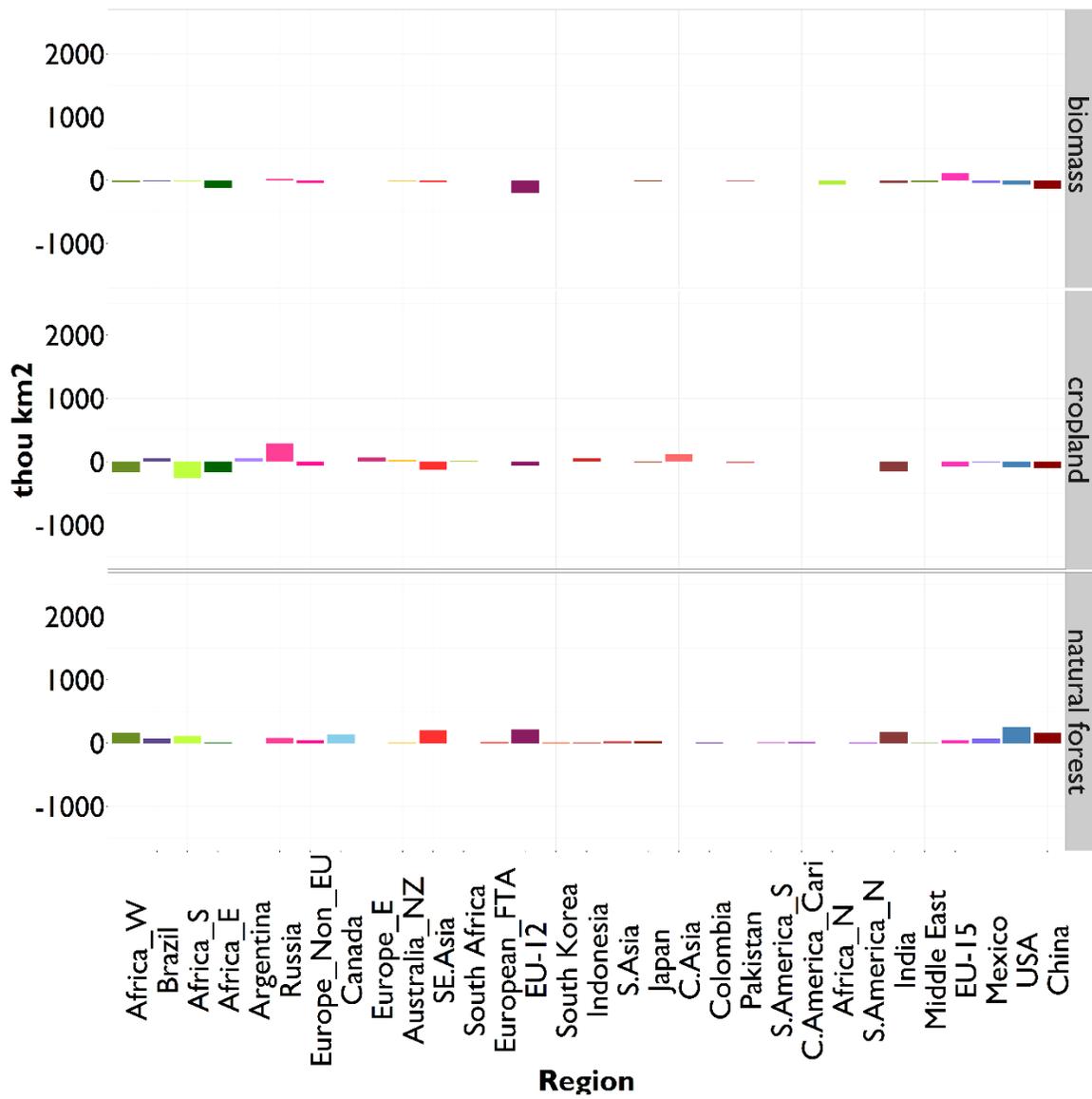


(b) SSP3

Figure A22 Land use change in 2050 from reference to FFICT, by region, under: (a) SSP1; and (b) SSP3



