# Climate Policy and the Energy-Water-Food Nexus:
## A Model Linkage Approach

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## 1. Introduction

There is a growing recognition that the ambitious UN Sustainable Development Goals (SDGs) to end hunger, achieve food security and promote sustainable agriculture (SDG 2), to ensure universal access to water and sanitation (SDG 6), to ensure universal access to affordable, reliable, sustainable and modern energy (SDG7) and to combat climate change and its impacts (SDG 13) are linked in complex ways. The emerging literature on the energy-water-food nexus[1] highlights the need to take account of the trade-offs and synergies among the goals arising from these linkages, but also underscores the need for further research to understand the quantitative relevance of the various channels through which measures towards the attainment of the goals affect each other.

The presence of multiple conceivable pathways to the achievement of the SDGs by 2030 as well as the numerous uncertainties surrounding medium- to long-run projections for the global food system[2] call for a scenario approach to development policy planning, and the development of plausible scenarios needs to be informed by quantitative modelling that captures the key linkages between energy, water, food and climate policy in a stylized form.

Dynamic standard global computable general equilibrium (CGE) models are able to capture the input-output linkages between agricultural, food processing and energy sectors and the impacts of population and economic growth on structural change, energy and food demand as well as the impacts of policy interventions, but due to their coarse regional aggregation structure they are not suitable to take account of physical water scarcity constraints in a persuasive manner. In contrast, existing partial equilibrium (PE) multi-market models of global agriculture can incorporate hydrological constraints at detailed regional scales and support a more disaggregated representation of agricultural commodities than CGE models, but fail to take systematic account of linkages between agriculture, energy and the rest of the economy.

To capture the advantages of both modelling approaches, the present study links a global dynamic multisector CGE model with a global dynamic PE multi-market model of agricultural supply, demand and trade. The linked modelling framework facilitates a quantitative analysis of the wider implications of agricultural sector scenario projections by taking systematic account of linkages between agriculture and the rest of the economy and allows a rigorous theory-grounded general equilibrium welfare analysis of shocks to agriculture. Conversely, the linked approach also supports a detailed analysis of the effects of shocks that initially hit non-agricultural sectors on agricultural variables and water security. In this paper, the approach is used to assess the impact of stylised climate change mitigation scenarios on energy prices, economic growth, food security and water availability.

[1] E.g. Hoff (2011), Ringler et al (2013), Chang et al (2016)
[2] Reilly and Willenbockel (2010), von Lampe et al (2014).

## 2. Modeling Approach

### 2.1. Rationale

Contemporary models in use for long-run projections of global agriculture and the food system can be classified into two broad categories – economy-wide computable general equilibrium (CGE) models and partial equilibrium (PE) multi-market models that focus only on agricultural sectors. CGE models consider all production sectors in an economy simultaneously and take full account of macroeconomic constraints and intersectoral linkages. With respect to the representation of the food system, their strength is that they include the entire value chain from agricultural production to food processing and distribution and finally to food consumption by households. In contrast, PE models focus on just one aspect of the value chain – unprocessed or first-stage processed agricultural products – and ignore macroeconomic constraints and linkages between agricultural production and aggregate income. This limits the domain of applicability of these partial-analytic models to scenarios in which the feedback effects of shocks to agriculture on aggregate income are small. On the other hand, PE models support a more detailed commodity disaggregation than CGE models and a finer spatial resolution on the supply side (Willenbockel and Robinson, 2014; Robinson, van Meijl, Willenbockel et al, 2014).

The basic rationale for linking IFPRI's global agricultural PE model IMPACT with a dynamic version of the multi-region CGE model GLOBE is to capture the advantages of both modelling approaches. The linked modelling framework facilitates a quantitative analysis of the wider implications of agricultural sector scenario projections generated by IMPACT by taking systematic account of linkages between agriculture and the rest of the economy and allows a rigorous theory-grounded general equilibrium welfare analysis of shocks to agriculture. Conversely, the linked approach supports a detailed analysis of the effects of shocks that initially hit non-agricultural sectors on agricultural variables and water security.

While several major recent scenario studies concerned with the future of global agriculture and food security employ soft-linked model ensembles, the linkages in these ensembles are primarily between bio-physical models and economic models. Prominent examples include the scenario analyses developed for the UN Millennium Ecosystem Assessment (Carpenter et al., 2005), for the International Assessment of Agricultural Science and Technology for Development (Rosegrant et al., 2009) and for the UNEP Global Environmental Outlook 4 (Rothman et al., 2007).[3] All three studies employ the global integrated assessment model IMAGE (Integrated Model to Assess the Global Environment) developed at the Dutch National Institute for Public Health and the Environment alongside IFPRI's IMPACT model and various other satellite models. IMAGE is designed to capture interactions between economic activity, land use, greenhouse gas (GHG) emissions, climate, crop yields and other environmental variables. It includes a carbon-cycle module to calculate GHG emissions resulting from economic activity including energy and land use, a land-use module and an atmosphere–ocean climate module that translates GHG emissions into climate outcomes. The model-determined

[3] See Reilly and Willenbockel (2010) and Willenbockel (2015b) for concise reviews of these and related scenario exercises from a food security perspective.

temperature and precipitation outcomes in turn feed back into the performance of the economic system via agricultural productivity impacts.

In these scenario exercises, predictions of crop yield changes due to climate change generated by IMAGE are passed on to IMPACT, and IMPACT's agricultural production projections serve as inputs to the IMAGE land cover model. However, although IMAGE includes an optional stylized multi-region computable general equilibrium model of global production and trade, there is no link between IMPACT and this CGE model, and hence no mechanism within the soft-linked system that would establish some form of consistency between the agricultural sector projections of the CGE model and the IMPACT projections or capture the repercussions of shocks to the agricultural sector on the rest of the economy.

In contrast, the model linkage approach pursued in the present project focuses specifically on the economic interdependencies between agriculture and the rest of the economy neglected in previous scenario studies that are based on soft-linked model ensembles.