(a) SSP1



(b) SSP3

Figure A23 Land use change in 2050 from reference to FFICT_Prot99, by region, under: (a) SSP1; and (b) SSP3

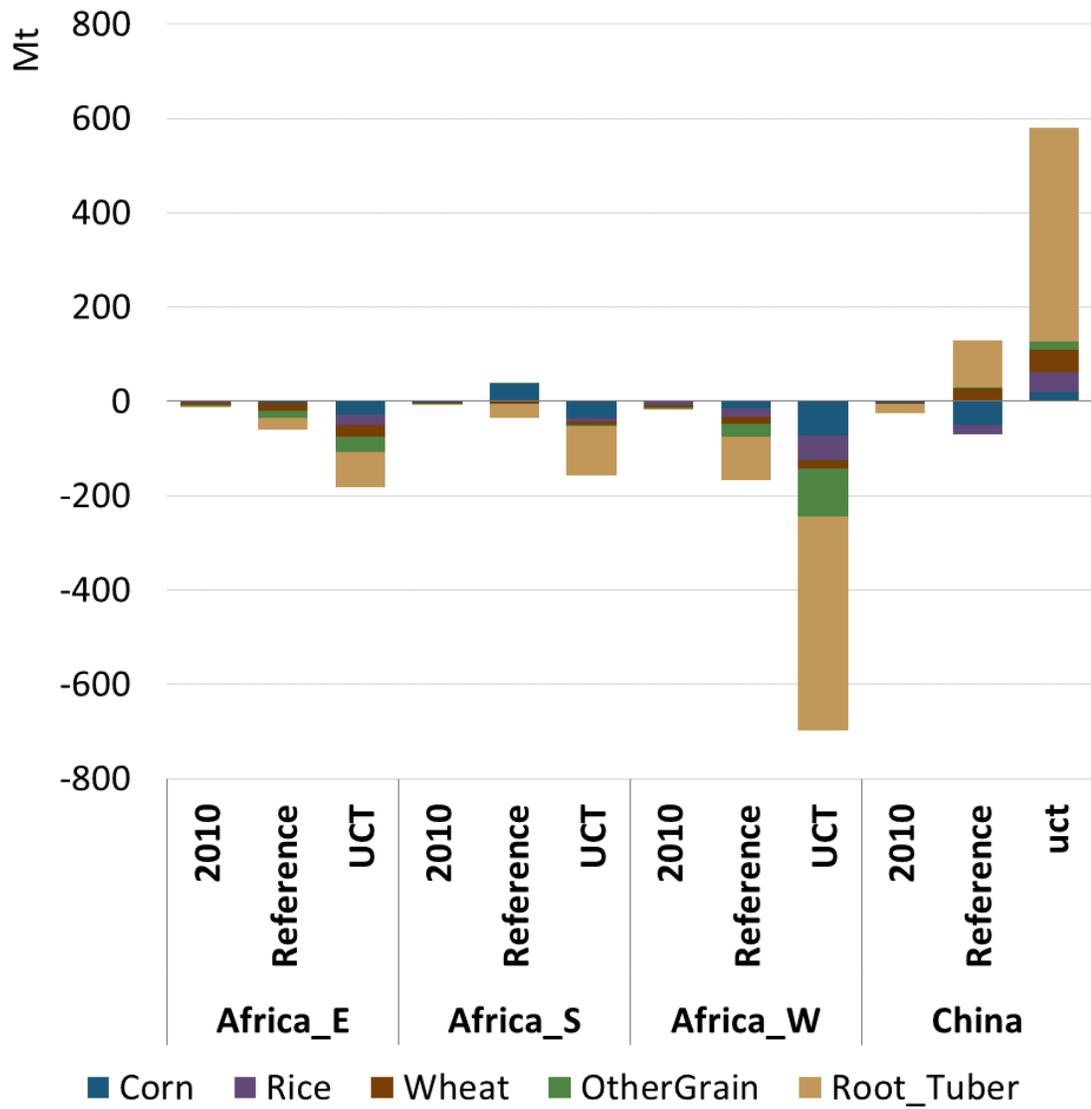


Figure A24 Net export of crops in selected regions in 2010 and 2050 (SSP3) under reference and UCT