The starting point for applications of the linked GLOBE-IMPACT modelling approach is a dynamic baseline scenario simulation generated by the IMPACT model. The IMPACT baseline paths for exogenous driver variables including GDP growth, population growth and agricultural land supply as well as the price projections for selected agricultural commodities generated by IMPACT are aggregated to match with the (application-specific user-defined) regional and sectoral aggregation structure of the GLOBE-Energy model. These time paths are passed to GLOBE and serve as inputs into the dynamic baseline calibration process for the CGE model.

In the course of this baseline calibration process, the activity-specific total factor productivity paths for the targeted agricultural sectors in GLOBE are adjusted residually so that the GLOBE baseline run exactly replicates the aggregated IMPACT baseline producer price paths for these sectors. Similarly, the time paths for the GLOBE model parameters governing economy-wide labor-augmenting technical progress by region are calibrated endogenously, so that the GLOBE baseline run replicates the real GDP growth rates of the IMPACT baseline scenario. To ensure that the baseline projections for agricultural quantity variables generated by GLOBE are broadly in line with the corresponding aggregated IMPACT projections as well, the parameters of the household consumer demand system are calibrated to be consistent with the aggregated household income elasticities of demand for the matched food commodity groups assumed in IMPACT.

To assess the economy-wide ripple-on effects triggered by agricultural supply shocks and to evaluate the resulting welfare effects, the dynamic GLOBE calibration process is repeated using the corresponding IMPACT simulation results for the shock scenario under consideration. This step effectively translates shocks to the IMPACT supply side into corresponding GLOBE agricultural productivity shocks that generate equivalent impacts on agricultural producer prices. The comparison of the two general equilibrium solutions generated by GLOBE then provides indications of the direction and order of magnitude of the knock-on effects for non-agricultural and macroeconomic variables, such as changes in factor prices and household incomes as well changes in relative commodity prices throughout the global economy. These simulated changes in turn allow an internally consistent assessment of the associated general equilibrium welfare impacts.

However, the linkage of IMPACT with the extended GLOBE-ENERGY model is primarily geared towards analysing the transmission of shocks that initially affect non-agricultural sectors *to* agriculture and food security outcomes. In this mode of analysis, the baseline synchronization of GLOBE agricultural prices with the corresponding IMPACT projections along the lines described above is followed by a simulation of the shock scenarios in GLOBE. The aggregate real income effects generated by GLOBE are then downscaled to the IMPACT regional aggregation level and passed back to IMPACT to analyse the detailed implications for agricultural variables, water and food security.

### 2.2. Methodology

The modeling methodology links the global computable general equilibrium (CGE) model GLOBE-Energy - an extended recursive-dynamic version of the comparative-static GLOBE model originally developed by McDonald, Thierfelder and Robinson (2007) - with IFPRI's International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) version 3 (Robinson et al, 2015). IMPACT3 is a modular integrated assessment model, linking information from climate models, crop simulation models and water models to a global partial equilibrium multi-market model of the agriculture sector. IMPACT3 has been designed to support longer-term scenario analysis through the integration of these multidisciplinary modules to provide researchers and policymakers with a flexible tool to assess and compare the potential effects of changes in biophysical systems, socioeconomic trends, agricultural technologies, and policies. The core multimarket model simulates food supply and demand for 159 countries. Agricultural production is further disaggregated to include 320 food production units (FPUs), which are intersections of river basins and national boundaries, that is, an intersection of 154 river basins with 159 economic regions. The multimarket model simulates 62 agricultural commodity markets, covering all key food as well as key non-food crops, such as cotton. The water models in IMPACT3 include a global hydrology model (IGHM) that simulates snow accumulation and melt and rainfall-runoff processes at 0.5-degree latitude by 0.5-degree longitude resolution, a water basin supply and demand model (IWSM) that operates at the FPU level, and the IMPACT crop water allocation and stress model that estimates the impact of water shortages on crop yields, also at the FPU level. These three modules allow for an assessment of climate variability and change on water availability for the agriculture and other sectors, as well as for an assessment of changes in water demand, investment in water storage and irrigation infrastructure, and technological improvements on water and food security. In particular, the IGHM model simulates natural hydrological processes, thus estimating water availability, while the IWSM model simulates human appropriation of surface water and groundwater, considering water infrastructure capacity and policies, based on which we water stress calculations. The model can also simulate impact of changes in fertilizer prices on food supply and changes in energy prices on the demand for hydropower development and on groundwater pumping.[4]

GLOBE-Energy is a recursive-dynamic multi-region CGE model which features a detailed representation of the technical substitution possibilities in the power sector.[5] The model is initially calibrated to the GTAP 8.1 database (Narayanan, Aguiar and McDougall, 2012) which represents the global economy-wide structure of production, demand and international trade at a regionally and sectorally disaggregated level for the benchmark year 2007. The model version employed in the present study distinguishes 24 commodity groups and production sectors (Table 1), and 15 geographical regions (Table 2).

In the development of a dynamic baseline for the present study, the growth rates of labor-augmenting technical progress by region are calibrated such that the regional baseline GDP growth rates replicate the GDP growth assumed in the IMPACT baseline projections. Moreover, for agricultural commodities, the sectoral total factor productivity parameters are calibrated such that the baseline producer price paths are consistent with the corresponding aggregated IMPACT producer price projections. To ensure that the baseline projections for agricultural quantity variables generated by GLOBE are broadly in line with the corresponding aggregated IMPACT projections as well, the parameters of the household consumer demand system are calibrated to be consistent with the aggregated household income elasticities of demand for the matched food commodity groups assumed in IMPACT.

The aggregate real income effects and changes in fertilizer prices associated with energy-related climate change mitigation measures generated by GLOBE are then downscaled to the IMPACT regional aggregation level and passed back to IMPACT to analyse the detailed implications for agricultural variables, water and food security.

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[4] For comparisons of IMPACT long-run projections with the projections of other global food system models under harmonized driver assumptions see von Lampe et al (2014), Nelson et al (2014a,b), Valin et al (2014) and Wiebe et al (2015)..

[5] For applications of earlier GLOBE versions in a food security context, see Willenbockel (2012) and Government Office for Science (2011).

## Table 1:  GLOBE Sector Aggregation

| Short Code | Description | GTAP Sector Code* |
|---|---|---|
| Rice | Rice | pdr,pcr |
| Wheat | Wheat | Wht |
| OCereals | Other Cereals | Gro |
| Oilseeds | Oil Seeds | Osd |
| SugarCane | Sugar Cane and Beet | c_b |
| OCrops | Other Crops | ocr,pfb |
| Cattle | Bovine cattle, sheep and goats, horses | Ctl |
| OLvstkPrd | Other Livestock Products | wol,oap,rmk |
| VegOils | Vegetable Oils and Fats | Vol |
| Sugar | Sugar | Sgr |
| OPrFood | Other  Processed Food | cmt,omt,mil,ofd,b_t |
| Coal | Coal | Coa |
| Oil | Crude Oil | Oil |
| NatGas | Natural Gas | gas,gdt |
| ONatRes | Other Natural Resources | omn,frs,fsh |
| LgtManuf | Light Manufacturing | tex,wap,lea,lum,ppp,omf |
| Petrol | Refined Petrols | p_c |
| Chemics | Chemicals, Rubber and Platics | Crp |
| OManuf | Other Manufacturing | nmm,i_s,nfm,fmp,mvh,otn,ele,omc |
| Electricity | Electricity | Ely |
| Water | Water Distribution | Wtr |
| Constrc | Construction | Cns |
| TrdTrns | Trade and Transport Services | trd,otp,wtp,atp |
| OServic | Other Services | cmn,ofi,isr,obs,ros,osg,dwe |

## Table 2: Example Region Aggregation

| Short Code | Description |
|---|---|
| Oceania | Australia, New Zealand and Other Oceania |
| China | China |
| OEastAsia | Other East Asia |
| India | India |
| OSthAsia | Other South Asia |
| HIAsia | High-Income Asia |
| NAmerica | North America |
| CAmerica | Central America and Caribbean |
| SAmerica | South America |
| EEA | European Economic Area |
| FSU | Former Soviet Union |
| MENA | Middle East and North Africa |
| WAfrica | West Africa |
| EAfrica | East and Central Africa |
| SAfrica | Southern Africa |

## 3. Scenario Design

The simulation analysis compares two baseline scenarios using SSP2 (Shared Socio-Economic Pathway[6] 2 – aka “middle of the road”) assumptions about population (Figure 3) and GDP growth (Figure 1) and no changes in fossil fuel taxes, with a range of energy price shock scenarios. In the first baseline scenario agricultural productivity grows according to IFPRI business-as-usual assumptions in the absence of climate change impacts on agricultural yields (NoCC). The second baseline scenario incorporates climate change impacts on agricultural productivity using climate projections generated by the HadGEM2-ES model under RCP (Representative Concentration Pathway) 8.5 radiative forcing assumptions.

In both baseline scenarios the global population rises from 6.8 billion in 2010 to 9.1 billion in 2050, whereby a large share of the net increase is projected for Sub-Saharan Africa (+931 million), South Asia (+743 million) and the MENA region (+255 million). Figure 2 compares the resulting average per-capita baseline income levels by aggregate GLOBE region for 2050 with 2010 in the absence of climate change impacts on agricultural yields. Figure 4 shows the impacts of climate change on aggregate real household income in 2050 relative to the NoCC baseline simulated by GLOBE and fed back to IMPACT.

The high fossil fuel user price scenario (HEP) assumes a gradual linear phasing-in of additional taxes on the use of primary fossil fuels globally from 2016 onwards up to 2050 on top of baseline taxes such that the additional ad valorem tax wedges between producer and user prices reach 70, 50 and 30 percent for coal, crude oil and natural gas respectively by 2050.

Scenario HEPAdap assumes the same fossil fuel tax increases as in HEP. In addition, first-generation biofuel feedstock demands by commodity and region rise by 30 percent above the levels assumed in the IMPACT baseline scenario and then gradually further up to 2050, such that in 2050 demands are 100 percent higher than in the baseline.

The low fossil fuel supply price scenario (LEP) assumes that from 2016 onwards the primary resource extraction in the coal, crude oil and natural gas sector rises gradually relative to the baseline such that by 2050 extraction levels are 50 percent higher than in the baseline.

[6] See O’Neill et al (2014,2015) for the SSP concept.