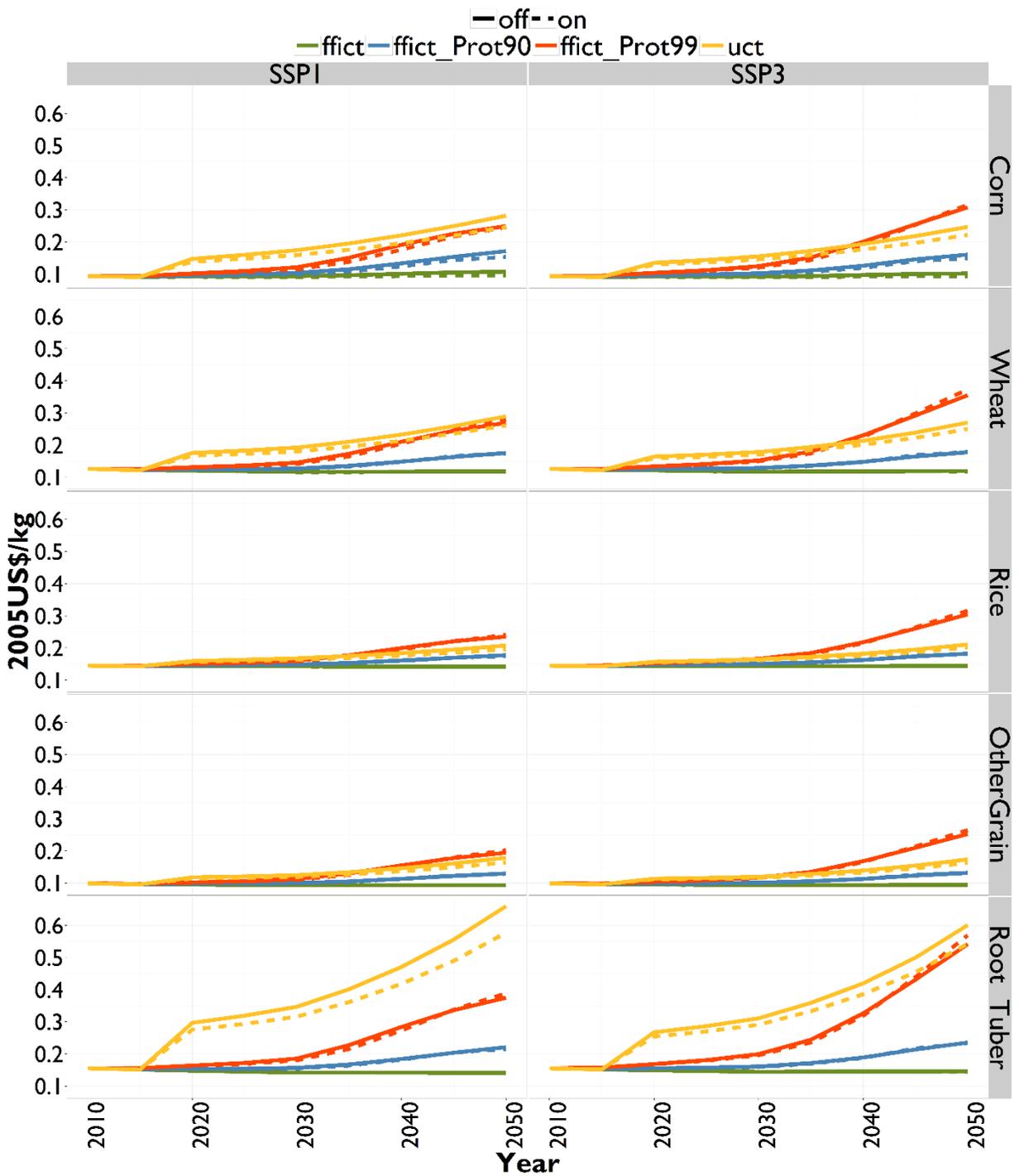


Figure A25 Global market price of staple commodities, 2010 – 2050, by climate policy and SSP, w/ and w/o BioCCS

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