**Figure 1: Baseline GDP Growth by Region 2007 to 2050 – SSP2 NoCC**

*(GDP Index 2007 = 1.00; Average annual GDP growth rate 2007-2050 in percent)*

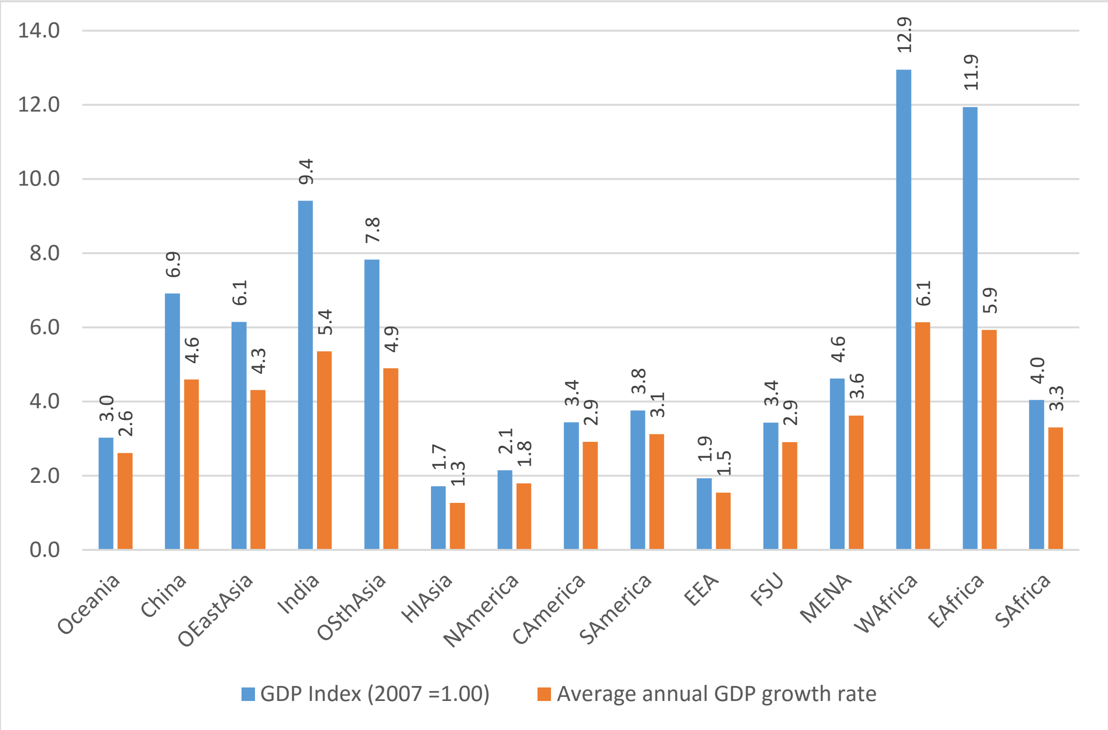



**Figure 2: Baseline Real GDP per Capita by Region 2010 and 2050 – SSP2**

*(In US$ 1000 at 2007 prices)*

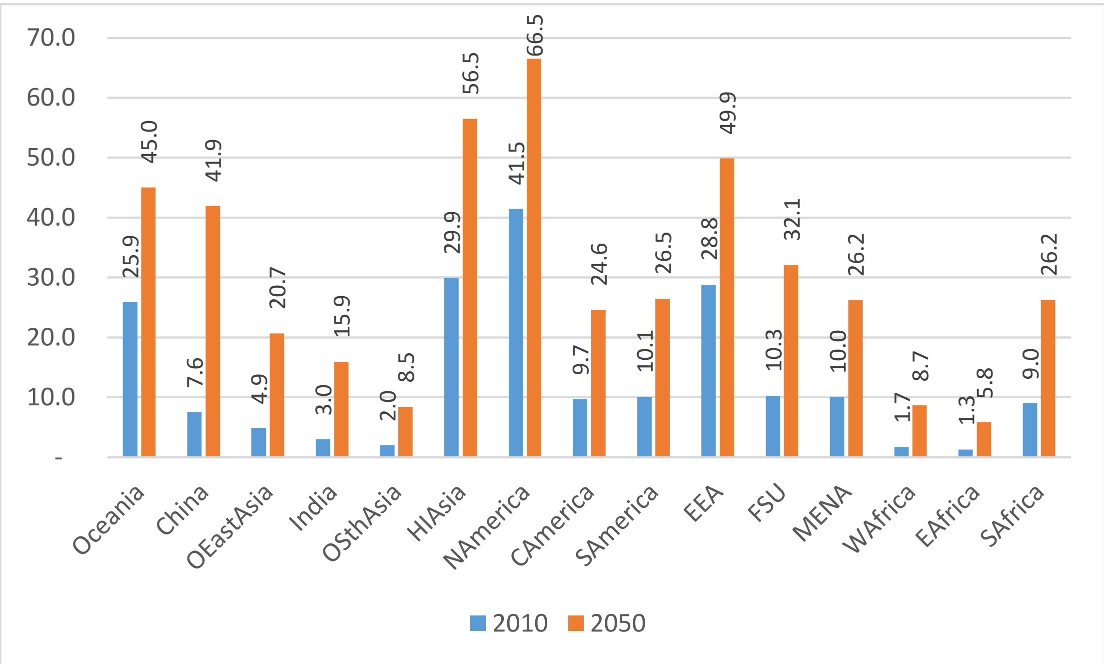


**Figure 3: Population by Region 2010 and 2050 – SSP2**

*(Million People)*

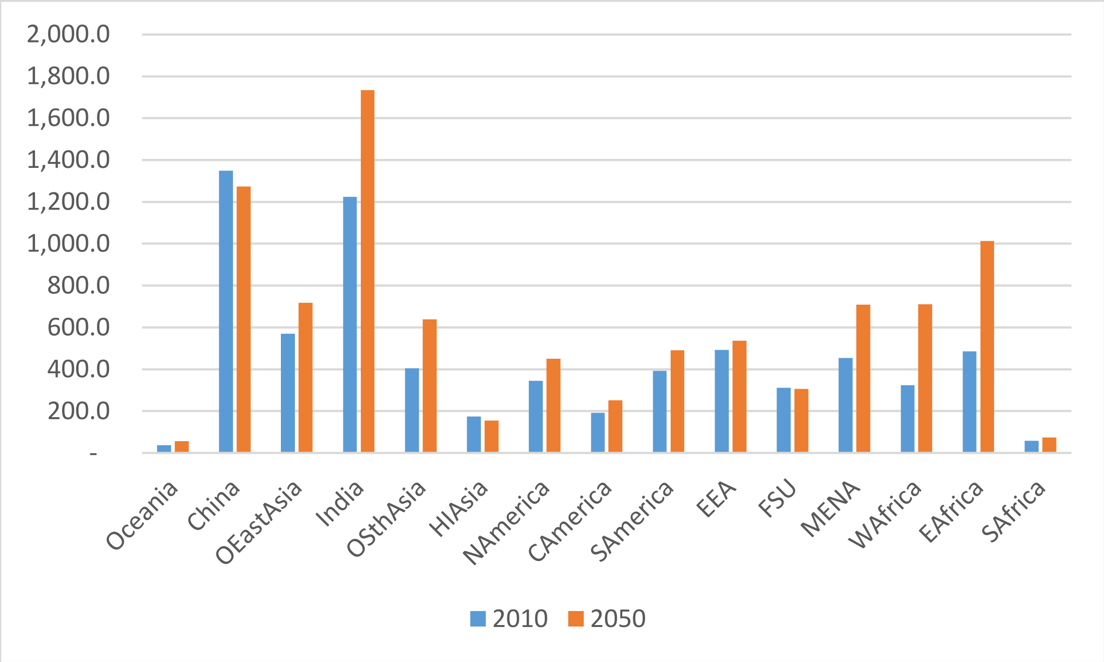
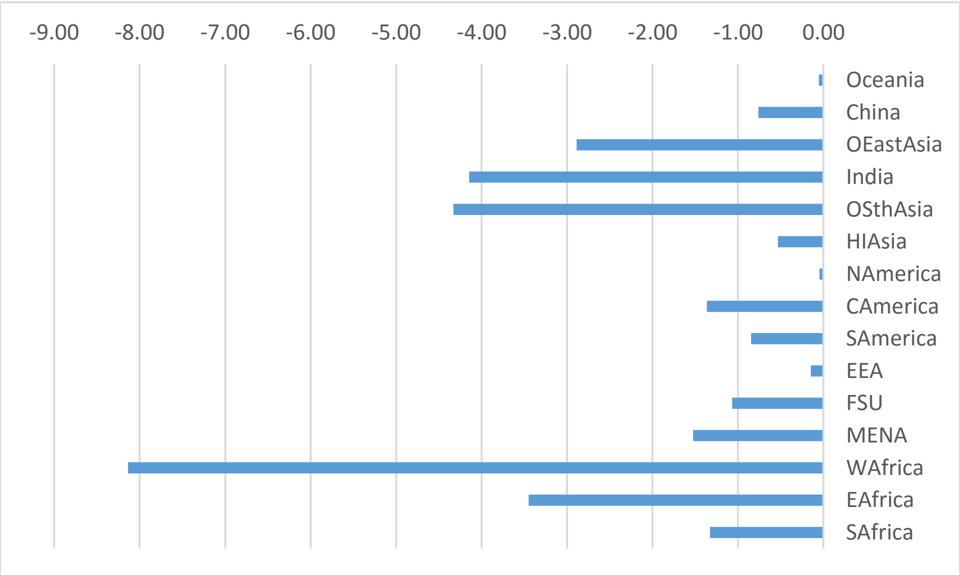



**Figure 4: Impact of HadGEM RCP 8.5. Climate Change on Real Income 2050**

*(Percentage deviations from No-CC Baseline)*



## 4. Results

The high energy price scenario (HEP) assumes a gradual linear phasing-in of additional fossil fuel taxes globally from 2016 onwards up to 2050 on top of baseline sales taxes such that the additional ad valorem tax wedges between producer and user prices reach 70, 50 and 30 percent for coal, crude oil and natural gas respectively by 2050. The resulting user price increases for the primary fossil fuels and petrol induce substitution effects towards renewable energy sources in production along with investments in more energy-efficient technologies as well as substitution effects towards less energy-intensive goods in final consumption. As a consequence, the demand for fossil fuels drops relative to the baseline and the producer prices for coal, crude oil and natural gas fall significantly, while the producer prices of refined petrol rise due to the increase in crude oil input costs.

From a macroeconomic perspective, these price shifts entail terms-of-trade gains for regions that are net importers of the primary fossil fuels and corresponding terms-of-trade losses for the net importers of these fuels (Table 3). Regions which are simultaneously net importers of primary fossil fuels and net exporters of refined petrol – namely India and High-Income Asia enjoy the largest terms-of-trade gains, while regions that are on balance net exporters of primary fossil fuels and net importers of refined petrol - namely Oceania, Other East Africa, Central America, East and West Africa – suffer pronounced terms-of-trade losses, as do net importers of both which are predominantly net importers of refined petrol (Other South Asia) or net exporters of both which are predominantly net exporters of crude oil (MENA, FSU, South America). Like Other South Asia, China, North America, the European Economic Area and Southern Africa are also net importers of both primary fossil fuels and petrol, but in contrast to Other South Asia primary fossil fuels dominate their net fuel imports bill, and thus these regions experience a positive terms-of-trade effect.

**Table 3: Terms-of-Trade Effects 2050**
*(% Deviation from Baseline Scenario)*

| | No Climate Change | | | With Climate Change | | |
|---|---|---|---|---|---|---|
| | HEP | HEPAdap | LEP | HEP | HEPAdap | LEP |
| **Oceania** | -2.7 | -2.6 | -0.7 | -2.7 | -2.5 | -0.7 |
| **China** | 0.9 | 0.9 | 2.5 | 0.9 | 0.8 | 2.5 |
| **OEastAsia** | -1.2 | -1.2 | 1.8 | -1.2 | -1.2 | 1.8 |
| **India** | 6.6 | 6.6 | 7.4 | 6.5 | 6.5 | 7.4 |
| **OSthAsia** | -3.9 | -3.9 | 7.0 | -3.9 | -3.9 | 7.0 |
| **HIAsia** | 5.2 | 5.1 | 2.6 | 5.1 | 5.0 | 2.6 |
| **NAmerica** | 2.0 | 2.0 | 2.1 | 2.0 | 2.1 | 2.1 |
| **CAmerica** | -2.2 | -2.2 | 0.8 | -2.1 | -2.1 | 0.8 |
| **SAmerica** | -1.1 | -0.9 | -0.8 | -1.1 | -0.8 | -0.8 |
| **EEA** | 1.0 | 1.0 | 1.1 | 1.0 | 1.0 | 1.1 |
| **FSU** | -2.9 | -2.9 | -8.4 | -2.8 | -2.8 | -8.4 |
| **MENA** | -6.0 | -6.1 | -10.8 | -5.9 | -6.0 | -10.8 |
| **WAfrica** | -10.8 | -10.8 | -6.9 | -10.7 | -10.7 | -6.9 |
| **EAfrica** | -5.1 | -5.1 | -3.3 | -5.1 | -5.1 | -3.3 |
| **SAfrica** | 1.6 | 1.6 | 1.4 | 1.5 | 1.5 | 1.4 |

Figure 7 depicts the impacts on the prices of chemical goods passed on to IMPACT, which serve as proxies for the impact on fertilizer prices. Regional variations are primarily due to differences in the shares of fossil fuels and electricity costs in the total production cost of chemicals.

Scenario HEPAdap assumes the same fossil fuel tax increases as in Scenario HEP. In addition, first-generation biofuel feedstock demands by commodity and region rise by 30 percent above the levels assumed in the IMPACT baseline scenario and then gradually further up to 2050, such that in 2050 demands are 100 percent higher than in the baseline. As shown in Table 3 and Figures 5 to 7, the impacts on macro aggregates and fertilizer prices are closely similar to scenario HEP.

The low energy price scenario (LEP) assumes that from 2016 onwards the primary resource extraction in the coal, crude oil and natural gas sector rises gradually relative to the baseline such that by 2050 extraction levels are 50 percent higher than in the baseline. As a result, world market fossil fuel prices in 2050 are around 25 percent lower than in the baseline. The dominant macroeconomic effects are again significant terms-of-trade losses for fossil fuel net export regions mirrored by terms-of-trade gains for the net-importing regions (Table 10). These terms-of-trade effects are the main drivers of the household real income effects depicted in Figures 5 and 6. Not surprisingly, fertilizer prices drop noticeably in all regions relative to the baseline (Figure 7).

A positive terms-of-trade effect is per se associated with a real income gain for the region, as each unit of aggregate real exports buys more aggregate real imports than before, while a negative terms-of-trade effect means a real income loss as more real exports are required per unit of aggregate imports than before (Figures 5 and 6). As shown in Figure 8, the terms-of – trade impacts are closely associated with the impacts on household real income passed on to IMPACT after downscaling.

To downscale the real income effects from aggregate GLOBE regions to IMPACT countries, we exploit the fact that – in line with the argument above - the household real income deviations from the baseline simulated are highly correlated with the initial ratios of net fossil fuel exports to GDP – e.g. this ratio explains 90 percent of the variation in real income effects for Scenario 2 in 2025 (see Figure 9). We calculate the initial net fossil fuel export ratios for all 135 regions in the fully disaggregated GTAP 8.1 database and use these figures in regressions of the type shown in Figure A1 to downscale the real income effects to GTAP regions. The results from this step are then rescaled so that the weighted average of GTAP region figures for any composite GLOBE region matches with the simulated GLOBE region results. Finally, the GTAP region results are then mapped to IMPACT regions.

**Figure 5: Impact of Energy Price Shocks on Real Household Income 2050**

*(% Deviation from With-Climate-Change Baseline)*

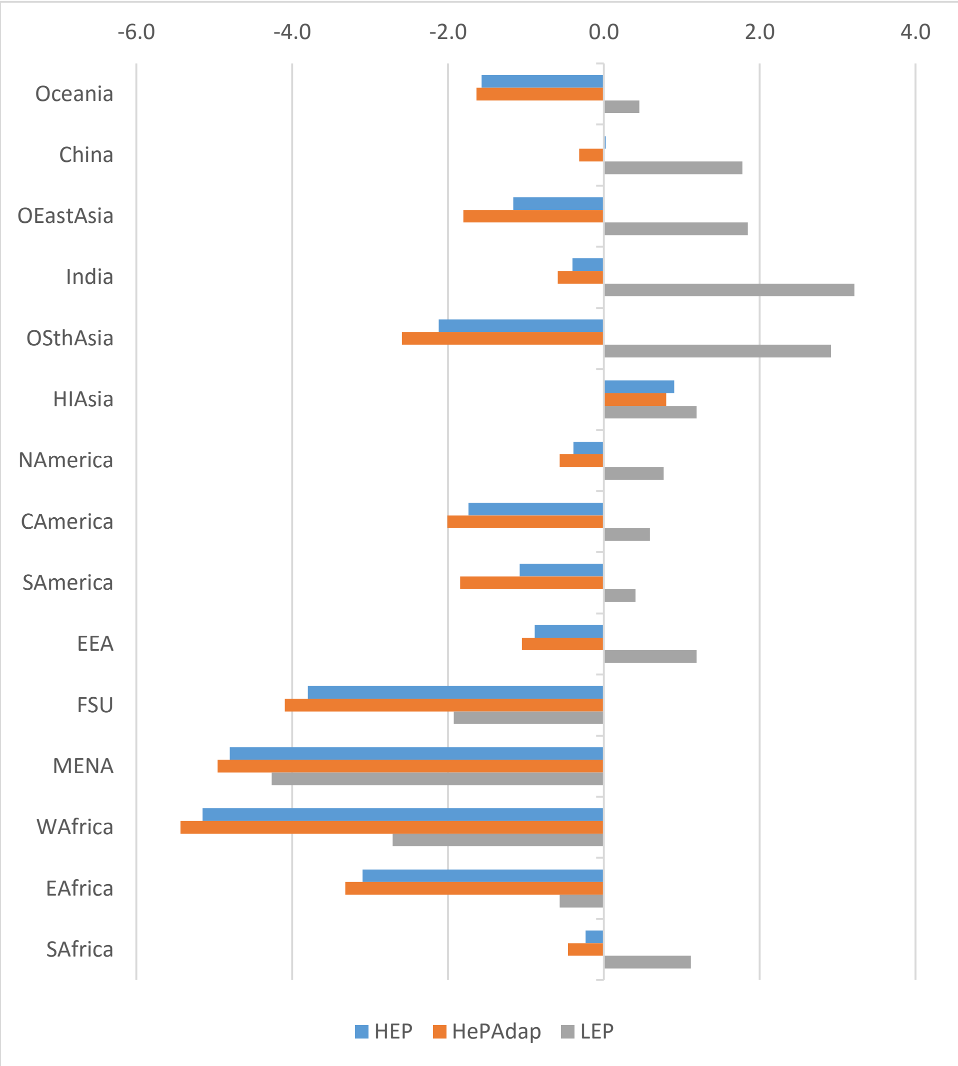


**Figure 6: Impact of Energy Price Shocks on Real Household Income 2050**

*(% Deviation from No-Climate-Change Baseline)*

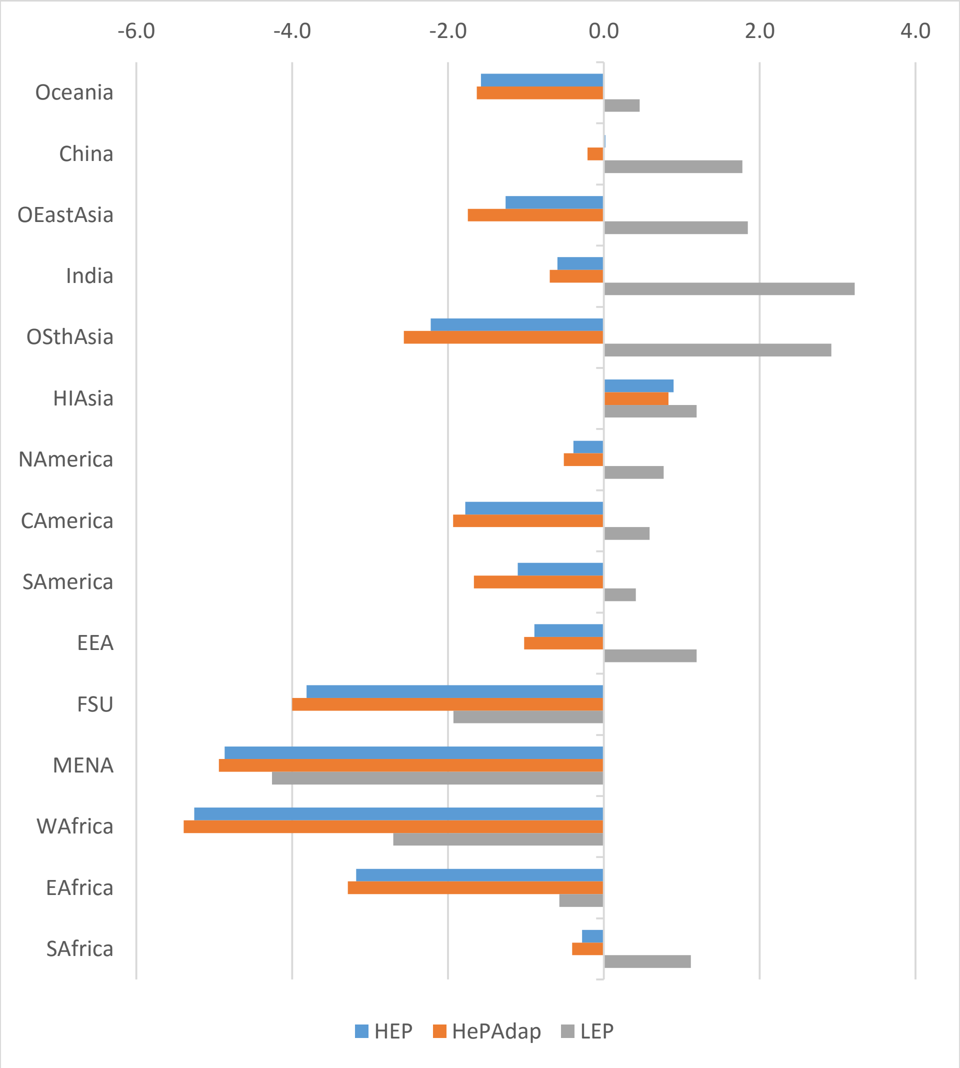


**Figure 7: Impact of Energy Shocks on Prices of Chemicals**

*(% Deviation from No-Climate-Change Baseline)*

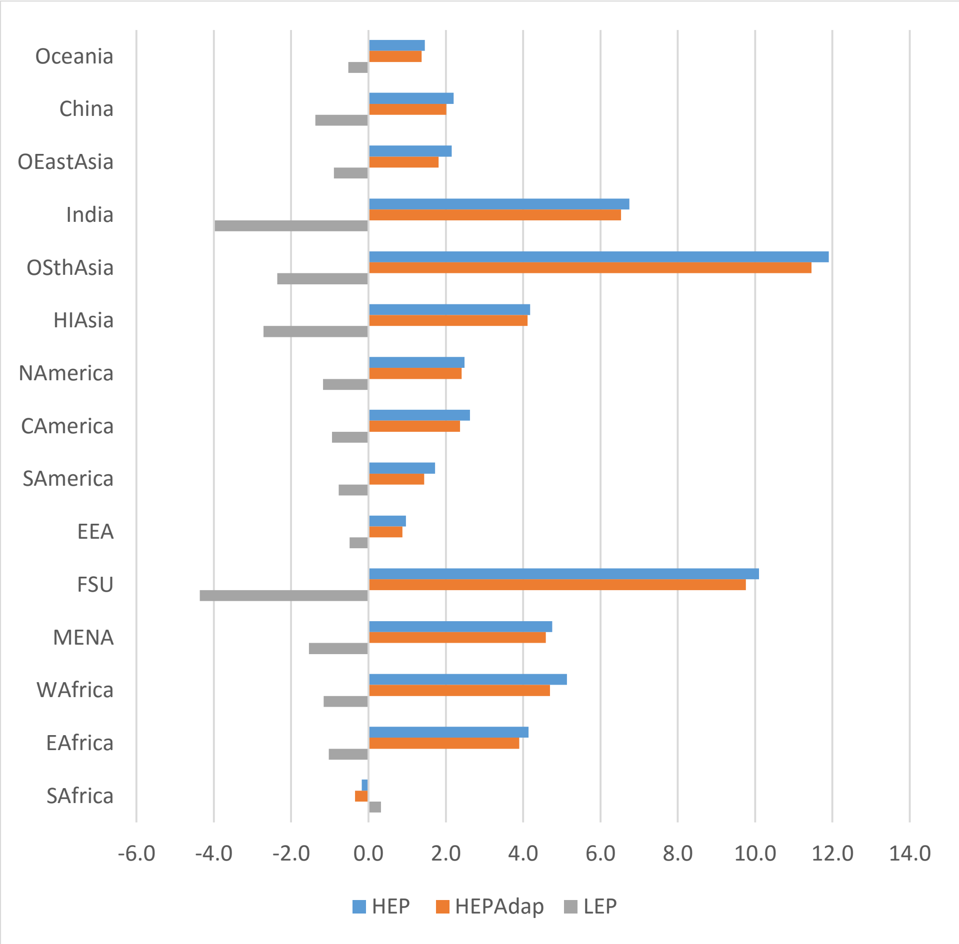


**Figure 8: Correlation of Terms-of-Trade and Real Income Impacts**

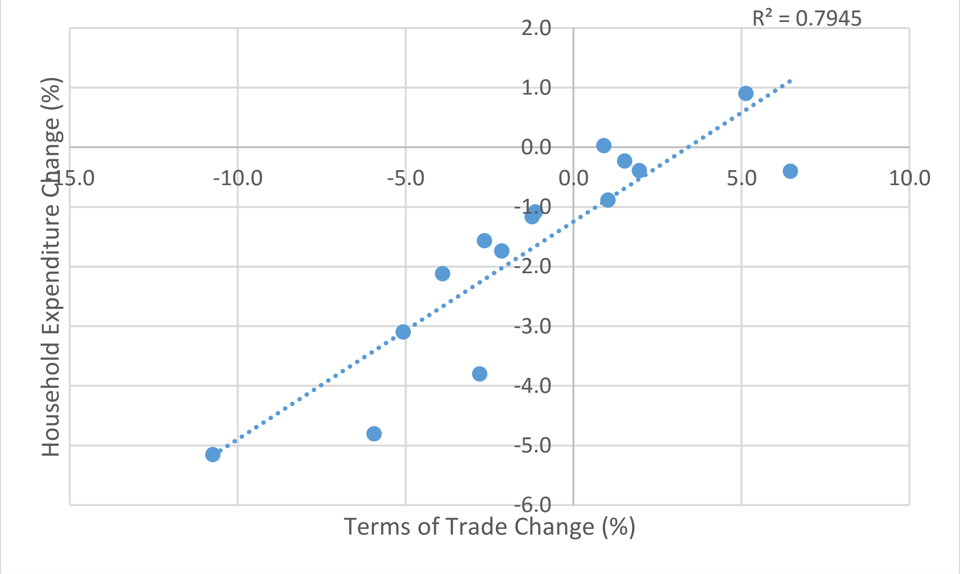
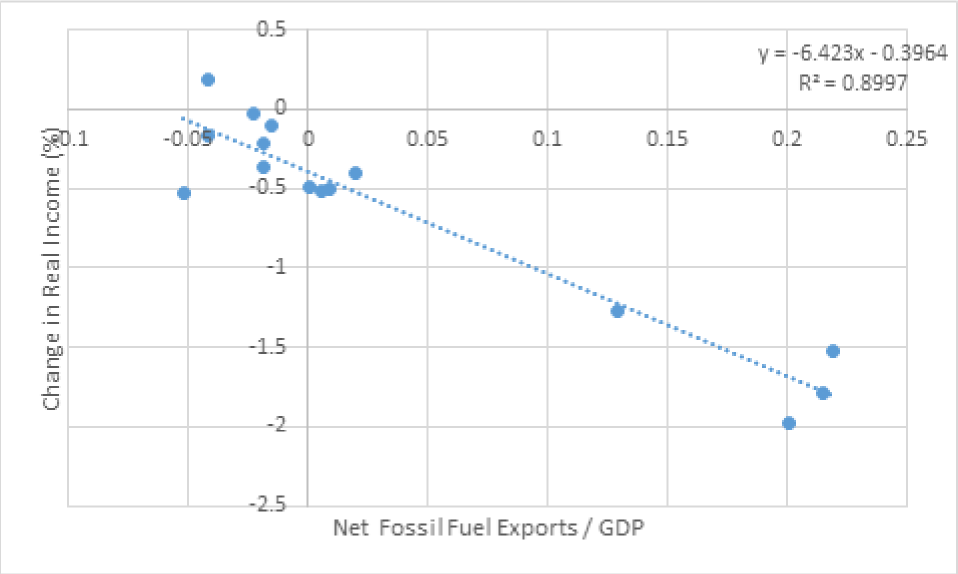



**Figure 9: Correlation between GLOBE Real Household Income Changes and Initial Net Fossil Fuel Exports / GDP Ratios (Example: HEP Scenario, 2025)**



The simulation results suggest only moderate indirect effects on agricultural prices and food security outcomes. While higher prices for chemical fertilizers and reduced groundwater pumping due to higher energy costs per se push crop prices up to some extent, the adverse real income effect on food demand pull crop prices in the opposite direction. The price effects are slightly more pronounced when the energy price increases are assumed to induce a significant increase in first-generation biofuel production relative to IMPACT baseline assumptions.

*[Table with IMPACT Results and discussion to be added]. See Ringler et al (2016) for initial results.*

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